Evolution of Servitised Circular Economy-Driven Models within a Nascent Business Case Study

Transformative Horizons:

Exploring Theory-in-Practice of Product Service Systems and Industry 4.0

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SUBMITTED IN PART FOR THE MSC IN ADVANCED INDUSTRY 4.0:

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Abstract

The significant effect of Industry 4.0 on global indicators such as climate, resource availability and energy-efficient production are well documented, spanning almost every conceivable area of consumption. The Ellen MacArthur Foundation posits efficiency can reduce energy and material use but resource consumption remains strongly coupled to economic growth. Industry 4.0 provisions for improvements in production through quality enhancements, increased productivity and more efficient utilisation of resources, both physical and human. Circular Economy (CE), Product Service Systems (PSS) and knowledge-based maintenance (KBM) approaches such as Prescriptive Maintenance are key pillars of Industry 4.0. To facilitate the delivery of a bespoke PSS, eclectic but complimentary strategies from Industry 4.0 can be called on, and digital services including Software as a Service (SaaS) and advanced manufacturing technologies are particularly relied on. The adoption of an overarching PSS approach does not guarantee CE aspirations or good practices are attainable, therefore implementation hurdles such as technological preparedness, availability of skilled application and deployment personnel, digital oversight and management are considered. This investigation considers a singular, although not atypical nascent case business wherein a Digital Servitisation (DS) approach was identified at an early stage as not only desirable but also critical. With the case business firmly in focus, this investigation explores the potentially transformative impact through the implementation of a DS strategy, incorporating the research community's perceived most appropriate Industry 4.0 technologies. The study considers the wider concepts of CE, illuminating the persistent interplay between CE and servitisation, why value retention is important and how it is potentially delivered through Industry 4.0 pillars of PSS, SaaS and KBM. The wider discussions will serve to inform a theory-to-practice framework to support business planning during the early phases of development and towards product launch.

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Author’s Declaration

I declare that the work in this dissertation was carried out in accordance with the regulations of UWTSD. The work is original except where indicated by special references in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the UWTSD.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

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Date 3Rd March 2023

Contents

List of Figures

List of Tables

Glossary

Acronym	Description
AEC	Architecture, Engineering, and Construction
ANN	Artificial Neural Network
ASP	Application Services Provision
BPM	Baseline Predictive Maintenance
CBM	Condition-Based Maintenance
CE	Circular Economy
CI	Critical Infrastructures
CC	Cloud Computing
CPS	Cyber-Physical Systems
DHI	Device Health Index
DT	Digital Twin
EOL	End of Life
EOU	End of Use
EMF	Ellen MacArthur Foundation
ERP	Enterprise Resource Planning
eDiM	Ease of Disassembly Metric
HI	Health Indicator
HS	Health State
IIoT	Industrial Internet of Things
IP	Intellectual Property
IPM	Intelligent Prediction Maintenance
IoT	Internet of Things
IaaS	Infrastructure as a Service
IS	Industrial Symbios
IT	Information Technology
KBM	Knowledge-Based Maintenance
ML	Machine Learning
NPD	New Product Development
OD	On-Demand
OTAUs	Over-The-Air Updates
PaaS	Platform as a Service
PSS	Product Service System
PPC	Production Planning and Control
PdM	Predictive Maintenance

Acronym	Description
PAYG	Pay As You Go
PM	Preventative Maintenance
RtR	Right to Repair
RUL	Remaining Useful Life
RxM	Prescriptive Maintenance
SaaS	Software as a Service
SCM	Supply Chain Management
SM	Spot Market
SBC	Single Board Computers
SCADA	Supervisory Control and Data Acquisition
TD	Target Device
TPU	Tensor Processing Units
TOC	Total Cost of Ownership
USPTO	United States Patent and Trademark Office
VRPs	Value-Retention Processes
VM	Virtual-Metrology
VPU	Video Processing Units

Chapter 1: Introduction

Background

The Author and Case Business

The author has a professional background in technical problem-solving for diverse manufacturers and service industries spanning three decades. More recently the author embarked on a program of postgraduate study on Advanced Industry 4.0 and Innovation Management. In parallel the author also had commenced the development of a new commercial enterprise which potentially could benefit from an in-depth understanding of the relationships between key pillars of Industry 4.0 and how that knowledge could facilitate a practical and affordable theory-to-practice exercise, in essence drawing a blueprint enabling an efficient and CE responsible corporate strategy. The author's enterprise forms the Case Business of this dissertation and is further elaborated on in Chapter 3.

Rationale

CE is frequently associated with the performance economy, characterised by business models that involve selling goods as services through methods such as renting, leasing, and sharing, with the manufacturer retaining ownership of the product (Stahel, 2010). A PSS is a business model innovation strategy aiming to fuse products and services, offering the potential to uncouple business success and economic growth from sole reliance on product sales, "a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs" (Tukker and Tischner, 2006, p. 1552). CE and PSS have emerged as promising and potentially synergistic strategies to mitigate or reverse the environmental, economic, and societal impacts (Ness and Xing, 2017).

To facilitate the delivery of a tailored PSS, complimentary Industry 4.0 technologies are explored, Software as a Service (SaaS) and advanced maintenance strategies, and in particular Prescriptive Maintenance (PdM). An assessment is necessary to qualify how effectively these selected technologies will support a proposed PSS oversight and potentially deliver a transformative product to a market, whilst meeting the ethical aspirations of the CE for the business, and simultaneously, the expectations of the end user in performance, cost and useful life expectancy.

Research Gap

Although PSS is seen as a viable business strategy for advancing the transition to a CE (Kjaer et al., 2019), the adoption of a PSS does not inherently assure the realisation of a CE ambition (Tukker, 2004; Kjaer et al., 2016), and CE strategies do not automatically result in the detachment of economic growth from resource consumption in absolute terms (Nancy et al., 2017). This transition encounters various practical obstacles, including issues related to technological preparedness and the seamless integration of both established and emerging products, manufacturing methods, as well as digital monitoring and management tools.

Being cognisant of the state of readiness or maturation of these methodologies and technologies when planning a new product, and how that product meets customer needs and performance expectations is key to achieving a higher degree of confidence in success outcomes. Integration of the technically supportive delivery methodology with a monetisation pathway to leverage optimal returns, while satisfying customer performance expectations is highly desirable and challenging, whilst meeting the ethical expectations of the consumer, the wider public and the regulatory bodies.

Aim and Objectives

Objectives

In investigating the dynamics of the contemporary business landscape, this dissertation embarks on an exploration of the transformative impact on the delivery by the case business of a commercial service, a physical product complimented by an added value digital support element. Of late, supportive third-party service provision has undergone evolutionary step changes, enabling the democratisation of scalable cloud-based business models. The advanced principles of Industry 4.0 power this evolution, and for this investigation, a particular focus is on a PSS model integrating advanced maintenance strategies and the desire to support a CE throughout consumption.

Aims

The aims of the study are:

1. to illuminate the complicated interplay between servitisation, Industry 4.0 principles, and the adoption of SaaS, within the context of a PSS,
2. to provide detailed insights into the challenges and opportunities that unfold in this dynamic landscape and, further,
3. to inform proposed business development roadmaps for consideration by the case business.
4. to identify opportunities and their associated barriers, towards incorporation of practices sympathetic to the theory of the CE, with the potential to improve overall profitability.

Research Question

Considering PSS models and CE strategies and addressing the duality of resource utilisation and waste reduction, the question arises:

Can a meticulously devised business development and delivery model be postulated, tailored to a specified use case, with the capacity to fulfil or potentially surpass the expectations and requisites of the end user? Furthermore, can such a model concurrently ensure an optimal revenue return while actively still contributing to the facilitation of a CE transition?

Methodology

The approach undertaken is that of a qualitative research study, using a literature review as a research methodology (Snyder, 2019), and further adopting a theory–in–use approach (Zeithaml et al., 2020; Muurinen and Kääriäinen, 2022; Ulaga and Reinartz, 2011) of a case business The case business familiar to the author, operates in the MedTech sector. A search term-directed literature review of the DS landscape was carried out using the internet search engines including academic library search engines and databases accessible through the author’s institute of study and generally available browser search engines such as Google and Bing.

The literature review considers the ethical, economic, and technical landscape, leading to the proposal of a servitisation framework. The existing developmental status within the context of the study business and its precursors inform the structure of the servitisation framework, from inception to its current state. The case business is considered as objectively as possible, although the author acknowledges subjectivity must also be acknowledged as a potential research weakness, consequent to the author's detailed familiarity with the case business.

Structure of the Dissertation

The dissertation structure encompasses a comprehensive exploration through a detailed literature review, focusing on the foundational elements crucial for supporting a proposed PSS model tailored for contemporary business development. The primary pillars under scrutiny include PSS, SaaS, CE, and PM. After the literature review, the acquired insights will undergo a systematic analysis employing a structured methodology aligned with a contrasting review approach. The resultant findings will then serve as the underpinning for a theoretical framework specifically designed to address the business requirements during the initial planning stages of business development. The proposed framework will undergo scrutiny to assess potential risks, benefits, and societal impacts associated with its implementation and sustained utilisation over the long term. The examination will involve careful consideration of industry-specific dynamics, aiming to provide valuable insights for the formulation of a well-informed business development strategy. In conclusion, the dissertation will present key findings, delineate the implications of the study, and offer recommendations for prospective avenues of theory into practice, for the case business and more extensively, facsimiles not limited to the case industry sector alone.

Scope and Limitations

To navigate this investigation, the methodology employed revolves around an extensive literature review with a contrasting approach, concentrating on the high-level PSS model as a pivotal and advanced strategy within the broader spectrum of maintenance methodologies, and the risks, challenges and benefits accompanying their integration.

Ethical Considerations

Where a level of detail may be subject to commercial sensitivity and in instances where disclosure may have a detrimental impact on the case business including but not limited to Intellectual Property (IP), those aspects and details will be appropriately respected.

Work produced by other authors and publications and referred to within this dissertation will be acknowledged by appropriate citation and credits.

Chapter 2: Literature Review

The Circular Economy (CE)

Background

"Circularity is not a trend; it's a culture shift"; Ken Webster (Webster and Ellen Macarthur Foundation, 2017). The Ellen MacArthur Foundation (EMF) further asserts that " Efficiency can lower the amount of energy and materials used per dollar of GDP but fails to decouple the consumption and degradation of resources from economic growth. This calls for system-level redesign. The CE provides a model which, if implemented correctly, would go much further than minimising waste." (www.ellenmacarthurfoundation.org, 2013, p.15).

CE continues to gain recognition as a solution to the ongoing challenge of resource scarcity while simultaneously promoting economic growth and job creation (European Commission, 2020). The CE introduced by environmental economists (Pearce and Turner, 1990) is founded on the principles of industrial ecology, on the journey physical resource undertakes, from extraction from resources and the energy consuming transformation into products and services. In industrial ecology, it is implied that a CE will be beneficial to society and the economy (Andersen, 2007).

However, CE functions as an umbrella conceptual framework (Blomsma and Brennan, 2017) consolidating various sub-concepts and empowering them with a renewed significance by emphasising common attributes. Blomsma and colleagues present extensive research on and rank many researchers who propose tools for outcome-based frameworks, guiding manufacturing entities towards the transition to CE practices within innovation activities. (Blomsma et al., 2019). This study aims to contribute to the body of frameworks with a focus on DS embodying responsible CE practice.

Three economic functions of the environment can be identified: provision of resources, life support system, and sink for waste and emissions (Ghisellini et al., 2016). The three fundamental functions should be assigned a monetary value. Nevertheless, in many instances environmental commodities, such as air and water quality or public goods, lack an associated price or a market, despite possessing discernible value or utility for people and societies.

Gains will accrue not solely through the reduction of environmental residuals but, arguably more significantly, through the mitigation of the consumption of virgin materials for economic endeavours. While the potential advantages may appear self-evident intuitively, it is crucial to emphasise that the conceptual framework inherent in the CE approach is rooted in physical, rather than economic, observations. (Andersen, 2007).

Amongst various models to support the transition to CE is Industrial Symbios (IS), (Jacobsen, 2006), characterised by Chertow, (2007, p.313), "The part of industrial ecology known as industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical ex-change of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity", although a recent newcomer to the CE ecosystem, IS has been engaged throughout the ages with people trading in commodities and exchanging goods (Rachel and Laybourn, 2012).

With opportunities to employ IS strategies, global CE endeavours can be considered directed towards one of three distinct levels, as delineated by (Yong, 2007; Yuan et al., 2008) Fig. 1 depicts a simple visualisation (Blomsma et al., 2019) and further identifies the nano level. The macro level concentrates on geographically delimited regions such as cities, provinces, and countries; the meso level focuses on eco-industrial networks wherein another company repurposes waste (material or energy) from one company; and the micro level directs attention to refining or enhancing the environmental performance within organisations. This involves strategies such as reducing resource consumption, minimising waste disposal, or manufacturing products with reduced environmental impact.

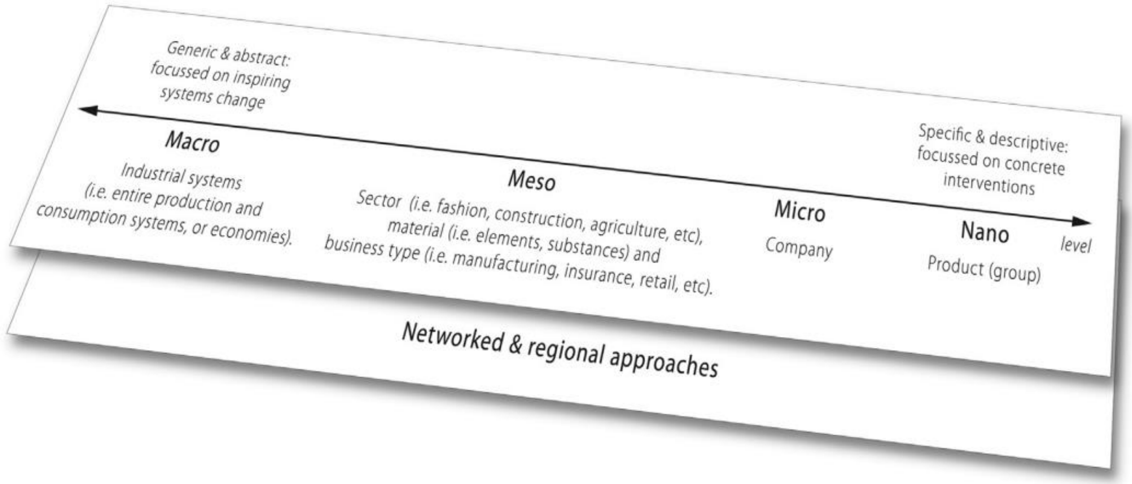


Figure 1 Schematic illustrating the coverage of frameworks on the macro-meso-micro-nano scale, but their relationship with frameworks covering networked and regional approaches. (Blomsma et al., 2019)

The Four Rs

Popular constructs enable circularity across all four levels of the scale feature one prominent strategy set. The strategies collectively denoted by the four Rs (reduction, repairing, remanufacturing, and recycling) represent deliberate or inadvertent approaches employed by organisations to enhance efficiency (Russell et al., 2023). The precursors and enablers to the Four Rs comprise to some extent on the approach to design (or redesign/ adaptation) of a product or service, and consideration of the 4Rs is particularly relevant to the current investigation. Fig. 2 Illustrates the relationships of the 4Rs in universal ‘cradle to cradle’ CE methodology for consideration (Kalmykova et al., 2018).

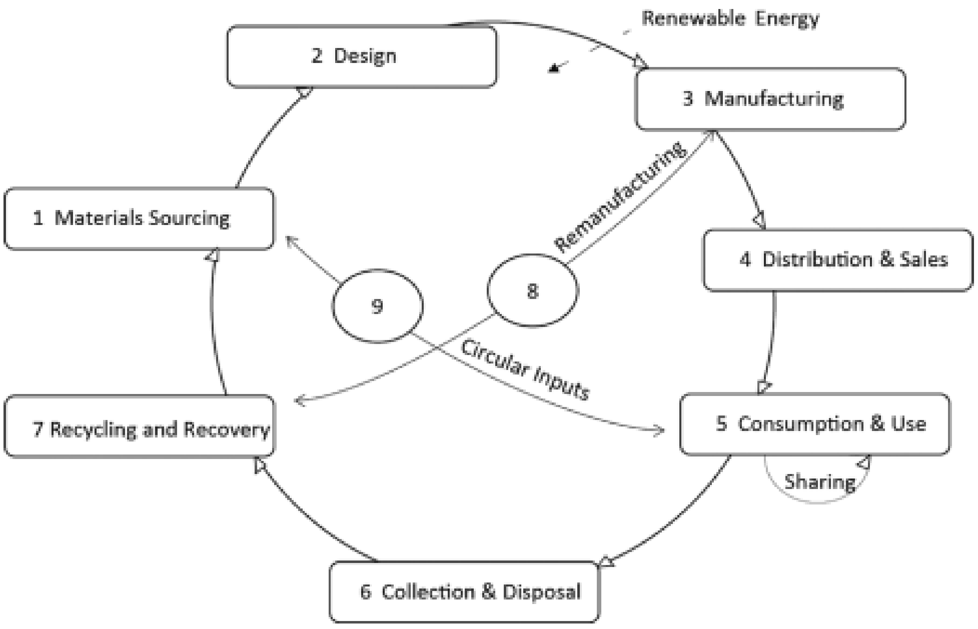


Figure 2 Resource flows through a value chain in a CE, from (Kalmykova et al., 2018) the numbers denote codes for parts of the value chain in Table 1. CE Strategies Database

Evolved mainly by design and manufacturing community, the message is that the close-to-centre loops of Fig. 3, product reuse, remanufacturing, and refurbishment, consume fewer resources and energy, become economically more efficient than traditional recycling of materials as raw materials and the duration the resources exist within the inner circles should be maximised. Materials should first be recovered for reuse, refurbishment, and repair, then for remanufacturing and only later for raw material utilisation, which has been the focus of traditional recycling (Korhonen et al., 2018). Combustion for energy should be a penultimate option while the ultimate is landfilling disposal. Thus, the product value chain strives to sustain the utmost worth and quality for the longest duration possible while concurrently optimising energy efficiency.

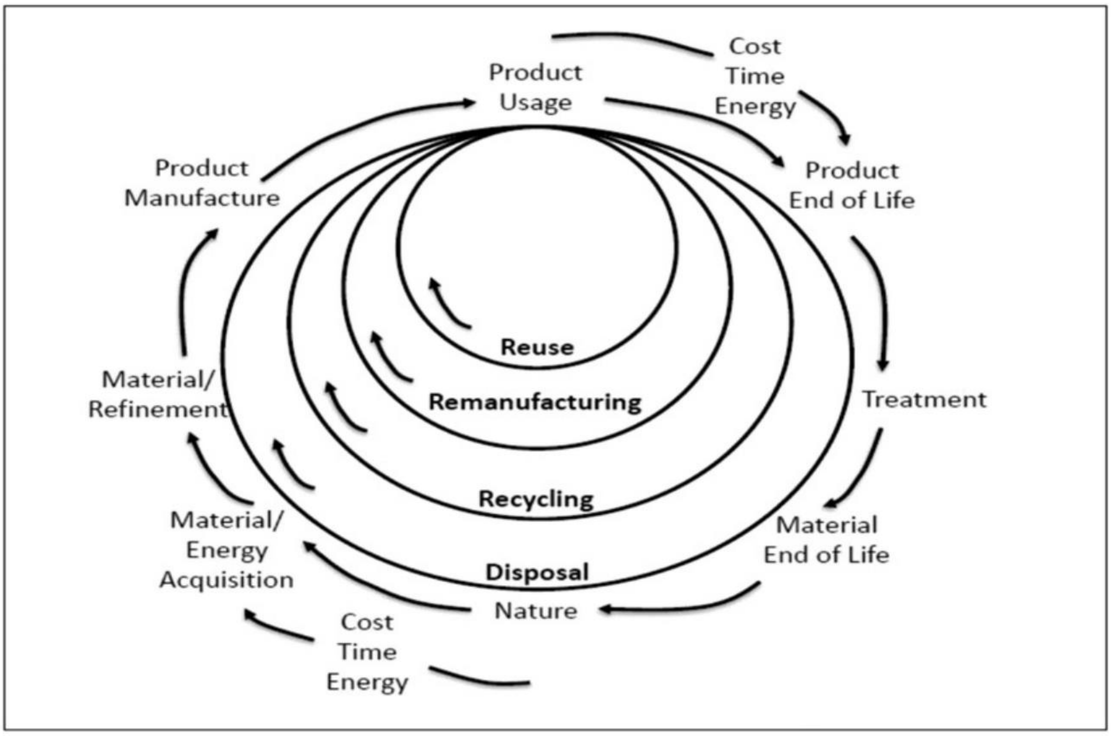


Figure 3 An eloquent depiction of desirable lifecycle loci in CE (Korhonen et al., 2018).

CE Implementation

Surveys conducted at the micro level, where the case business resides, concerning the adoption of CE strategies reveal that a considerable proportion of organisations lack a comprehensive understanding of the four Rs, while there is an emphasis on reduction and recycling, comparatively less attention to repair and refurbishing. A significant gap even among those utilising the four Rs to enhance their business practice. Evidence suggests that despite claims of explicit adoption of CE practices, the actual implementation remains suboptimal (Barreiro-Gen and Lozano, 2020). To close the loop in CE and enhance operational efficiencies, closer integration between theory and practice can be achieved by involving collaborative engagement with stakeholders, i.e. those who are impacted by or have a stake in organisational activities, and even extending to the good citizen.

Enabling the strategies outlined in Fig. 1 and Fig. 2, three foundational principles aimed at achieving beneficial outcomes are proposed (Nancy et al., 2017):

(1) Slowing resource loops: Through the design of long-life goods and product-life extension (i.e., service loops to extend a product's life, for instance through repair, remanufacturing), the utilisation period of products is extended and/or intensified, resulting in a slowdown of the flow of resources.
(2) Closing resource loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources. These two approaches are distinct from a third approach toward reducing resource flows:
(3) Resource efficiency or narrowing resource flows: aimed at using fewer resources per product.

Collectively the illustrations of Figures 2 and 3 with the three principles encapsulated by Nancy and colleagues (2017) form an easily understood guide when businesses are in early-stage planning of a CE friendly initiative.

Consumption and Legislation

To curb wanton consumerism, enforcement by the legislative authorities is continually evolving. “we cannot keep living in that way, we have to change ourselves from self-interested to socially reciprocating, from fixed preferences to fluid values and from isolated to interdependent ones” (Raworth, 2017, p.84), the model of take, make, use, lose, consumers persist in purchasing new products as soon as available funds permit (McCollough, 2020). To address these undesirable consumer habits CE has evolved to a new level making the entire society answerable in meeting evolving targets. Kirchherr et al., (2017, p.9) on a review of 114 CE definitions relays the impression, “some of the authors […] seem to have no idea about what [CE] is about”. Therefore, it unsurprising consumers persist in these undesirable habits by making the final decision to either retain and use or to buy new, without any perceptible dependence on their view of the eco-credentials of the new product (Ackermann et al., 2018). Business perspective and guidance from the bottom up are being emphasised repeatedly, (Milios, 2021) with the European Union setting out action plans to promote the adoption of CE principles to focus manufacturers and associated businesses on activities enabling consumer participation. Lowering the barriers to collective reuse, residual value capture and product life extension through policy-driven changes to existing practice is often embraced by the incumbent actors and their political lobbyists (Geels, 2014). It is imperative every business not only considers existing legislation but looks to the CE relevant legal horizon continually in preparation.

Refurb, Reuse & Social Sharing

The case business will have a product in which resources have been invested, however products are no longer perceived as mere commodities but are regarded as assets carrying associated responsibilities. Within the general concept of design for repair, including aspects of refurbishment, the effectiveness of design for refurbishment is contingent upon the identity of the refurbishing entity, be it the manufacturer, an independent company, or an individual. While design for repair can be reformed for individual consumers with adequate technical guidance and skills, more extensive design effort is necessary to facilitate large-scale refurbishment for larger entities.

legislation and policies are being put in place to promote the Right to Repair (RtR), (Hughes, 2021 to help ease the adoption of retention and reuse by consumers and motivate manufacturers towards product lifecycle management (Roskladka et al., 2023).

To aid design-for-repair awareness, Vanegas et al. (2018) advocate for the utilisation of a robust methodology termed "eDiM" (Ease of Disassembly Metric) for calculating disassembly time. eDim is derived from the Maynard Operation Sequence Technique (MOST). As ecolabels and national CE directives evolve, the adoption of eDiM or a comparable relative metric has the potential to aid manufacturers in awareness of the significance of integrating ease of disassembly into design considerations. In turn, this facilitates the implementation of measurable design iterations to improve the prospects for future refurbishment, repair, and the recovery of materials or sub-components for reuse or appropriate sorting for recycling purposes.

Reike et al. (2018) outline the process of educating consumer behaviours to mitigate recurring demand, encompassing practices such as user acknowledgement of diminished frequency of product use, good product stewardship, and extension of product lifespan through repair. This educational initiative also involves participation in social sharing mechanisms, including simultaneous utilisation through pooling and sequential sharing of products. Conversely, the refurb and repair paradigm, specifically refurbishment, entails interventions without altering ownership and implies the involvement of distinct repair actors in the process.

Temporary Ownership

Evertoys (Evertoys, 2023), a 2017 start-up operating in Romania offered an interesting take on the ownership-sharing premise (Nastase et al., 2022) and brings attention to the cost of temporary ownership close to the centre of CE principals. Although articulated within the toy industry as novel, the concept of leasing, cars or tools etc, and within the home as handed down items, has been prevalent for a long time before CE was proposed. The concept of temporary ownership as a business model in relatively low to medium-value consumer items is not so embedded. The diagram of Fig. 4 illustrates the conceptual relationships between the terms CE and sharing economy, along with the facilitating factors influencing the transition to the CE, including sustainability, technology, and the cost of temporary ownership.

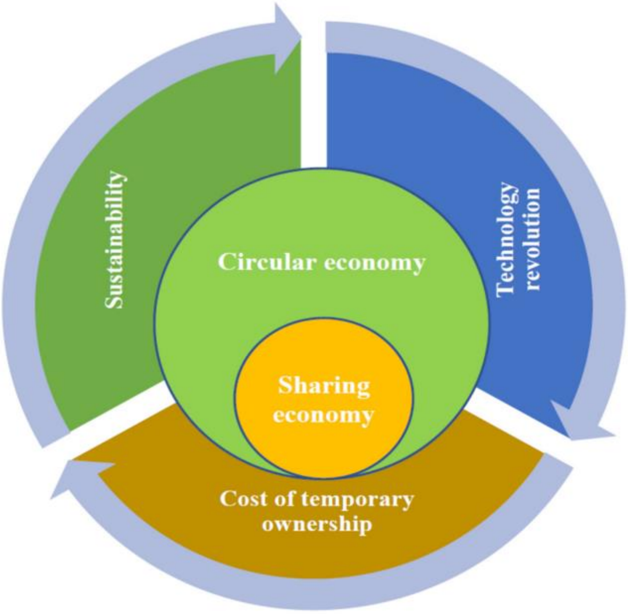


Figure 4 The sharing economy and interplay with influencing factors around CE (Nastase et al., 2022)

The movement towards reuse and sharing, and the erosion of the concept of absolute ownership points towards a promising ecological and environmentally useful extended life span encompassing many cycles of temporary ownership before the terminal degradation of even the humblest of consumer items, toys, exemplified by Evertoys' aspirational business model.

The Potential and Challenge of Value-Retention Processes (VRPs)

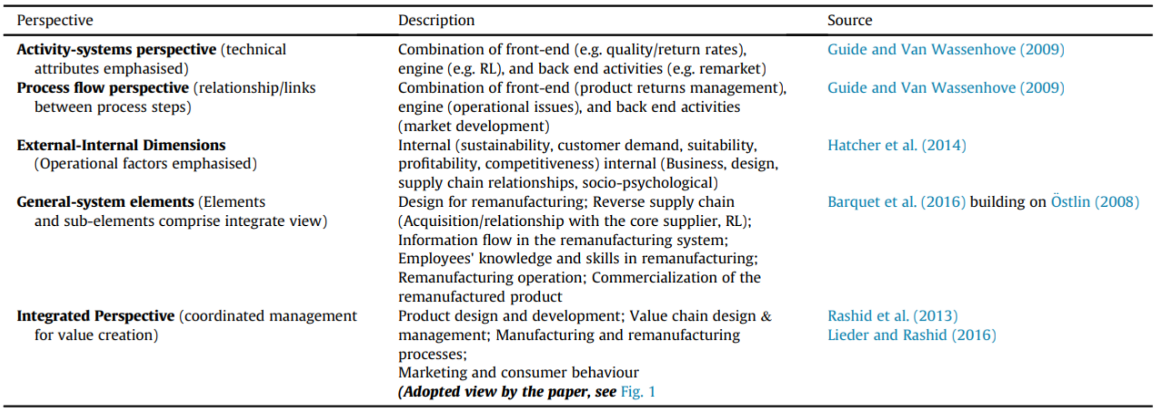
Often non-owning entities undertake repairs beyond the competency of private owners, without access specialist tools or even spare parts. Within a mounting cooperative CE responsibility, commitment to refurb, repair, share and recycle no longer has a identified minimum value (Blomsma et al., 2019).

In its essence, VRPs permit the re-entry of a product into multiple cycles of use while maintaining the product largely in its original form with the objective of either extending its service life or increasing the re-entry opportunities. Service life can be interpreted as a product's use period with one user or the period over which it is economically used. Under the umbrella of VRPs mapping, end of use (EOU) and end of life (EOL) are discrete useful opportunities to inform the manufacturer of the product's durability (Russell et al., 2023). The anticipated operational lifespan of a product, when coupled with information derived from product testing, serves as a basis for determining the intended durability and duration of the product. This involves specifying the number of cycles, kilometres, minutes etc., the product should achieve before necessitating maintenance intercessions to ensure optimal performance (e.g., repair or refurbishment), as well as establishing the feasibility of conducting a certain number of repair or refurbish interventions.

Product EOU marks a critical potential terminus for the resources invested in the product, an opportunity to direct the product for dismantling, secondary spare parts markets, or recycling and recovery of useful material, or disposal to the final destination of fully consumed materials. The choice may largely be dependent on the infrastructure available to enable the choices alternate to landfill disposal. However, resource scarcity or elevated material costs promote opportunities and drive motivation such as the ability to remanufacture as-new parts with a lower invested cost and consumed energy, leading to the creation of positive conditions, to birth the absent recovery infrastructures (Gaustad et al., 2018).

Consumers and secondary market actors alike have been innovative in finding VRP pathways, the refurbed and refilled inkjet and laser cartridge is now universally accepted as substantially equivalent to an original manufactured part. Auto parts have long been subject to accepted refurbishment with an extensive infrastructure allowing widely distributed and accessible over-the-counter facilities, a point of consumer disposal and immediate exchange for new-equivalent reconditioned parts. The convenient drop off for products at the end of their consumer EOU, but not necessarily EOL (although that is frequently provisioned for) is driving a shift towards endowing used products with a tangible value, both in monetary and ecological terms. This benefits the consumer directly with a monetary discount and enabling industry actors to acquire component elements directly fitting their manufacturing component needs.

Table 2 (Jensen et al., 2019) concisely identifies key dimensions coupling the user/industry actor interplay important to and enabling the fuller utilisation of VRPs which have been described in a wider context in the preceding paragraphs.



Perspective	Description	Source
Activity-systems perspective (technical attributes emphasised)	Combination of front-end (e.g. quality/return rates), engine (e.g. RL), and back end activities (e.g. remarket)	Guide and Van Wassenhove (2009)
Process flow perspective (relationship/links between process steps)	Combination of front-end (product returns management), engine (operational issues), and back end activities (market development)	Guide and Van Wassenhove (2009)
External-Internal Dimensions (Operational factors emphasised)	Internal (sustainability, customer demand, suitability, profitability, competitiveness) internal (Business, design, supply chain relationships, socio-psychological)	Hatcher et al. (2014)
General-system elements (Elements and sub-elements comprise integrate view)	Design for remanufacturing; Reverse supply chain (Acquisition/relationship with the core supplier, RL); Information flow in the remanufacturing system; Employees' knowledge and skills in remanufacturing; Remanufacturing operation; Commercialization of the remanufactured product	Barquet et al. (2016) building on Östlin (2008)
Integrated Perspective (coordinated management for value creation)	Product design and development; Value chain design & management; Manufacturing and remanufacturing processes; Marketing and consumer behaviour ***(Adopted view by the paper, see*** Fig. 1	Rashid et al. (2013) Lieder and Rashid (2016)

Table 1 Perspectives on remanufacturing from academic literature (Jensen et al., 2019)

CE Conclusion

From the breath of strategies and even legislation, co-reliant and coexisting in the primordial CE soup, it is not difficult to anticipate the confusion eager new adopters and policymakers encounter when embarking on this journey. Specifying exactly how the embryonic business model should be birthed and mature, the mission statements they will make about their CE credentials and aspirations, and the fit with the product-service they intend to deploy, and importantly profit ethically from, will be complex. Although considered from a general perspective, the overview of CE landscape laid out within this chapter can prove informative, particularly flagging the opportunities of the four Rs, benefits of VRPs, and the future legislative pitfalls to avoid, in context of the case business.

Circular Economy Strategies Database.

		1- MATERIALS SOURCING
8	Diversity and cross-sector linkages	Establishment of industry standards to promote cross-sector collaboration through transparency, financial and risk-management tools, regulation and infrastructure development and education.
14	Energy production/Energy autonomy	Energy production from by-products and/or residual/process/waste heat recovery to support facility operation.
19	Green procurement	A process whereby public authorities/companies choose to procure goods and services with the same primary function but lower environmental impact as measured, for example, by LCA-based comparison of goods and services.
23	Life Cycle Assessment (LCA)	LCA is a structured, comprehensive and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (EC, 2010).
25	Material substitution	Replacing materials for the more abundant/renewable, hence making the production process more resilient to price fluctuations and resource scarcity.
41	Taxation	Taxes on technologies, products and inputs that are associated with negative externalities.
42	Tax credits and subsidies	Reducing the tax on resources, for example on bio-based materials and products.
		2- DESIGN
5	Customization/made to order	Products are tailor-made to meet the needs and preferences of the customer. Can reduce waste and prevent over-production. Customers who are satisfied with the products will return to the manufacturer to extend the service life of the products and keep their preferred features. Customer loyalty to the manufacturer is built in.
6	Design for disassembly/recycling	Design that considers the need to disassemble products for repair, refurbishment or recycling.
7	Design for modularity	Products composed of functional modules so that the products can be upgraded with newer features and/or functionalities. The modules can be individually repaired or replaced, thereby increasing longevity of the product core.
10	Eco design	Product design with a focus on its environmental impacts during the whole lifecycle.
30	Reduction	Design and manufacturing involving reduction in use of materials and elimination of harmful substances use.
		3- MANUFACTURING
13	Energy efficiency	Providing the required services with reduced energy input, which can be achieved by reduced consumption and energy efficient processes.
26	Material productivity	At the company level: the amount of economic value generated by a unit of material input or material consumption. On the economy-wide level: GDP per material input/consumption.
32	Reproducible & adaptable manufacturing	A transparent and scalable production technology that can be emulated at other places using indigenously available resources and skills.
		4- DISTRIBUTION AND SALES
27	Optimized packaging design	Efficient packaging design strategies abiding regulations and utilizing end-of-life of packaging material.
35	Redistribute and Resell	Resale extends the product life by second hand use. Therefore, fewer products, which serve for the same purpose, have to be produced. The complete products or their components can be re-sold.
		5- CONSUMPTION AND USE
4	Community involvement	The voluntary involvement of community and different stakeholders in organizing sharing platforms and providing guidance on product repair and replacement.
11	Eco-labelling	A voluntary environmental protection certification of proven environmental preference of a product/service within its respective category. Credible and impartial labelling of product/service is usually overseen by public or private third parties.
28	Product as a service or Product Service System	The ownership of the product rests with the producer who provides design, usage, maintenance, repair and recycling throughout the lifetime of the product. The customer pays a rent for the time of its usage.
29	Product labelling	Aimed to guarantee that consumers have full information on the constituents, origin of raw materials etc. to enable them to make informed decisions. Indicates no environmental or otherwise preference for certain products, in contrast to #11 Eco-labelling.
34	Re-use	Direct secondary re-usage extends the product life by second hand use. Therefore, fewer products, which serve for the same purpose, have to be produced. The complete products or their components can be re-used.
37	Sharing	Shared use/access/ownership of for example space and products and sharing platforms enabling shared use. Multi-purpose space.
38	Socially responsible consumption	A socially responsible consumer purchases products and services that are perceived to have less negative influence on the environment and/or that support businesses that also have positive social impact.
39	Stewardship	Taking responsibility in protecting the resource through conservation, recycling, regeneration, and restoration. A common good is considered, for example a natural resource, in contrast to #16 Extended Producer Responsibility
45	Virtualize	Dematerialization. For example electronic books/CDs, online shopping, use of telecommunication to decrease use of office space and travel.
		6- COLLECTION AND DISPOSAL
16	Extended Producer Responsibility (E.P.R)	"Extended Producer Responsibility is as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle" (OECD, 2015).
21	Incentivized recycling	A method for rewarding consistent and repeated recycling of recyclable materials, for example a deposit refund
24	Logistics/Infrastructure building	Facilities to promote cost-effective, time-saving and environmentally safe post-consumer collection and disposal. Solutions that render optimum collection.
36	Separation	The biological constituents should be separated from the technical or man-made/inorganic constituents. The technical nutrients ought to be used for remanufacture and the biological nutrients are to be restored or degraded naturally.
40	Take-back and trade-in systems	Efficient take-back systems ensure that the products are recovered from the consumer after end of life and proceed to be remanufactured. Take-back systems could ensure a continuous flow of material for remanufacture.
		7- RECYCLING AND RECOVERY
2	By-products use	Byproducts from other manufacturing processes and their corresponding value chains are used as raw materials for manufacturing new products.
3	Cascading	Materials and components used across different value streams after end of life. The embedded extraction, labor and capital are conserved across the cascade.
9	Downcycling	It is the process of converting used products into different new products of lower quality or reduced functionality.
12	Element/substance recovery	The process of recovering metals, non-metals and other re-usable substances from a material waste stream.
15	Energy recovery	The conversion of waste materials into useable heat, electricity, or fuel through a variety of waste-to-energy processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery.

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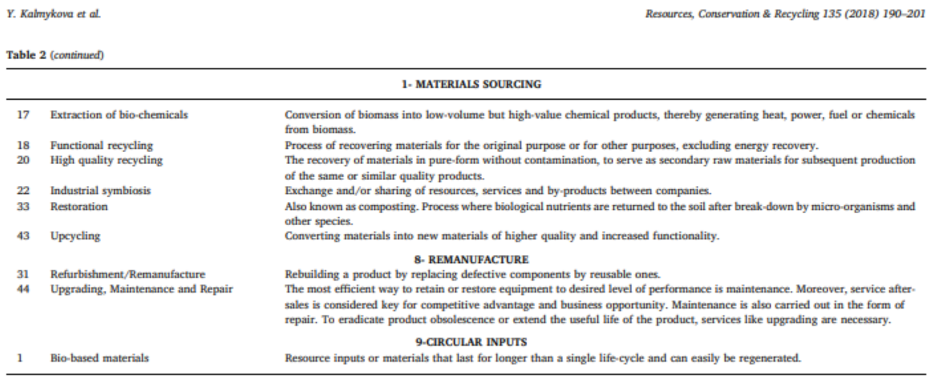


Table 2 (*continued*)

		1- MATERIALS SOURCING
17	Extraction of bio-chemicals	Conversion of biomass into low-volume but high-value chemical products, thereby generating heat, power, fuel or chemicals from biomass.
18	Functional recycling	Process of recovering materials for the original purpose or for other purposes, excluding energy recovery.
20	High quality recycling	The recovery of materials in pure-form without contamination, to serve as secondary raw materials for subsequent production of the same or similar quality products.
22	Industrial symbiosis	Exchange and/or sharing of resources, services and by-products between companies.
33	Restoration	Also known as composting. Process where biological nutrients are returned to the soil after break-down by micro-organisms and other species.
43	Upcycling	Converting materials into new materials of higher quality and increased functionality.
		8- REMANUFACTURE
31	Refurbishment/Remanufacture	Rebuilding a product by replacing defective components by reusable ones.
44	Upgrading, Maintenance and Repair	The most efficient way to retain or restore equipment to desired level of performance is maintenance. Moreover, service after-sales is considered key for competitive advantage and business opportunity. Maintenance is also carried out in the form of repair. To eradicate product obsolescence or extend the useful life of the product, services like upgrading are necessary.
		9-CIRCULAR INPUTS
1	Bio-based materials	Resource inputs or materials that last for longer than a single life-cycle and can easily be regenerated.

Table 2 denotes codes for parts of the value chain according to the CE Strategies Database (Kalmykova et al., 2018)

Maintenance and Estimated RUL

Introduction

Enabling good CE practice within product-service delivery, where a physical product is a key component, necessitates the business appreciates the breath of technologies available, the appropriateness to their holistic offering, and the relative efficiencies endowed by informed adoption. Evolving Industry 4.0 offers complex solutions to support products and digital services and once again, the interleaving nature of components within Cyber-Physical Systems (CPS) render planning difficult. To aid in understanding, a high-level view of CPS, advanced maintenance strategies and the role of Artificial Intelligence (AI) will be considered, and of particular relevance to the case business, how a crafted approach can contribute to extending the useful service life of a product, with minimal physical maintenance.

Throughout this chapter and further, the reader will appreciate PdM references may also equally refer to prescriptive (RxM) strategies, as both invariably require data from deployed assets.

Cyber-Physical Systems as Foundations

As technological advancements have progressed, the convergence of the Internet of Things (IoT), artificial intelligence (AI), and the accessibility of cloud computing has disrupted the foundational principles governing the deployment of Internet-enabled and mass-produced innovations in eclectic industry sectors. In the context of the smart factory, CPS, the Internet of Services, and the integration of IoT and big data collectively constituting Industry 4.0, harness the latent potential to enhance smart manufacturing, performance and quality across services and products (Adamson et al., 2017).

Investigations (Perera et al., 2014; Perera et al., 2013) underscore the essential role assigned to intelligence within the domains of the IoT, (Georgakopoulos and Jayaraman, 2016) and CPS. These domains possess cognitive capabilities, enabling them to be identifiable, perceive events, engage in interactions, and autonomously compute actions. In combination, IoT serves as a foundational platform facilitating the interconnection of all CPS, wherein CPS seamlessly collaborate across tangible and virtual environments. Therefore, it can be asserted that the existence of CPS is contingent upon IoT, and the attainment of Industry 4.0 necessitates the interplay of both CPS and IoT. (Cheng, 2022, p45)

Extending from the smart manufacturing of products, opportunities arise to support both the design, build and maintain the product or asset, in use. The concept of the digital twin (DT) has gained prominence in asset maintenance, initially articulated by Grieves in 2012. Grieves conceptualised the DT as the amalgamation of a physical asset and its virtual counterpart, being connected through the exchange of information as data. However, the implementation of DT technology leads to a voluminous inflow of data (Kritzinger et al., 2018), potentially resulting in an excess of exact but inconsequential or more plainly put, useless information.

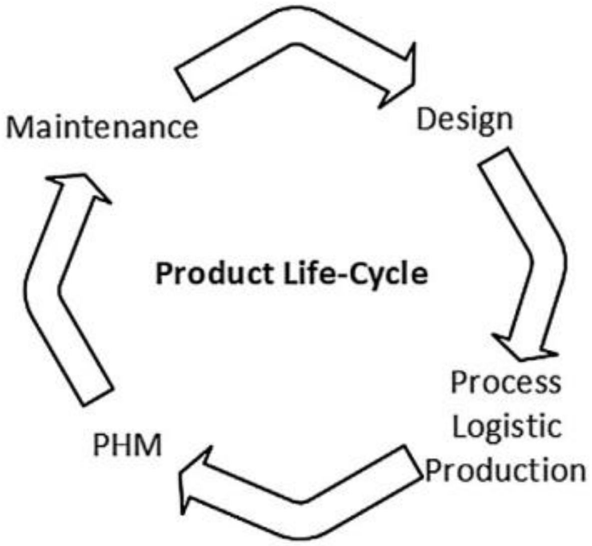


Figure 5 Product life cycle (Errandonea et al., 2020)

In Virtualisation, artificial environments reflecting exact or close approximations to the real environment can be enabled by data transparency of the CPS including DTs. Harvesting sensor data, the virtual system can monitor and actively modify the operational characteristics of the real asset, while feeding back device activity metrics, thereby continually updating the CPS understanding of potentially changing operational characteristics of the real asset. Virtualisation provisions for remote maintenance opportunities, and potentially informs iterative design improvement. (Mabkhot et al., 2018). Consequently, a strategic approach is necessary to maximise the meaningful improvements derived from such abundant intelligence (Liu et al., 2020). Data-driven methods are not only useful to inform and compute compensatory control on assets in active use, but also to calculate RUL, representing a significant intelligence resource in respect of making the asset supply chain smart (replacements or upgrades).

Maintenance strategies

Approaches to Maintenance

Ansari et al, (2019, p. 485) summarise four preferred approaches to maintenance in concise paragraphs.

“Descriptive maintenance (Type I, Low Complexity, Low Maturity) answers the question ‘What happened?’ by providing information about previous maintenance operations. Thus, it supports information collection and analysis and increases the level of information visibility.

Diagnostic maintenance (Type II, Medium Complexity, Low Maturity) answers the question ‘Why did it happen?’ by analysing cause-effect relations, reasoning, and providing further technical details about former maintenance operations. Therefore, it supports knowledge generation and increases the level of knowledge transparency.

Predictive maintenance (Type III, High Complexity, Medium Maturity) answers the question ‘What will happen when?’ by learning from historical maintenance data, possibly in real-time, *and predicting future events. Thus, it supports knowledge discovery and enhances the level of (semi-)supervised or unsupervised prognostic capabilities. Notably, this is often referred to as 'Smart Maintenance', 'Data-Driven Maintenance' and 'Maintenance 4.0', not only in scientific but also in commercial contexts.*

Prescriptive maintenance (Type IV, High Complexity, High Maturity) answers the question 'How can we control the occurrence of a specific event?' (How should it happen?) by providing actionable recommendations for decision-making and improving and/or optimising forthcoming maintenance processes. It also refers to the recent advances in enhancing self-organisation and self-direction capabilities of CPPS, which ideally aim at machine self-diagnosis and self-scheduled maintenance. Hence, prescriptive maintenance may reach the highest degree of maturity which involves complex methods to produce and reinforce adaptation and optimisation capability".

Reactive
In the Industry 4.0 era, adopting Reactive Maintenance would yield limited advantages unless there exists an exceptionally high level of confidence in the operational resilience of the product throughout its entire service life. In such instances, service cost savings could be optimised through a 'deploy and forget' strategy.

Preventative
Preventative Maintenance involves a fixed cost, but not every service event may be necessary potentially resulting in inefficiency. Nevertheless, users may derive tangible peace of mind from the knowledge that their asset is optimally maintained.

Condition-based maintenance (CBM).
CBM necessitates asset monitoring with additional costs incurred for the application of appropriate instrumentation to collect relevant parameters. Technologies to facilitate the communication of this metrology data to a local or remote service for further analysis and decision-making are necessary.

Predictive
Predictive Maintenance relies on establishing a behavioural model for the asset over its operational service life, involving historical data and a mathematical model for statistically predicting potential occurrences and their likely severity.

Prescriptive
Prescriptive maintenance strives to amalgamate maintenance information derived from actual operational data analysis with associated data variables, for example production and resource planning. This approach facilitates decision-making within a comprehensive maintenance management framework (Ansari et al., 2019). On one hand, the implementation of data-driven maintenance strategies necessitates expertise and extensive skills in data analysis, leading to elevated direct maintenance costs attributable to the employment of highly skilled labour. Beneficially however, this strategy results in reduced spare parts inventory, maximised operating time, decreased frequency of maintenance interventions, and improved predictive capabilities for better scheduling.

This study comprehensively addresses maintenance strategies grounded in machinery or process data, encompassing KBM, Predictive Maintenance (PdM), and Prescriptive Maintenance (RxM), all of which are categorised as data-driven maintenance methodologies.

Remaining useful life (RUL)

A precursor to RUL estimation is the opportunity to optimise the asset's operational efficiencies, including extending service life, through selection of the appropriate maintenance strategy, a decision flow selection method Fig. 6 is outlined by Errandonea et al., (2020).

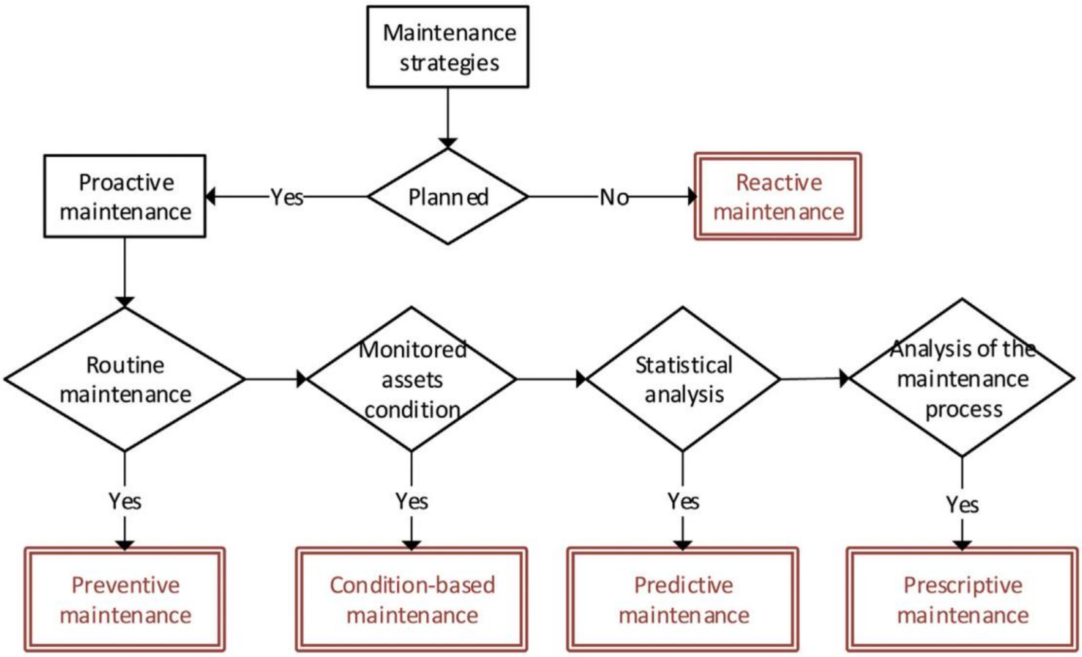


Figure 6 Maintenance strategies flow diagram from (Errandonea et al., 2020)

The capability of a strategy to yield data upon which an estimated RUL may be computed becomes an important element in the application of KBM and the above models in practical deployment. RUL is fundamental in determining device health and the decision-making to either repair or retire.

A brief description of the Baseline Predictive Maintenance (BPM) Scheme in the Intelligent Prediction Maintenance (IPM) Server is presented by Chiu et al. (2017), providing a concise structure of the BPM scheme within the framework of the Intelligent Prediction Maintenance (IPM) Server. The IPM Server is equipped with a virtual-metrology-based (VM-based) BPM scheme, highlighting components such as the Target Device (TD) baseline model, Device

Health Index (DHI) module, and an RUL predictive module, as in Figure 7.

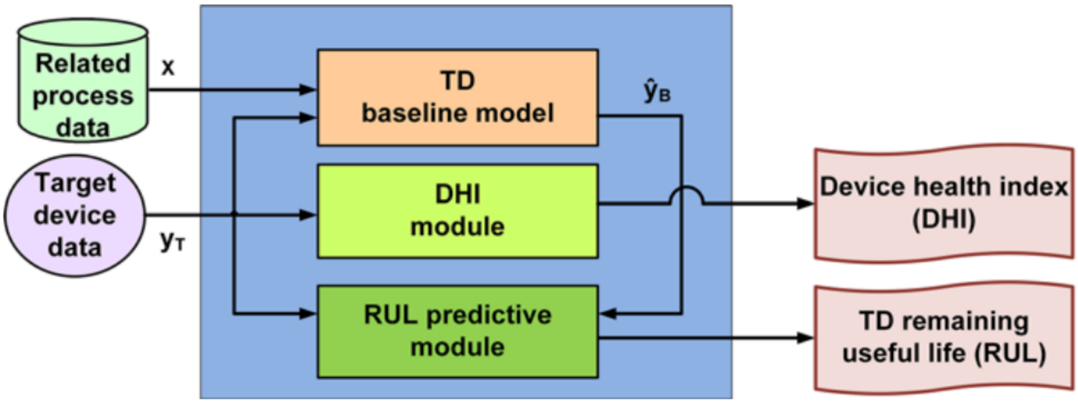


Figure 7 reproduced from Chiu et al. (2017)

The BPM scheme serves as the fundamental module within the IPM server. Employing the VM technique, the TD baseline model is generated and utilised as a benchmark for detecting sset health degradation. The implementation of the BPM scheme facilitates the accomplishment of fault diagnosis and prognosis.

Referring to Figure 7, the BPM generates the baseline of TD (ŷB) by considering crucial samples from both process data (X) and TD data (yT). Subsequently, the Diagnostic Health Index (DHI) is formulated to assess the current health state of TD. Upon entry into a sick state, the RUL is estimated for the TD. The TD undergoes five states: initial, active, inactive, sick, and dead, illustrated in Fig.8.

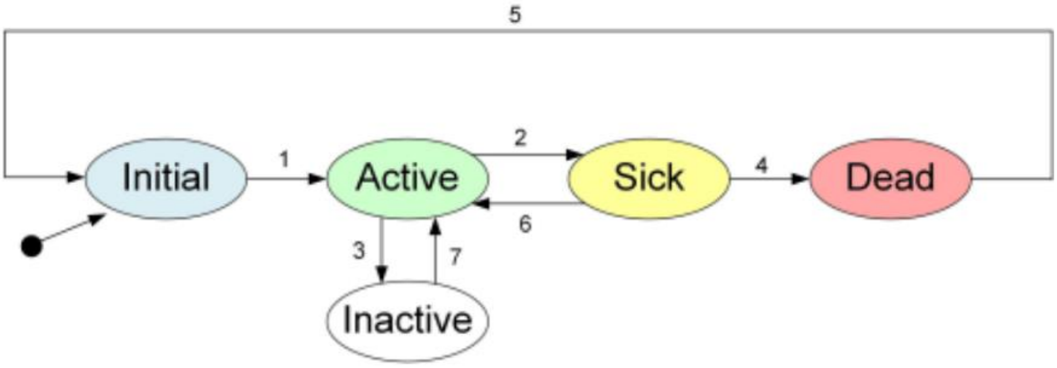


Figure 8 State diagram of a device, (Chiu et al. 2017)

Ordinarily, the TD is in an active state when in good health, transitioning to the sick state when yT surpasses a predefined threshold. In the event of further deterioration, progress to the dead state occurs, depleting the available resources of the TD and resulting in equipment downtime.

In the first three states, all is well, however, Cheng, (2021) state diagram fails to elucidate the opportunity in some instances, for an intervention by remote means, to modify the behaviour of the TD, to mitigate the sickness and prolong the RUL. This could be achieved through TD reconfiguration via a remote agent, for example by restricting the maximum load presented to an ageing battery cell, or by reducing the speed of a lathe tool to compensate for cutting tool wear. Effectively the sickness can be medicated to prolong the sickness period before eventual death.

The Choice, Model-driven or Data-driven

The selection of maintenance strategy may be based in part on whether a data-driven model is optimal, requiring the asset to be capable of returning operational detail itself, or by external observation and as shown by (Zhao et al., 2023), some RUL conundrums can be solved in more than one approach as shown in Fig. 9, directed at a rechargeable battery application, where RUL in the form of SOC is especially relevant.

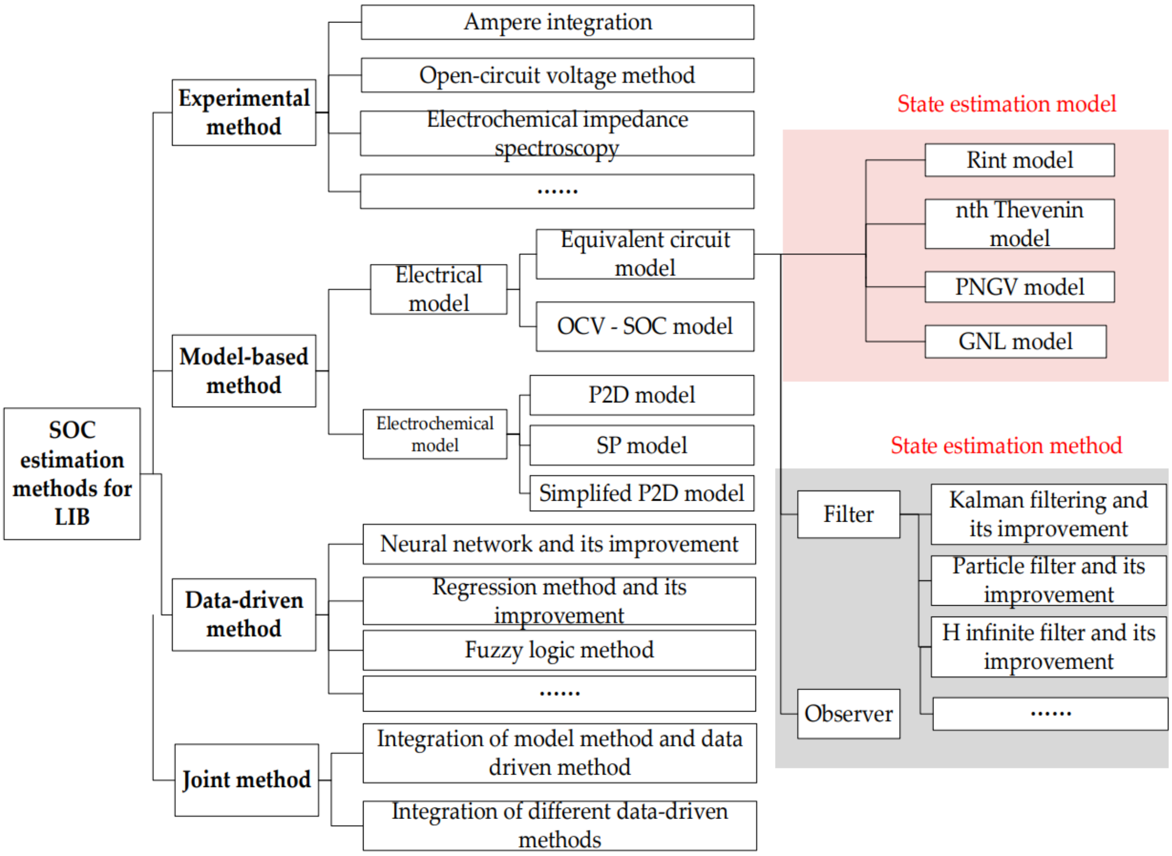


Figure 9 Classification of lithium-ion battery SOC estimation methods (Zhao et al., 2023)

It can be necessary to have an accurate mathematical model of the asset or system in a model-driven paradigm. Such systems are capable of precisely predicting the degradation time course of their assets (Khorasgani et al., 2016). Artificial Intelligence (AI) and neural networks are increasingly becoming useful and efficient computational tools (RincónMaya et al., 2023).

Data-driven methodologies, including hybrid approaches that combine models with data-driven techniques, offer a notable advantage over model-driven approaches for predicting RUL, as they do not necessitate an exhaustive comprehension of intricate physical and mechanical degradation processes (Hoffmann and Lasch, 2023). The domain of data-driven RUL estimations encompasses both statistical techniques and AI methods.

Frameworks within the Product Cycle

CPS and KBM are not only considerations within the product-service offering, but potentially begin in manufacturing, perhaps the product cycle also is an opportunity. Literature reviews in the field (Ferreira and Gonçalves, 2022) point towards the need for a framework combining maintenance with production planning. Hoffmann and Lasch, (2023) proposed an implementation framework to assess the suitability of the use case to a data-driven maintenance approach and strongly recommended an AI approach to data analysis, on the premise that in dealing with large amounts of data, AI algorithms are more capable of detecting a degrading pattern in the data sets.

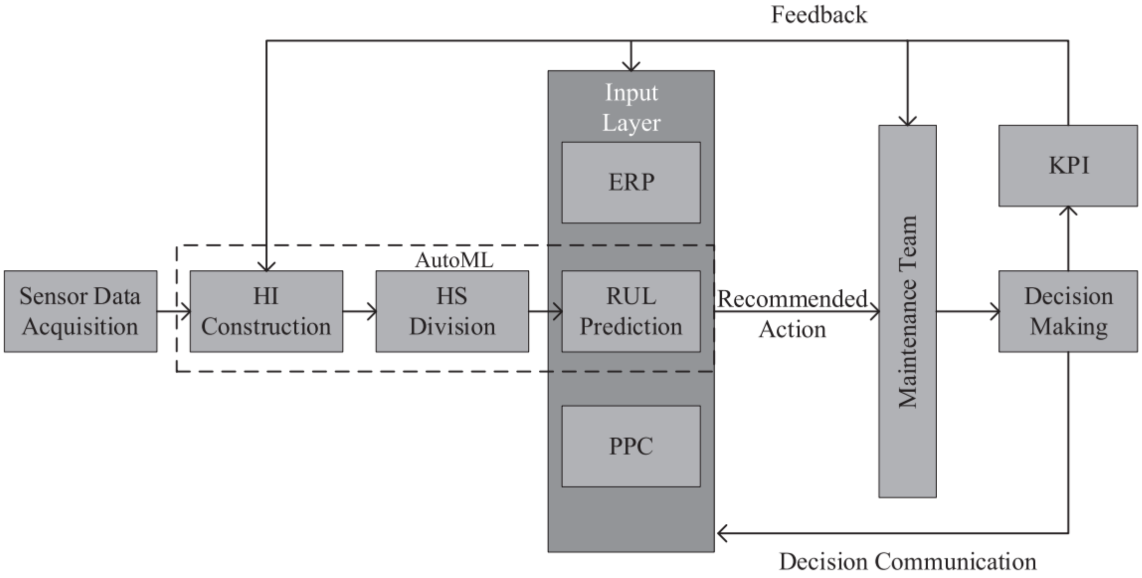


Figure 10 Holistic data-driven maintenance framework from (Hoffmann and Lasch, 2023).

Adaptable to manufacturing product cycles and products in use, Fig. 10 health indicator (HI) features and health state (HS) are derived from the input data (source from sensors) and as part of the Machine Learning (ML) generate an estimation of RUL. RUL is further collaboratively processed with Enterprise resource planning (ERP) and Production planning and control (PPC) modules to generate a recommended action for the maintenance actor. The closed loop returns the feedback to multiple new entry points allowing continuous new state estimation and process decision-making to act on, optimising the system operation.

KBM Conclusion

Within the maintenance strategy landscape, the nascent business faces technically sophisticated choices. The legacy reactive approach has a relatively low budgetary burden at the early stages but is not capable of fulfilling customer expectations of no or minimal unscheduled maintenance downtime, reduced periodic servicing interruptions and continuity of product-service availability, and not least longevity of product-service. Arguably these statements apply in all but the simplest of technical product-service delivery. The choices of maintenance may have origins in the product design, reaching into the production and manufacturing cycle and in the product-service operation by the consumer, however, these are far from sequential disparate decisions or junctures in the business roadmap. The decisions are networked and intertwined and require a cocktail of complex planning, outcome objectives, technical appreciation, available resources, and budgetary constraints to be considered, ideally in the earliest planning stages.

ANYTHING as a Service

The National Institute of Standards and Technology (NIST) advocates a widely recognised cloud framework that delineates three distinct service models (Sturm, Pollard, and Craig, 2017). According to the framework:

1. The Infrastructure as a Service (IaaS) model (Varghese, 2019) involves the management of IT infrastructures by a provider who delivers infrastructure services to customers, such as through service rentals.
2. The Software as a Service (SaaS) model operates on the premise that both software and associated IT infrastructures are overseen by an IT service provider, allowing customers to utilise the software as a service Similarly, SaaS has been further defined as “an application or service that is deployed from a centralised data centre across a network, providing access and use on a recurring fee basis, where users normally rent the applications/services from a central provider” (Seethamraju, 2015, p. 476).
3. The Platform as a Service (PaaS) model closely mirrors the SaaS model (Gonçalves and Ballon, 2011), with the distinction that a platform is operated and provided by the IT service provider instead of software.

IT departments are facing a growing challenge in the replacement of outdated applications with innovative solutions, including Software as a Service (SaaS) solutions (Benlian and Hess, 2011, Kim, et al., 2017)), hosted on third-party cloud platforms or in some instances private (business owned) platforms. This transition aims to enhance and modernise the organisation's business processes. A new business use case presents a different set of challenges and risks associated with the optimal DS selection to address a very specific set of requirements, so the following overview assists the new business choice.

ASP to ? As A Service

Arguably, SaaS has evolved from application services provision (ASP) and is in the highest echelon of cloud computing (CC). Economies of scale are created, enabled by the sharing of infrastructure, normally owned, and maintained by third-party vendors facilitating the remote utilisation of business software and services (Benlian and Hess, 2011).

The multi-tenancy architecture of SaaS allows users (tenants) in all tiers, the end-users, content contributors and solution/service resellers, to share time on services, databases, hardware, and software resources (Kabbedijk et al., 2015), without the time or financial costs of maintaining the physical infrastructure, operating systems and the increasingly necessary and sophisticated cyber security elements.

Enterprise software applications are frequently large, reconfigurable, and generic software applications that assist large enterprises in capturing cost savings and adhering to industry sector best practices and where necessary, regulatory guidelines (Howcroft and Light, 2006). However, packaged software is no longer the only professionally generated solution available to address the challenges of ERP and supply chain management (SCM), customer relationship management (CRM) and human resource management. As an alternative, businesses actively seeking to acquire information technology (IT) products and services are increasingly opting for a cloud-first strategy when replacement or new requirement criteria arise (Stamford, 2019). Even the established business recognises the drive to change, 40,000 Microsoft salespersons made paradigm shifts from merchandising legacy on-premises software to promoting more cloud use (The Economist, 2019).

Upgrade- When to Transition?

Cost

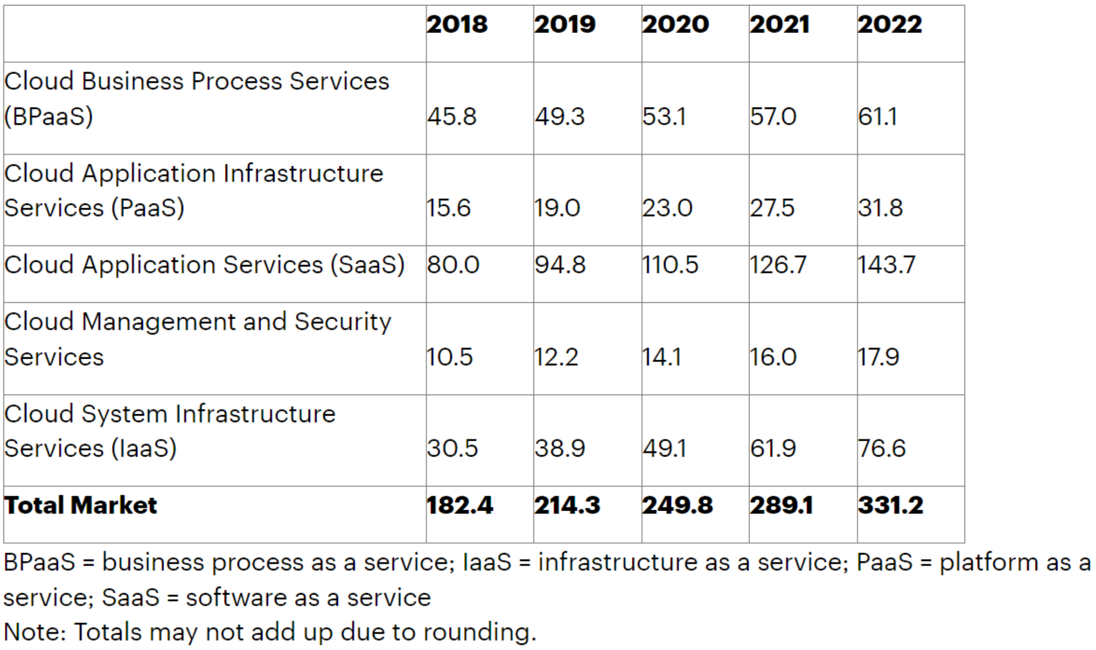
Due to the expenses and intricacies associated with transitioning to a new software version, some existing users exhibit reluctance to upgrade each time new iterations are introduced, particularly in the case of on-premises enterprise application software. Consequently, the presence of upgrade costs significantly influences consumers' decision-making processes. Nonetheless, the extent of consumer responsiveness to associated costs varies due to differences in their degree of knowledge, information technology proficiencies, and financial budgets. For example, expert users exhibit lower sensitivity to the expenses incurred in software installation and upgrading, whereas novices may perceive the activities as being more costly in time and effort. An interview study by Kim et al., (2017) concluded enterprises with substantial investments in current programs tend to be hesitant to replace their on-premises software. Capital constraints foremost in most enterprises-lead executive committees to withhold approval for on-premises application software implementations. This state is particularly notable among start-ups and small to medium-sized enterprises, although the affect of implementation costs is likely to be less severe for well-funded large-enterprise users.

Risk

The impediments encountered in the adoption of cloud service implementation, for example, SaaS, relate to both performance and security risks and therefore present notable challenges. Conversely, the positive impact of SaaS was the scope to enhance the quality and efficiency of business processes. The overall intention to adopt SaaS is further influenced by a competitive environment, in particular the adoption of cloud service models by their close competitors, and the critical backing of top management. Limited financial resources and information technology capabilities of small enterprises, render them less resilient to performance and security risks. Conversely, the inherent automation of business processes within SaaS contributes to the anticipation of improvements in product and service quality, as well as the streamlining of business operations, leads to a positive perception held by small businesses operating in competitive environments towards the benefits of SaaS adoption.

Cloud Services Growth

As a result of the positive perception of the benefits of services delivered by cloud computing methodologies, packaged software investment can be expected to continue to decline as cloud-serviced pipelines increasingly meet consumer requirements, while cloud services are projected to dramatically increase (Costello and Rimol, 2021).



	2018	2019	2020	2021	2022
Cloud Business Process Services (BPaaS)	45.8	49.3	53.1	57.0	61.1
Cloud Application Infrastructure Services (PaaS)	15.6	19.0	23.0	27.5	31.8
Cloud Application Services (SaaS)	80.0	94.8	110.5	126.7	143.7
Cloud Management and Security Services	10.5	12.2	14.1	16.0	17.9
Cloud System Infrastructure Services (IaaS)	30.5	38.9	49.1	61.9	76.6
Total Market	**182.4**	**214.3**	**249.8**	**289.1**	**331.2**

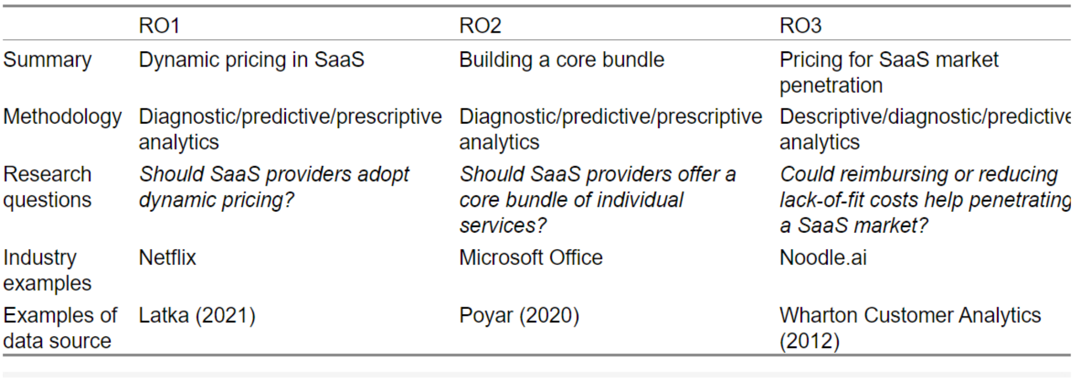
BPaaS = business process as a service; IaaS = infrastructure as a service; PaaS = platform as a service; SaaS = software as a service
Note: Totals may not add up due to rounding.

Table 3 Worldwide Public Cloud Service Sales Revenue (Billions of U.S. Dollars) (Costello and Rimol, 2021)

Costello and Rimol, (2021) also posit new software investment will migrate from cloud-first to cloud-only, shifting revenue models from annual licencing to subscription-based, usage frequency or data volume-based models, Table 2. As cloud services evolve and become even more mainstream, the technology service providers will expect to experience market pressure to deliver solutions which integrate experience and execution efficacy with the ability for clients to rapidly scale or even hyper scale.

Pricing models

Pricing plans are dynamically introduced to the market to connect the consumer and provider both in response to new delivery technologies and products and also by a change in consumer behaviours and expectations, a proposed research framework illustrates three models, each with a related enterprise provider, Table 3, from Li and Kumar, (2022)



	RO1	RO2	RO3
Summary	Dynamic pricing in SaaS	Building a core bundle	Pricing for SaaS market penetration
Methodology	Diagnostic/predictive/prescriptive analytics	Diagnostic/predictive/prescriptive analytics	Descriptive/diagnostic/predictive analytics
Research questions	*Should SaaS providers adopt dynamic pricing?*	*Should SaaS providers offer a core bundle of individual services?*	*Could reimbursing or reducing lack-of-fit costs help penetrating a SaaS market?*
Industry examples	Netflix	Microsoft Office	Noodle.ai
Examples of data source	Latka (2021)	Poyar (2020)	Wharton Customer Analytics (2012)

Table 4 Industry examples of three monetisation models (Li and Kumar, 2022)

From the user perspective, as the user has a significant role in driving the business success, three main pricing schemes are prevalent in IaaS, namely, Pay As You Go (PAYG), on-demand

(OD) and Spot Market (SM) pricing rules. All three pricing rules can coexist as exemplified by Amazon's EC2 services, Amazon is positioned amongst the main global IaaS providers, with revenues approximating 15.5$bln and a 48% share of the world market in 2018, versus about 5$bln revenues and a 15.5% market share enjoyed by Microsoft, figures from Gartner, market report (Gartner, 2018)

Revenue models include:

PAYG
PAYG users can reserve the use of machine time by paying a flat fee for a given period and then paying per unit resource consumed.

On-demand
When a user asks to consume resources on demand without paying a fixed fee to reserve machine time, the demand for resources has more likely probability it will be refused. This can be perceived as an opportunity for the resource provider as an opportunity to direct the user towards a preferred pricing model, by shifting that rejection probability factor positively, to either load balance the available resources or where a user wishes and values resource immediacy, to obtain higher unit revenue.

Spot Market
Spot Market pricing reflects the current demand-supply balance-driven costing. The consumer may take advantage of peak and off-peak fluctuations in supply to achieve better resources per cost unit or simply to demand to access machine time even when demand is peaked.

Business' therefore have flexible well-structured options available when deciding on how revenue is collected based on the use of their product -services, and potentially sympathetic to the needs and budgets of their customers.

Product Service System (PSS)
Described as the merging of digitalisation and servitisation (Favoretto et al., 2022), DS holds substantial relevance (Lerch and Gotsch, 2015). Both industry and academia recognise DS as a pivotal concept (Kohtamaki, et al., 2020; Paschou et al., 2018). Within the sphere of DS, digitalisation can be viewed as a progression from remote monitoring to optimisation, control, and the realisation of autonomous systems (Porter and Heppelmann,2014). Servitisation is also construed as the shift from standalone products to seamlessly integrated PSS (Baines et al., 2013).

The concept of DS to combine digitalisation and servitisation, can be defined as "…The transition towards smart solutions (product-service software systems) that enable value creation and capture through monitoring, control, optimisation, and autonomous function. DS emphasises value creation through the interplay between products, services, and software." (Kohtamäki et al., 2019, p.383)

Research on the DS trend is primarily within the domain of PSS (Baines et al., 2007; Beuren et al., 2013). PSS is conceptualised as a marketable combination of products and services that together fulfil customers' needs economically and sustainably (Tukker, 2004). Despite the recognition of the potential benefits of PSS, the established literature acknowledges a lack of insights into how companies can effectively adopt and implement PSS business models (Baines et al., 2007; Gaiardelli et al., 2014; Yoon et al., 2011).

Adopting a life-cycle cost perspective through PSS, the integration of product and service solutions creates incentives for optimising energy and consumables while extending the lifespan of products (Tukker, 2004). The potential benefits associated with offering integrated product and service solutions also apply to economic, social, and environmental dimensions, as companies seek opportunities to optimise resource utilisation and competitiveness (Beuren et al., 2013; Gaiardelli et al., 2014).

However, caution should be used when making the decision to transition to a PSS model. For existing businesses, the opportunity to realise PSS benefits necessitate significant change to most, if not all, of their extant models (Reim et al., 2024) and obstacles in timely collaboration and effective communications during implementation lead to value being lost.

Reim et al. (2024, p.5-7) elucidate: "

a) Value Creation/Delivery Alignment Problems: the provider needs to develop the capabilities and delivery competence of its entire network…….
b) Value Creation/Capture Alignment Problems: Lack of appropriate knowledge and competence to manage customer processes is therefore a major challenge for companies in order to customize functions and integrate PSS into customer processes effectively……
c) Value Delivery/Capture Alignment Problems: when provider companies promise to supply a certain benefit or result rather than a direct product, customers are hesitant to make a financial commitment because they have difficulty judging the merits of the services they are being offered………
d) Value Leakage From PSS Business Model Alignment Problems: even if the PSS offer generates considerable revenue, the need for orchestration across business units in order to divide the profits equitably is no less pressing. "

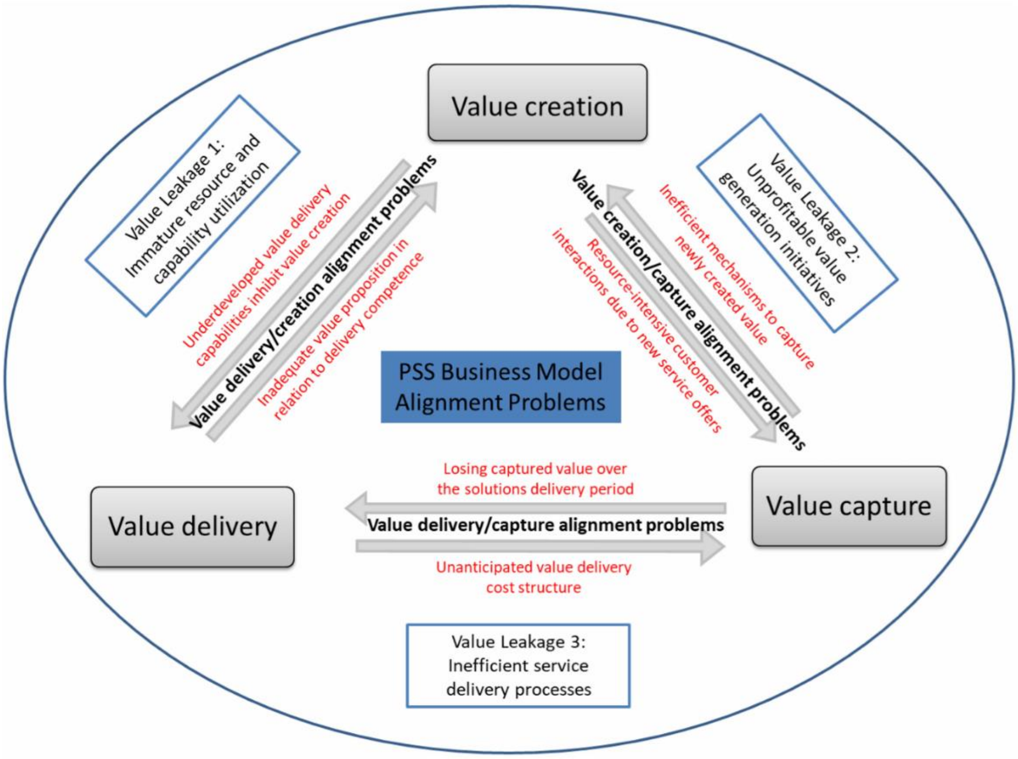


Figure 11 Value leakage resulting from PSS business model alignment problems (Reim et al., 2024)

Limited comprehensions into the negative consequences of transitional efforts from value-in-transaction to a value-in-use culture (Adrodegari and Saccani, 2017; Annarelli et al., 2017) fail to disclose the challenges encountered addressing delivering advanced services (Baines et al., 2017) of as opposed to well understood legacy transactional commerce.

PSS conclusion

Moving towards the implementation of PSS business models as a potential avenue for sustainable resource use necessitates radical practice and thought changes for both product and service-oriented companies at the value-chain and industrial levels (Martinez et al., 2010). Further, evaluation of PSS is important to avoid offsetting environmental potential benefits with rebound effects and less well-considered behaviour (Kuo, 2011; Tukker, 2004). The chosen approaches can be viewed as tactical choices that complement a preferred business model and should align with the company's operations (CasadesusMasanell and Ricart, 2010; Evans et al., 2007). Each business can consider the opportunities offered through DS as enabling, a proven route to efficiency, against the skills and costs related to implementation.

Chapter 3: Case Study

The Case Business

The case business under examination was founded in 2021 with the prime objective of resolving a particular critical pain experienced within the global healthcare sector. The fundamental skill set within the team is firmware and electronic design, complimented by engineering problem-solving. Other staff members have extensive healthcare procedural knowledge background.

A Problem Discovered

"Never waste a good crisis" is often quoted as the driver for responsive innovation (Chiu et al., 2022, p. 1), and in this case, the emergence of the COVID-19 pandemic in 2020 presented such a critical and wide-reaching crisis. A persistent problem became very visible through dialogue between the business principle and healthcare professionals. The healthcare management responsible for infection control installed a team of nurses tasked solely with mixing medicines within a central isolated location in response to orders delivered to the distal wards within the district General Hospital site. The prime objective was to release nurses from medicine reconstitution tasks and thereby increase patient care time, and as a consequence patient care staff, normally physically constrained by the use of personal protective equipment could carry out focussed patient care. The case business responded with an automated mixing device.

"Information is central to the operation of firms. It is the stimulus for knowledge, know-how, skills and expertise and is one of the key drivers of the innovation process." (Trott, 2021, p. 378) and the author of this study embarked on extensive research and face to face interviews to elucidate the problem characteristics.

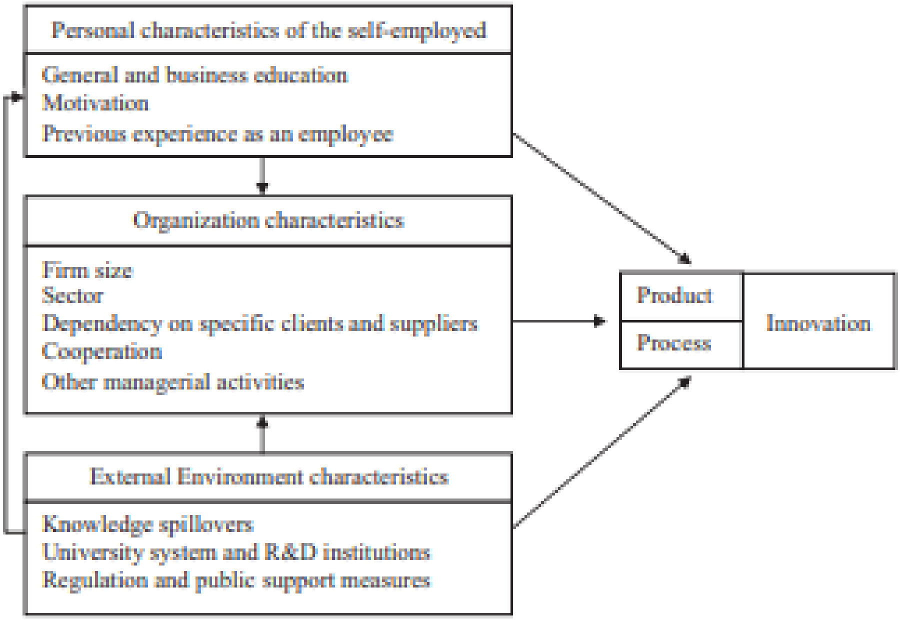


Figure 12 Innovation promoting prerequisites (Romero and MartínezRomán, 2012)

Contemplating the determinants of successful innovation within the micro business context, attention is accorded to factors such as business size and entrepreneurial aspirations Fig. 12. Insights from a survey (Romero and MartínezRomán, 2012) underscore the significance of personal characteristics in shaping innovation trajectory. Romero and colleagues (2021) illuminate those attributes including educational background, prior experiences, attitudes toward novel technologies, intrinsic versus extrinsic motivation, and psychological reactions to perceived risks which play pivotal roles in assessing the probability of micro businesses achieving successful innovation. The author and business founders’ skills and experience could be assessed positively in this context.

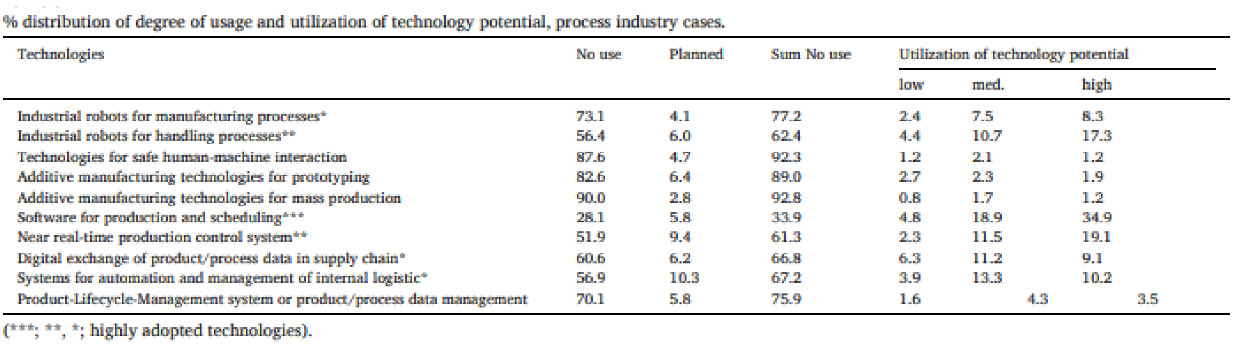
A Solution and Potential Benefits

The enterprise was founded on the problem statement, information around the nature and the quantum of the problem, its impact on the healthcare community and patient care and the appropriate attributes of the business team. That core team comprised an experienced NHS specialist nurse and a similarly experienced solution provider with a background in innovative eclectic applications of engineering and cloud services.

The micro nature of the business and the level of risk associated with general MedTech innovation and market acceptance, caused the early focus to be on the technical solution, rather than a fundamental consideration of how the business could penetrate and scale within the difficult regulatory-driven market sector. Navigating the myriad of hurdles relating to product-solution visibility, validation, credibility, and adoption by the healthcare sector, and developing a viable business strategy and a service delivery strategy, which mandated scalability and reliability in its architectural fabric, began to reveal a sizable task set.

The case business recognised the transformative potential of integrating Industry 4.0 principles and emerging technologies into both manufacturing processes and remote service delivery mechanisms. This recognition prompted a strategic decision to embed these principles into the business roadmap, guiding the direction and decisions around operations from the initial conceptualisation phase through to the projected launch of products and services.

Extensive literature research underscores the degree of utilisation associated with the planned adoption of digital technologies on both product and service innovation in industry process cases, as shown in Table 4, (Blichfeldt and Faullant, 2021). The scale of adoption emphasises how broadly similar businesses are also leveraging digital technologies. While the business' (Table 4) products and accompanying services span numerous technological domains, the early focus primarily resided on manufacturing. The case business will assume the role of the manufacturer in the future encompassing maintenance, scheduling, process management, and outcome analysis and is encouraged by evidence of peer businesses’ wide adoption.



% distribution of degree of usage and utilization of technology potential, process industry cases.

Technologies	No use	Planned	Sum No use	Utilization of technology potential		
				low	med.	high
Industrial robots for manufacturing processes*	73.1	4.1	77.2	2.4	7.5	8.3
Industrial robots for handling processes**	56.4	6.0	62.4	4.4	10.7	17.3
Technologies for safe human-machine interaction	87.6	4.7	92.3	1.2	2.1	1.2
Additive manufacturing technologies for prototyping	82.6	6.4	89.0	2.7	2.3	1.9
Additive manufacturing technologies for mass production	90.0	2.8	92.8	0.8	1.7	1.2
Software for production and scheduling***	28.1	5.8	33.9	4.8	18.9	34.9
Near real-time production control system**	51.9	9.4	61.3	2.3	11.5	19.1
Digital exchange of product/process data in supply chain*	60.6	6.2	66.8	6.3	11.2	9.1
Systems for automation and management of internal logistic*	56.9	10.3	67.2	3.9	13.3	10.2
Product-Lifecycle-Management system or product/process data management	70.1	5.8	75.9	1.6	4.3	3.5

(***; **, *; highly adopted technologies).

Table 5 Usage distribution of Industry 4.0 technologies (Blichfeldt and Faullant, 2021)

IoT and the Industrial Internet of Things (IIoT) have emerged as fundamental building blocks for numerous technology products and services particularly in healthcare technology (Rotter, 2016) playing a pivotal role in ongoing New Product Development (NPD). Highlighted by Kao et al. (2019), the significance of a resilient and dynamic IIoT infrastructure, steered by governmental policies fostering IoT related technological innovation is well acknowledged.

A Tentative Roadmap

As the problem focus, the company had encountered a technical challenge relating to the effective mixing of crystalline or powdered compounds with liquids or diluents exhibiting limited affinity. Through meticulous research and development efforts, a sophisticated technical solution was devised, one that elegantly overcomes the barriers posed by interface saturation between powder and liquid components. This concluded in the implementation of a processor-controlled electromechanical agitator-based solution showcasing the company's innovative capabilities.

With the principles of Advanced Industry 4.0 widely embraced and implemented during the initial stages of development, the company recognised the potential for leveraging cloud-based service delivery and monetisation, particularly in the context of DS. This focus on servitisation emerged as a critical consideration, aiming to provision for future scalability and profitability while maintaining the ethical principles of resource stewardship embraced by the business.

The strategic vision has a particular emphasis on the judicious use of materials and energy. This philosophy underscored activities aimed at extending product lifespans and curbing waste generation through innovative practices such as component repurposing and material recycling. Furthermore, a conscientious effort was made to minimise the environmental footprint associated with service provision, with strategies in place to reduce transportation distances. This included a preference for localised third-party logistics providers over centralised distribution channels. Mitigation of carbon emissions stemming from extensive travel undertaken by service and repair teams was also identified. To achieve this objective, the adoption of remote maintenance protocols for IoT enabled products facilitated by cloud-based ML agents and Over-The-Air Updates (OTAUs), emerged as a forward-thinking solution.

Intellectual Property Considerations

In a proactive stance toward safeguarding intellectual property rights and ensuring operational autonomy, the business addressed potential obstacles to freedom to operate at the earliest opportunity. This proactive approach entailed the diligent compilation and filing of patent applications after successful prototype validation. Following a rigorous examination process conducted by the United States Patent and Trademark Office (USPTO), the patent applications were duly granted and published, conferring exclusive rights.

Current status

The business is presently engaged in active deliberations concerning the architecture of its predominantly cloud-based services, with a specific emphasis on facilitating scalability and enhancing user satisfaction. These considerations are encapsulated in an ongoing internal review and analysis aimed at assessing the readiness of the existing product platform for optimal servitisation models. The evaluation encompasses an examination of associated costs and benefits, as well as an exploration of how customers—both individual end-users and organisational purchasers—will perceive the advantages and potential enhancements that a cloud-based and serviced product can offer over a more familiar legacy approach, availability of detailed data on each mixing event is one such example.

Chapter 4: Theoretical Framework

Introduction

In contemporary competitive environments, choosing the most appropriate maintenance strategy hinges upon a myriad of quantitative and qualitative factors, posing a significant challenge for maintenance engineers. A plethora of solution approaches have emerged to address this multi-criteria decision-making (MCDM) challenge within maintenance engineering. The framework of this study takes the form of an informative guide, credibly sourced from reliable literature and contrasted against theory in practice instances, intended to ease the DS and CE focussed deliberations faced by the emerging product- service business, similar to the case business.

In the present landscape, companies grapple with concerns surrounding their preparedness levels and experience a sense of being inundated by the anticipated costs associated with readiness efforts. This sentiment is prevalent among organisations currently transitioning from reactive and preventive maintenance approaches to KBM methodologies. In contrast, the case business, not encumbered by the legacy of implemented strategies and the uncertainty of expense of upgrading their methodologies, has a quite different starting point. This viewpoint is shared by many new innovative enterprises, seeing a fresh new start as a distinct advantage, the objective is to leverage the best of Industry 4.0 and continue horizon viewing of emerging technologies and digital capabilities.

The literature review provides a basis for the examination and analysis of the interaction between key strategies and technologies broadly resident under the umbrella of Industry 4.0. The convergence of DS, Industry 4.0, Product- Platform or Software as a Service and advances with 3D printing technologies signals a new epoch in innovation and value creation. This chapter provides an overview, sympathetic to and focussed mainly forward from, the embryonic stage of the case business. In particularly the advantageous, albeit unavoidable, interplay between the design, manufacturing, in-service support, and the generation of value. The opportunity to adopt CE-orientated methodologies is discussed, and in which manner it adds to the perceived value of the service and product by the customer, the business, and the public, who may carry weights as investors as well as citizen observers and who may also exert force of influence.

A Contextual Analysis

Product Design Burden

The case business has the opportunity to choose the design approach, building on an early prototype, the solution to the problem had already been resolved. As with any early-stage innovative business, decisions made at this juncture have consequences leading to the eventual success or failure of the enterprise, or potentially an under-exploited opportunity.

At an early stage, the case business considered maintenance strategies, and how the choice would affect the design of the products. Legacy reactive maintenance strategies were discounted early on, being unsuitable for the level of product operating parameters to be communicated and the bidirectional control load, the product communicates data describing the packaging and metrology data during operation, in this respect with sensors and data pipelines mandated, KBM strategies were already provisioned for.

The significance of maintenance strategies in ensuring availability and cost-effectiveness has been widely acknowledged in scholarly literature and reviews, as highlighted by Ding and Kamaruddin (2015). According to Sielaff and Lucke (2021), many research papers addressing maintenance strategy selection tend to concentrate on particular scenarios or applications, with manufacturing or production being a prevalent focus. Leveraging theories and implementation frameworks from such studies can offer valuable insights into our case business context. Given that the case business product-service entails the operation of a pharmaceutical mixing unit, adapting these frameworks can provide complementary guidance in developing the business case operational framework.

In making the choice, several considerations should be weighed. Consideration of PdM fuels the adoption of design for reliability, while necessitating the additional design burden of embedding sensors and IoT connectivity. Temperature, humidity, vibration and motion, as necessary, as well as device usage patterns provision for predictive algorithms to forecast future degradation leading to unacceptable performance, and potential sudden catastrophic failures. The cost of designing in and instrumentation hardware of the sensor network is far from the complete burden. To enable predictive analytics algorithms to forecast potential failures, product designers must collaborate closely with data scientists and software engineers to determine the optimal placement and configuration of sensors (Perera et al., 2013) within the product architecture, ensuring seamless data collection and analysis capabilities. These activities entail significant investment in related expertise and may in themselves require iterative optimisation and adaption.

Design for Reliability

Estimated maintenance costs range from 15% to 70% of the cost of items sold (Thomas, 2018).

The case product contained a critical component of particular interest, a moving structural spring subject to repeated substantial stresses and strains. Product designers prioritise robustness, durability, and fault tolerance in product design. By understanding the failure modes and in the case of the product, critical components susceptible to fatigue stresses and degradation, designers can attempt to incorporate redundancy, modularity, and fail-safe mechanisms into the product architecture, thereby enhancing its reliability and serviceability. Reinforcing the drive for reliability and the effect on the wider activities, are the negative consequences of failure on stakeholders, beyond early-stage fault detection and estimation of RUL, keeping a product operationally effective is paramount.

Preserving Operational Service Life

KBM considerations influence the design of user interfaces and diagnostic tools to facilitate proactive maintenance activities. User-friendly interfaces provide operators and maintenance personnel with intuitive access to real-time equipment health data, actionable insights, and recommended maintenance actions. Diagnostic tools equipped with predictive analytics capabilities enable rapid fault diagnosis, root cause analysis, and decision support, empowering remote maintenance teams/ intelligent resources to pre-emptively address potential issues and minimise downtime.

KBM Strategy Selection Tools

Every new technology business which is service-orientated must find the question posed, *How do we ensure maximum uptime for our products and services?* According to Ulansky and Rana (2023, p.2), the following observations can be derived from the extant research upon which to begin to base at least a part of that decision-making process, in response to the question.
"

(1) Performance indicators are considered at three levels of maintenance control: strategic, tactical, and operational.
(2) An analysis of the published studies revealed that diverse types of maintenance performance indicators exist in the literature for each level of maintenance control.
(3)) At the operational stage, the most frequently used maintenance indicators are instantaneous availability, steady-state availability, average availability, inherent availability, mission availability, operational reliability, long-run average profit per unit time, long-run average cost per unit time, and average lifetime maintenance costs.
(4) To date, several classifications of maintenance performance indicators have been developed, including, for example, such categories of indicators as equipment-related, maintenance task-related, cost-related, and so on. However, the signs by which indicators should be selected in each group for systems of various purposes have not been indicated. Since a formalised approach to selecting the indicators has not been developed, users are forced to subjectively choose suitable indicators for their circumstances from a set of known indicators.
(5) The same effectiveness indicators were used for diverse types of maintenance, including preventive, corrective, condition-based, predictive, and prescriptive maintenance. Simultaneously, there is no formal classification of maintenance models that allows an appropriate model to be objectively chosen according to certain features.
(6) There is no formalised approach to the classification of systems for selecting maintenance effectiveness indicators and for the classification of the maintenance models necessary to calculate the selected indicators.
(7) In the existing preventive, corrective, condition-based, and predictive maintenance models, it is assumed that failures are detected using periodic (or sequential) inspections and/or continuous condition monitoring.
(8) Prescriptive maintenance uses condition monitoring and artificial intelligence to track a larger range of data and predict when maintenance is necessary in real-time."

Users of diverse technical solutions, the case business being one example, encounter three primary maintenance hurdles: reducing maintenance expenses, enhancing availability or operational reliability, and determining the most suitable methodologies to enhance operational performance. The literature review summary indicates prescriptive maintenance (RxM) of point (8) (Ulansky and Rana 2023) would appear to be the most appropriate for the case application, given both the size of the data packets, frequency, and pseudo-real-time nature of communication through cloud connectivity is a prerequisite to the use of the product. Ulansky and Rana (2023) further developed a tool for adopters to assess maintenance effectiveness indicators, and the mathematical models used to calculate them were elucidated in detail in their research publication. An alternative less complex approach is desirable for the small team of the case business.

Searching for easy-to-understand models, *MEthodology for DAta-Driven techniques and Expert Knowledge combination for PreDictive Maintenance* (MEDADEK-PdM) (Serradilla et al., 2022) promises to contribute towards an alternative structured framework Fig 13 , for the business to select a KBM and DS model strategy. Containing four main groups, and sequential stages, each following the outcomes of the previous stage.

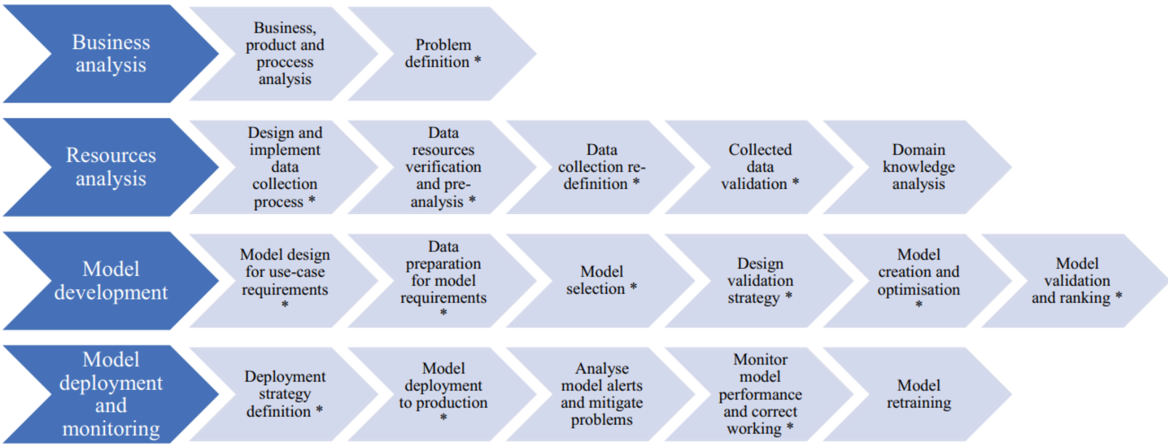


Figure 13 Scheme of proposed data-driven PdM methodology, which consists of four stages and their steps - MEDADEK-PdM (Serradilla et al., 2022)

The case business has to some lesser degree and informally followed this analytic process, without prior knowledge of the structured guidance. As a first step of Business Analysis, the business, product, and process analysis involved understanding the company's offerings, business model, and their connection to manufacturing. This enabled prioritisation of challenges like optimising product parameters, quality control, accuracy and repeatability in operation, and selecting maintenance strategies to meet business needs efficiently. The most critical assets, those with the highest potential impact, were analysed, focussing on a spring element as part of the problem definition. During the design phase, Finite Element Analysis identified key loci of potential failure. This analysis led to RxM as opposed to periodic maintenance or corrective maintenance as the maintenance choice. The decision process moved to the second stage of Resource Analysis. Business Analysis is the single-stage level where all three required knowledge profiles collaborate, the business managers define business perspective and business requirements, the domain technician contributes the technical operating expertise and the data scientist helps guide, whilst gaining an understanding of the overall objectives. To follow a more formalised structured decision pathway, MEDADEK-PdM recommend two critical documents be created:

> Document 1.1 Resource characteristics provide an encapsulation of the operational intricacies of a business, encapsulating its fundamental workings, business model,

array of products and services, and the underlying mechanics of its manufacturing processes and:

Document 1.2 details the problem at hand, identifying critical manufacturing assets based on their impact, delineating the maintenance requirements for these assets and their components, and evaluating the suitability of maintenance strategies.

This involves a comprehensive analysis aimed at understanding the significance of each asset, assessing the specific maintenance needs they entail, and determining the most effective strategies to ensure their optimal performance and longevity.

Conclusion

Selecting the right maintenance strategy and supporting infrastructure entails significant risk, with efficiency being a primary concern; however, errors and failures may still occur due to incomplete or insufficiently detailed data (Florian et al., 2021) should early-stage problem assessments and technical appreciation be insufficient. By systematically examining these factors, organisations can develop targeted maintenance plans tailored to the unique characteristics and operational demands of their manufacturing assets. The approaches (Serradilla et al., 2022; Ulansky and Rana 2023), and similar selection tools (Carnero, 2005), (although MEDADEK-PdM is an advanced tool at the time of writing) when fully developed, validated and more widely disseminated, promise both existing and new machine or product manufacturers a useful route to select or optimise their maintenance strategy choice with a degree of certainty.

Cost balance of KBM implementation

Ensuring optimal maintenance provision is essential for maintaining the technical availability of production tools or deployed product, a critical aspect for PSS, all while minimising resource utilisation (Praedicow et al., 2021). Diligently implemented PdM (or RxM) guarantees the uninterrupted availability of integral components within the overall service or product by actively monitoring their condition and intervening as needed, especially when failure is imminent. The selection of KBM serves as the cornerstone for utilising technical resources effectively and ensuring timely availability of technical capabilities (Patil et al., 2022). Through the adoption of PdM practices, companies streamline production schedules, enhance the efficiency of maintenance schedules, and reduce the consumption of spare parts, leading to substantial cost savings that outweigh the implementation costs of PdM. Once a specific type of KBM is chosen, be it knowledge-driven or data-driven, businesses must then weigh the implementation costs against the breadth or value of the benefits provided. The case business had specified a low service burden, achieved through design for reliability and supported by remote intelligent cloud-based agents. The intelligent agents, realised as bespoke algorithms modifying the operational characteristics of the product, mitigate anticipated performance deterioration, and forces the product persistence in the desired performance envelope. The data-driven approach does still incur significant expertise and associated costs to enable the ML-driven intelligent agents (cloud-based algorithms), however, the benefits associated with a product-service remaining in acceptable operation, with a no boots on the ground approach to local service personnel is incredibly attractive.

The costs can be considered in three distinct silos.

a) The ML-supported algorithms, a cloud function.
b) Instrumentation and bidirectional communication hardware, a cost per product unit deployed as a function of N (number of products) units in a fleet in service.
c) Data dialogue between the connected fleet and cloud infrastructure, again a function of N fleet devices.

The opportunity to amortise the singular investment in data-driven cloud-based architecture becomes commercially viable when a critical deployment scale is achieved. As the cost of the data scientists' effort is largely a known fixed expenditure for a given specification, commercial success lies with the quantum of the customer base and the associated number of deployed units. It can be difficult to model this relationship as meeting the minimum customer performance expectation has a binary influence on the buying decision, if performance is not perceived, the customer will not purchase. Promising a guaranteed performance encourages ownership and helps achieve the scale inflexion point where N brings the ML resource amortisation to an acceptable budgetary figure per unit in the field.

ML-Based PdM

As discussed in the previous sections, implementing an ML-based PdM strategy means developing and installing online models. (Florian et al., 2021). The case business must consider which of the alternative condition monitoring paradigms beneficially contribute to the Total Cost Of Ownership (TOC) (Roda et al., 2019) and is again is faced with a plethora of competent frameworks for this purpose. The case business is not an established enterprise with a large team and significant revenue streams, but an infant enterprise with limited resources. Empirical evaluation of ML implementations is not possible, as might be the case of established enterprises with existing plant and possibly extensive sensor data sets on which simulations and evaluation can be carried out. However, the infant business has several distinct advantages. Design of the product, selection of sensors, resolution and frequency of data harvesting and frequency of communication to the cloud agents (Cheng et al., 2020), are mainly still extremely fluid, and without existing infrastructure investment to consider, significantly more dramatic choices can be justified.

The case business has a series of hierarchical priorities to consider concerning TCO:

a) Reliability, the customer will not be prepared to tolerate any device failure in the critical MedTech sector.
b) The means to compensate for normal-usage subsystem deterioration and still maintain the performance within an acceptable envelope.
c) Remote device maintenance through OTAUs and reliable data communication in a challenging environment (hospitals and pharmacy suites may not be optimal for radio-based communications) and the air is a crowded space.
d) Extended product service life, the no boots on the ground approach, to maintain the products to the satisfaction of the customer without requiring service engineer physical access to the facilities and the devices, exacerbating unwelcome disruption.

Complexity persists at every decision stage. The case business must weigh the data scientist effort costs with available resources once again and select which ML methodologies best fit their business case criteria, as might be generated from the Business Analysis stage of the promising MEDADEK-PdM framework (Serradilla et al., 2022),

As demonstrated by Fig. 14. The plethora of methodologies are mainly categorised as:

A. supervised learning requires pre-generated classification datasets, sets of similar datasets describing a similar instance or outcome.
B. unsupervised learning, large data sets required to determine unknown classes of items by clustering (Jainet al.,)
C. reinforced learning, the algorithm must attempt based on a best guess starting point, which action generates the best outcomes, without external coaching (Wuest et al., 2016).

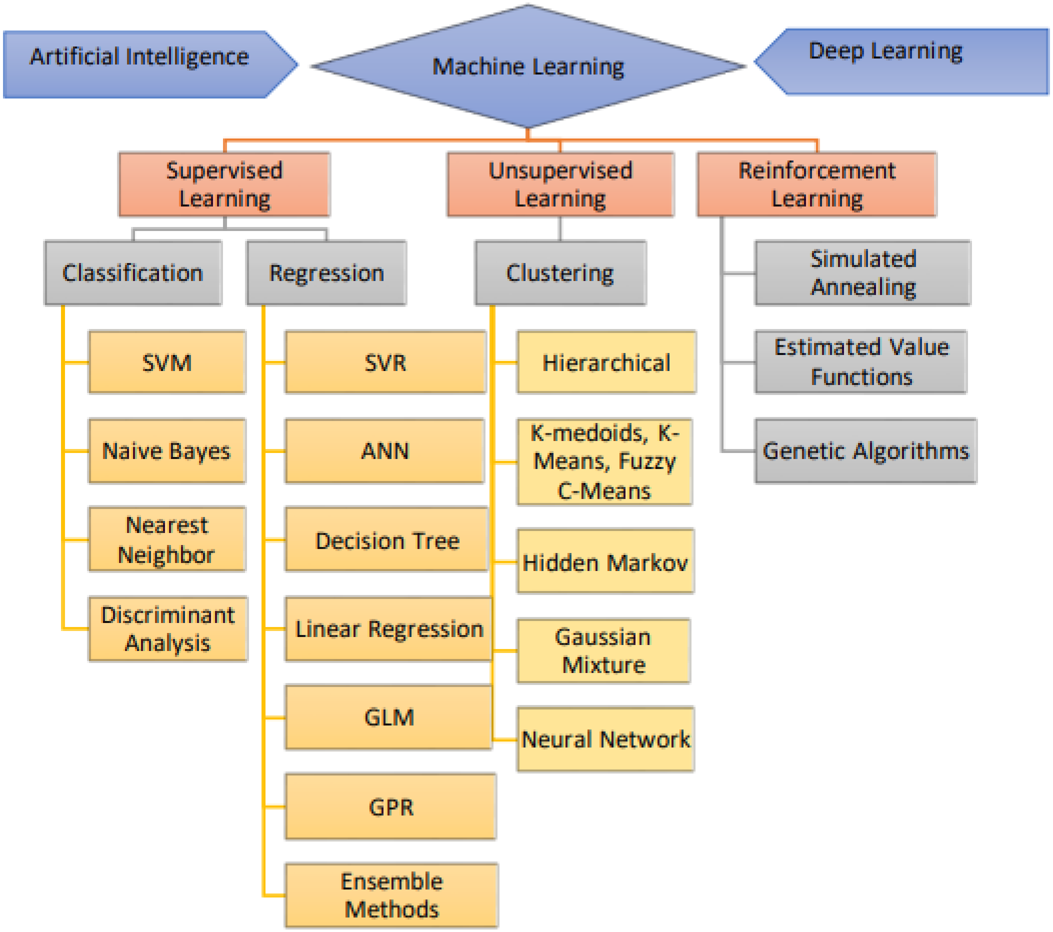


Figure 14 Classifications within ML techniques (Çınar et al., 2020)

Therefore, with the cost of effort considered, it would be wise to select an ML strategy, at least in the first instance of a small number of deployed devices, which avoids human intervention and generation of validated classifications and cluster parameters, discounting supervised and reinforcement learning ML. Consequentially, the Artificial Neural Network (ANN) may be considered a viable option to mitigate TCO. ANNs work in a similar role to the human brain (Sampaio et al., 2019). ANN models find extensive application across various disciplines owing to their adeptness at learning from examples. Unlike traditional ML algorithms, ANNs possess distinct advantages in handling random, fuzzy, and nonlinear data. Particularly suited for systems characterised by complex structures and ambiguous information, ANNs emerge as a preferred choice (Zhang et al., 2019), their versatility is evidenced by their widespread use, establishing them as one of the most prevalent ML algorithms. Furthermore, ANNs have been recommended for numerous industrial applications, including soft sensing and predictive control systems (Shin et al., 2018).

PdM Health Monitoring Summary

Presently, the PdM health monitoring system stands as a reliable approach for ensuring equipment operational efficiency by continually monitoring its condition, including defect detection, and estimating its RUL. Made possible through the systematic integration of AI and IT technologies to analyse current testing data, PdM offers not only cost savings in maintenance but also extends the equipment's RUL. By accurately predicting potential issues before they escalate into critical failures, proactive measures can be taken to address them promptly via cloud-based ANN agents. Using frameworks such as MEDADEK-PdM and focusing on TCO as a financial driver for decision-making, ANNs promise to help deliver an economy of effort and costs in the implementation of PdM within an interlaced environment of the business case, broadly similar to Fig. 15.

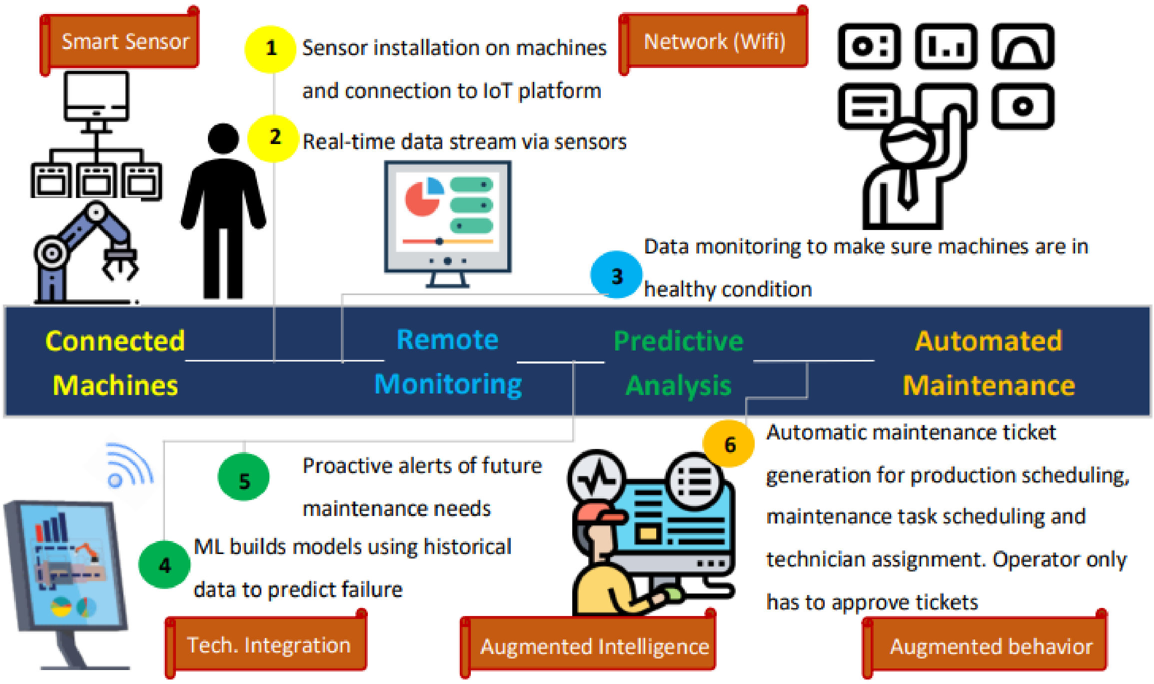


Figure 15 PdM process and technologies to drive PdM (Çınar et al., 2020)

Beneath the Cloud

Enabling Hardware

KBM strategies are often supported primarily by distal cloud-based resources, which by inference necessitates a resilient and relatively frequent digital dialogue between the managed asset and the complimentary supervisory resources resident in physically remote physical servers. The question arises of what happens when, which is more likely than if, the communication link is broken, unstable or unavailable (Lynn et al., 2020 p.73-74). Possible nefarious threats for data mutation, corruption or privacy-violating interception are discussed in Cyber Security, however, an increasingly popular adaption of KBM has been enabled by the cost, capability, and software support in small resource-limited devices. Additional road bumps in the journey of data exchange between assets and centralised remote servers slow the speed of communications, introducing latency and proliferating extant data in the cloud ecosystem. Edge Computing (EC) presents an opportunity to address latency and speed barriers and reduce the amount of data persisting in the network at any one time. Edge devices capable of varying degrees of computational processing, enabled with embedded memory have been capable of semi-independent asset support for some time, the emerging transformative wave of innovation accompanies significant scaling of legacy computational power (GarciaPerez et al., 2023). Accelerated by AI-compatible hardware units such as Tensor Processing Units (TPU) and Video Processing Units (VPU). AI accelerated Single Board Computers (SBC) such as the Jetson Nano (NVIDIA Developer, 2019) are now both cost-effective enough for ubiquitous deployment in asset support and capable of deep learning, computer vision, graphics, multimedia, and general input/ output control.

Reducing Costs and Risk

Apart from low latency, EC provisions for significant advantages when processing and analysing data where it is generated. By reducing the data volume transferred to the cloud, network bandwidth reductions are realised, and consequentially less infrastructure is required thereby saving energy and associated costs (Caporuscio et al., 2020). When more data are processed at the edge layer, less is processed in the cloud. As cloud service providers generally meter bidirectional data packets to charge customers, costs to use are reduced. By keeping the data in a local environment, that is, without leaving the facilities of the company or even the entity that generated and consumes, confidentiality and privacy risks are reduced.

Cyber Security

The need to consider connected devices and threats is underlined when it is considered there were 8.4 billion devices connected to the internet, setting the stage for an estimated 20.6 billion devices connected by 2020 (Gartner, 2019).

However, with the decision to make the product connected comes the bad actor threat, and that entails a new element of cost Fig. 16. (Gartner, 2018a)

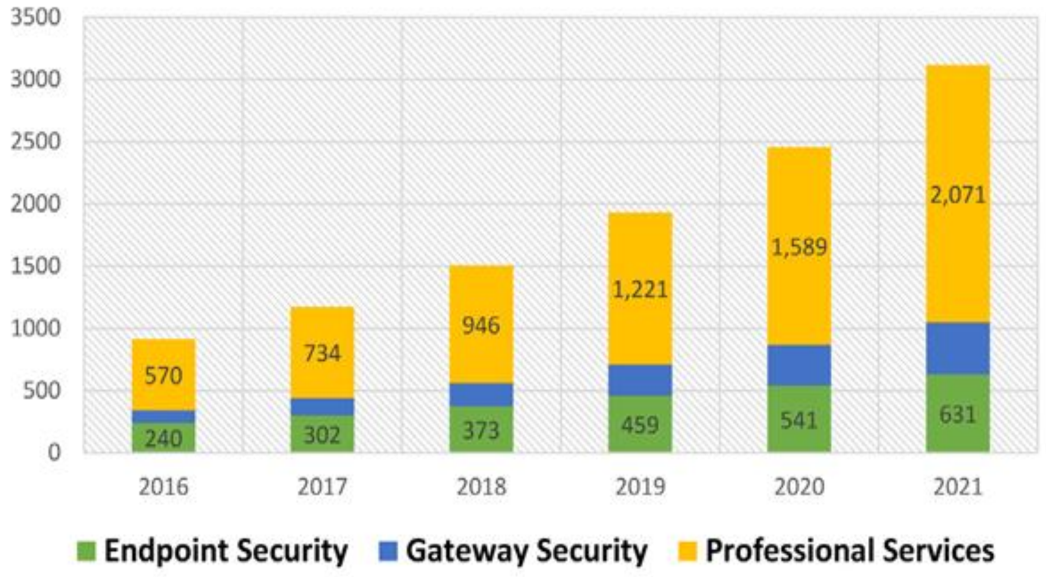


Figure 16 Protected Global IoT Security Spending in Million USD (Gartner, 2018a)

The significant amounts of budget allocation to combatting disruptive, often malicious attacks on CPS ought to, and does present concern for the case business. The case Product -Service evolution potentially begins with the specifications generated using the MEDADEK-PdM) (Serradilla et al., 2022) framework, and implicitly demands the product-service be connected.

Threat Mitigation, Defensive- Offensive

Caporuscio et al., (2020, p.681) posed the question, relevant to the business case ‘‘How can we promptly recognize anomalies in heterogeneous connected devices (including Embedded Systems, CPS and the IoT), and (semi)automatically apply appropriate troubleshooting solutions based on available information, to restore correct system operation, reduce the time-to-repair and the probability of maintenance mistakes?’’

DS by its control and reporting nature prioritises resilience and security in the face of deliberate attempts towards information and commercial disruption is vulnerable. Supervisory Control and Data Acquisition (SCADA) including systems that monitor and control Critical Infrastructures (CI), such as energy and potable water plants. (Hossain et al., 2022) are instances subject to deliberate interference. The case business application can also be considered as CI, responsible for medicine preparation within the healthcare system. Javorník and Husák, (2022) describe mitigating approaches to determine the resilience of CPS to attack and detail two novel models, Privilege-Exploit Attack Graph and Bayesian Privilege Attack Graph, which reduce complex attack graphs into a single comprehensible graph. The models are based on the knowledge of the attacker’s posture and the system vulnerabilities, a useful calculation of the likelihood the system will not be disrupted can be made. These tools can be useful but researchers continually present novel relatively complex and distracting examples and literature to small under-resourced enterprises. The case business does not have a cyber security team, individual, or access to costly third-party experts, so must look to affordable and available alternatives.

Affordable Cyber Security

Micro and small enterprises in the last relatively number of years have had access to a level of cyber security defences, previously only accessible to the largest corporation with financial resources sufficient to maintain their own IT security expertise. Enterprise-level security is embedded within many if not all the third-party DS providers, taking responsibility, more often perceived as a burden, of hosting DS as a part of their DS product delivery. “Strong security at the core of an organization enables digital transformation and innovation. AWS helps organizations to develop and evolve security, identity, and compliance into key business enablers.” (AWS, 2019). Amazon Web Services is one of the major providers supporting the digital transformation and service industry. Should a new business choose third-party digital service adoption, the level of confidence in industry actors such as AWS to develop continually evolving and threat-reactive security solutions can be high. Consequentially businesses, including the case business, can concentrate on their innovation activities and be significantly more assured of the resilience of their holistic product offerings against weak defenses or malicious attention.

Chapter 5: Conclusion

Summary of key findings.

Adopting a life-cycle cost perspective, the integration of product and service solutions creates incentives for optimising energy and consumables while extending the lifespan of products (Tukker, 2004). As the growing business, such as the case business, commences planning the delivery vehicle and their product-service offering, they may anticipate the scrutiny of their investors, customers, and the public in general. The business should focus on sustainability through good design where practical, provisioning for consumption respect for the environmental commodities of air and water, the reuse of materials, mitigation of environmental residuals and consumption of virgin resources. A note of caution applies to established businesses with product and delivery cycles in place, reviews of theory into practice examples in the real world have indicated understanding between the differing disparate silo of activity and coordination are mandatory to mitigate possible value leakage within creation-capture-delivery permutations of the value chain.

The impact of the device in service presents opportunities for good practice, and sympathetic product design, both physical and their associated maintenance strategies leading to economies through extended service life and mitigation of attending service personnel boots on the ground, inextricably linked to carbon-producing transport. The cradle to cradle template for consideration of inter-related resource pathways through the value chain Fig. 2, (Kalmykova et al., 2018) provides a useful primer for CE factor prospecting in conjunction with Fig.3, (Korhonen et al., 2018). With the National legislatures simultaneously enforcing waste management and promoting refurbishment and reuse through RtR, product lifecycles are now under active management, the case business should acknowledge its obligations in this domain. The importance of VRPs shaped by the connected nature of advanced maintenance strategies defined within KBM, serve to inform when and how the materials consumed in the deployed product-service must be dealt with in a CE sympathetic manner. For the case business, where the product may experience varying degrees of duty-cycles usage, a VRP might direct load balancing, by relocating devices intra-site to effectively manage the rate of deterioration.

Frameworks which are readily understood within the product cycle, manufacturing through to consumption, in particular, the importance of the role of AI in health monitoring methodologies have been particularly evident. The study has revealed the complexity of making early decisions, approaches to resolve the quandaries are eloquent and readily assimilated when presented as logical sequences. MEDADEK-PdM (Serradilla et al., 2022) guides the decision teams through processes that identify the needs and optimal solutions with validation steps interposed. The framework also encourages the consideration of the associated costs in the implementation of architectures and bespoke algorithms that accompany many of the KBM solutions.

DS is the prevalent choice over legacy inefficient and resource-hungry approaches, enabling value-in-transaction to a value-in-use, the key differences being internet delivery and multitenancy of DS, allowing investment in focussed virtual service silos to be amortised efficiently across a wider deployed product fleet and leverage the integrated assets from third-party providers. Pricing policies are adaptable to encourage consumption of services by skewing the TCO, such as eliminating the capital cost of adoption, opting alternatively for a leasing model, based on daily ownership fees and additional per-event, PAYG, or On-demand without ongoing periodically defined charges, but at a premium per-event. With a particular focus on the case business similar, where manpower and financial resources are constrained at the very early stages, the availability of SaaS and its sibling offerings is particularly attractive. AWS for example, allows even the most financially challenged a robust, multiple redundancy managed off-site server network on which solid SaaS frameworks can be deployed on various pricing plans. Inhouse privacy countermeasures within cyber security is an unattainable goal within SMEs, that only the larger corporations can afford. Web services again exemplified by AWS and Google (Google, 2019) appreciate security is not an optional extra, but mandatory in today's ubiquitous connected society and offer seamless integration within cloud service models.

With reliance on a connected servitisation model comes the risk of being disconnected. Fortunately, the pace of technological development advances to alleviate, albeit at a cost above the minimum viable implementation. Software deployable within computational and memory-constrained devices has emerged to mitigate this very risk, and the on-chip hardware accelerators to execute. ML active on or close to the connected device have emerged in response to this very risk. In reply to additional costs, EC and FC compensate their users with tangible cost reductions, performance enhancements through latency reductions and some valuable additional guarantees of operational health while temporarily disconnected.

Implications of the study.

This study, in the context of the case business, has illuminated the mycelial nature of Industry 4.0, a symbiosis of CE aspiration enabled by and reliant on digital connectivity with centralised remote reliable networks, secured by third-party DS providers, leveraging enterprise-level investment beyond the financial purses of micro and SMEs. The intertwining of specification evolution to product realisation with policy and strategies to eventual product and supporting digital servicing, is complex, although can be eased by important research on the methodologies, including business case reviews of theory in practice, and by applied guiding frameworks.

Despite this mycelial-like behaviour of Industry 4.0 entities, it can be nurtured to advantage the newly emerging digital enterprise, bringing about resource efficiency, performance optimisation and ethical global environmental stewardship.

Recommendations for future research.

A further investigation focussed in detail on the product-service of the case business:

1. to further investigate and review literature pertaining to theory-in-practice examples within the MedTech sector, to illuminate where value is typically created, diminished, or amplified.
2. advanced manufacturing technologies and where they may nest amongst traditional manufacturing approaches would inform the overall design-production cycle, especially contrasting cost-benefits concerning agile supply chains of raw materials.
3. revenue collection as an integrated component of third-party cloud service provision, and the fees charged versus alternative financial remuneration methodologies.
4. With efficiencies come loss of labour, in resource extraction and manufacturing, in servicing and maintenance, the human cost of Industry 4.0 efficiencies on populations reliant of executing these activities merits closer scrutiny, how can we compensate industry 4.0 losers.

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