Nested Lifecycles-Improving the Visibility of Product Lifespans in Smart Factories

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Within the smart factory environment, we have a complex system of systems composed of Industry 4.0/digital technologies and assets with varying lifespans. Different degrees of innovation maturity and different lifespans of integrated assets within the industrial internet of things (IIOT) are considered problematic and lead to different perspectives on asset lifecycles as they impact significantly on the asset lifespans. This leads to the loss of a clear end-of-life phase defined in existing Product Lifecycle Management (PLM) models. Through an integrative literature review, this study introduces the concept of nested lifecycles that takes a systems perspective to asset management, and considers subsystems with different lifespans that must be managed holistically by different actors with different perspectives. Additionally, this study provides a framework to derive strategies for lifecycle management by allowing the nested lifecycles to be clearly identified and then addressed. From the theoretical perspective, the notion of nested lifecycles provides a novel viewpoint for the asset management and PLM research community. From the managerial perspective, the proposed framework will help managers identify why and where collaboration between different actors may create difficulties due to their varying outlooks and training.

Keywords: smart factory, lifecycle management, asset renewal, product service system, nested lifecycle framework

INTRODUCTION

In today's sustainability debate, and considering the responsibility of manufacturing companies, the view of 'R-based approaches' is becoming increasingly established (Bag et al., 2021). Today, these approaches comprise up to 10 principles, ranging from recycle, remanufacture and repair, to rethink, refuse (Potting et al., 2017). In the transformation from linear to circular value creation, these principles are used to utilize materials more sensibly, to extend the lifespan of products, and to manufacture and develop products more intelligently to replace the end-of-life phase "with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes" (Kichherr et al., 2017). To achieve this, many manufacturing companies aim to leverage Smart Factory approaches (Herrmann et al., 2014). The shift to Smart Factories begins with the digital transformation of "everything related to production systems" (Roblek et al., 2021), starting with the assets themselves.

One promising trend in this digital transformation to Smart Factories is the emergence of Product-Service System (PSS) business models (Tukker and Tischner, 2006), in which product sales and consumption are taking a back seat to service that extends the life of assets (Vendrell-Herrero,

TABLE 1 | Definitions used in this paper.

Term	Understanding	Literature Sources
Lifecycle	Phase model from the beginning, through use-phase cycles until the end of life ('cradle to grave') of a product or system	Terzi et al. (2010)
Lifecycle management	Integrated concept supported by ICT, to manage knowledge, data and activities for achieving desired performances and sustainability for the product and related services in the different lifecycle phases	Terzi et al. (2010)
		United Nations Environment Programme (2007)
		Itskos et al. (2016)
Lifespan	Timeframe in which a product can be used (longevity) before reaching its end of life	Vendrell-Herero et al. (2021)
Nested lifecycle management	A systems perspective to asset management considering subsystems with different lifespans that must be managed holistically by different actors with different perspectives.	—

2021). Today, this trend is being reinforced by digitalization and, in many areas, it is the move to digital that makes it possible in the first place (Coreynen et al., 2017). Due to digitalization and the Industrial Internet of Things (IIoT) new complex systems in form of smart PSS (Kuhlenkötter et al., 2017) or smart service systems (Beverungen et al., 2019) emerge. Within such systems, hardware and software components of different actors are integrated into bundled offerings, leading to servitized business ecosystems, where value is co-created (Lightfoot et al., 2013). Especially for suppliers of long-lifespan products, this transformation seems to have a positive impact on firms' performance (Vendrell-Herero, 2021). In the context of digitalization, the question arises of how to deal with the fact that products with long lifespans are combined with components with short lifespans. This has a considerable influence on PLM, where a systemic view is needed.

The discipline of Systems Engineering is concerned with the integration of discrete systems (Kossiakoff, 2014) to consider the entire system from a holistic point of view, mainly from a technical perspective. Lifecycles in this paper are considered from the systems development perspective, less so for management and control. Lifecycle management mainly focuses on single products or assets, rather than the system from which the products or assets result and are integrated. Further, PSS, according to Tukker (2004), focuses on the offering's perspective rather than a holistic perspective from the firm regarding and considering not only the offering but also the entire organization's activities for value creation.

Many researchers have investigated the role of lifecycle management of industrial equipment throughout the manufacturing sectors (Terzi et al., 2010). Product Lifecycle Management (PLM) is defined as a "systematic, controlled concept for managing and developing assets and product-related information", according to Saaksvuori and Immonen (2005). Other studies (Hamraz, Caldwell and Clarkson, 2013) focus on engineering change management and design version control in use. Cerri and Terzi (2016) proposed a sustainability-focused lifecycle costing model at a system level, and consider the different phases of an asset's life (e.g., beginning of life, middle of life, and end of life). The operational phase can be further subdivided into more discrete activities: operation, planned and routine maintenance, breakdown and repair, and asset renewal. West and Pascual (2015) advance this and consider the importance of lifecycles for the identification of value-driven service opportunities for sales across different phases of industrial assets' life.

A distinction should be made between the concepts of asset lifecycle and lifespan. The lifecycle is concerned with the phased aging process of the asset and covers stages from the initial purchase to planned obsolescence (**Table 1**). By contrast, an asset's lifespan defines the remaining useful operational life (Yaguo Lei, 2017) of the asset, which is typically considered in financial terms of investment, depreciation, and amortization, and is a key consideration in decisions to replace or refurbish.

Limited research has been conducted on the lifecycle impact of the IIoT when integrated with traditional equipment. Much has been written on the challenges associated with digitalization (Anderson, West and Harrison, 2021) and how to innovate digitally-enabled solutions or Smart Products. However, the conflict in product lifespan (or operational life) expectations (Vendrell-Herrero et al., 2021) stems in part from the different perspectives on PLM. For example, some components within a system may remain operational for decades with ongoing maintenance and repair, and other mechanical systems may need replacement more regularly, whereas some digital components have lifespans of just a few years. Limited research has been conducted on the lifecycle aspects of the entire system comprising many individual assets, in particular the lifespan aspect. Consequently, there are limited practitioner frameworks to operationally manage this beyond the established ISO 55001 standard (Ma, Zhou, and Sheng, 2014), which focusses upon risk mitigation and optimizing asset value at a process level.

The research arises from these apparent gaps in the literature, in particular the impact of such lifecycles as an interconnected system of nested lifecycles, incorporating both traditional and digital technologies, within a multi-actor industrial environment. Each actor has different perceptions of lifespan and asset obsolescence, based upon their intuition, and often without full awareness of adjacent operational functions, or the integrated lifecycles that are captive within the larger interconnected system.

Research question: What are the effects on PLM when bundling assets with diverse operational lifespans in digitally enabled product-service systems?

This study aims to explore this in the lifecycle management of interconnected assets that are typically found within a

factory or production facility. In doing so, it will create a framework that can be used to support the long-term sustainability of the operation through a systems-based approach to asset management.

RESEARCH FRAMEWORK AND METHODOLOGY

An integrative literature review can be used to investigate a research gap and build a framework that can then be tested (Snyder, 2019). The literature that considers the different perspectives of the lifecycle and the implications for management is rather fragmented, although there is a weight of literature that focuses on lifecycle management during the beginning of life, often from a technological perspective (Terzi et al., 2010). The nesting of lifecycles and the inclusion of lifespan appears to be poorly integrated into the existing frameworks. For this reason, an integrative literature review has been chosen as the most appropriate approach, bounded by the operations within a factory, roles of various actors within a factory, and the asset lifespan within a factory, allowing the integration of knowledge from other disciplines (Snyder, 2019). To answer the research question and to address the gaps in the interdisciplinary space, our integrative literature review is divided into three phases to allow us to assess the problems that are faced:

1) The first part of the review is to understand the context of a factory, its purpose and its general operation. The section is relatively concise, nevertheless, it is required to provide the necessary boundary conditions for the following parts of the literature review.
2) The second part was designed to describe the roles of the actors within a factory. The internal actors were described based on Porter's value chain, as it provides a framework for synthesizing and structuring research from a management perspective (de Mozota, 1998).
3) The third part was designed to identify the different lifespans of equipment for the factory and different subsystems within the factory. From the literature and online databases, a table of asset classes and lifespans has been created.

The final step (presented in **Section 4** of this paper) follows on from the three phases of the literature review to build a framework to support the integration of the findings. In this form, researchers and practitioners can understand the difficulties of integrating different asset classes within a smart factory environment.

INTEGRATIVE LITERATURE REVIEW

This section describes first the factory as a system, then moves to consider asset renewal within a smart factory based on each asset's anticipated lifespan, before ending with a section on the actors who are active within a smart factory environment.

The Factory as a System

The primary activities of a typical factory mainly relates to the transformation of incoming materials into outbound goods (Porter, 1985). There are also supporting activities, such as quality control and warehousing, that are required to enable the primary activities. **Figure 1** provides an overview of a typical production environment based on Porter (1985). According to Benotsmane et al. (2019) a smart factory is one that adapts to changes by integrating data from different sources to enable flexibility to respond to changes in demands. Both views, separated by over 30 years, represent similar views on the purpose of the factory. The use of digital technologies has become embedded within the traditional infrastructure of factories to improve quality and efficiency, and increase speed (Romero et al., 2016). On this basis, the literature has been assessed based upon the value chain, albeit focusing on the activities that are closely related with production, as seen in **Table 2**. Although the literature often focuses on greenfield Smart Factories, there is a growing appreciation for the evolution of a brownfield factory into a Smart Factory through the integration of new emerging digital technologies as part of Industry 4.0 (Jaspert et al., 2021; Mantravadi et al., 2022).

In the context of research into Industry 4.0 and the implementation of the vision of networked smart factories, Sjödin et al. (2018) have identified different maturity stages for successful implementation of a smart factory. According to the authors, the three principles to advance across the maturity stages include 1) introduction of agile processes, 2) cultivation of digital people and thereby new skills and job profiles, and 3) modular configuration of technologies. The smart factory vision promises to help make processes more efficient, reduce operational costs, maximize quality and safety, and minimize resource use and environmental impact. Within the smart factory, reference models like RAMI 4.0 and IIRA emerged (Resman et al., 2019; Osterrieder, Budde and Friedli, 2020). These models are structured around layers that reach from the physical asset layer to a more abstract application layer, with sensor, connectivity and data layers in between, which can be considered for understanding the value generation in smart manufacturing (Porter and Heppelmann, 2014; Fleisch et al., 2015; Zheng et al., 2019; Jaspert et al., 2021).

Even smaller companies might benefit from implementing a smart factory, especially if they are open to the breadth of technologies and try to incorporate them along the value chain (Büchi, 2020). Examples of enabling technologies include internet of things cloud computing, big data analytics, and augmented reality (Büchi, 2020). These Industry 4.0 technologies can be integrated horizontally and/or vertically: the former for efficiency gains inside the organization, and the latter for easier and better communication with suppliers and customers for enhanced value propositions (Coreynen et al., 2017).

The value proposition is considered the most important building block of business models in the industrial internet of things (Dijkman et al., 2015). Successful companies are demonstrating how a stronger end-customer focus and
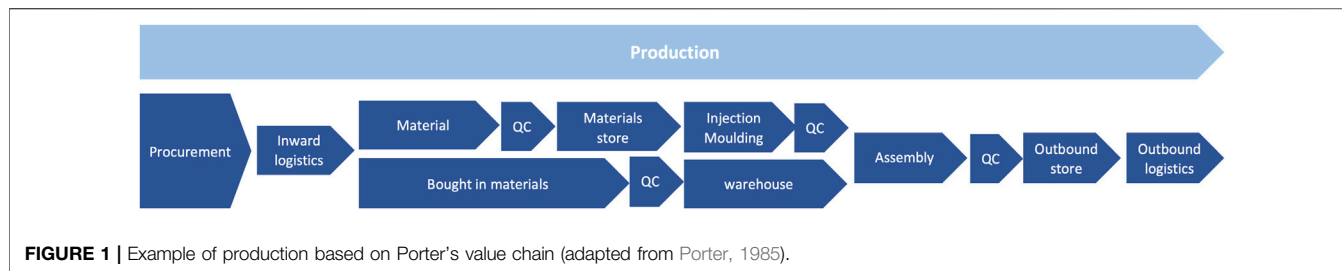
FIGURE 1 | Example of production based on Porter's value chain (adapted from Porter, 1985).

TABLE 2 | Literature review of the factory as a system focused on operations (adapted from Porter, 1985).

Activity Type	Activity	Purpose	Literature Sources
Support	Technology	Managing the PLM processes with the help of technology	Saaksvuori and Immonen (2005)
Support	Procurement	Managing suppliers to ensure materials are available as needed by production according to the Bill of Materials (BOM)	Chenini et al. (2021)
Primary	Inbound logistics	Ensuring inbound materials and components are received, stored, of correct quality, and assigned to right destination	Wang and Koh (2010)
Primary	Operations (manufacture)	Transforming raw materials into semi-finished products	Mital et al. (2014)
Primary	Operations (Assembly)	Assembling the semi-finished products with purchased goods into the final goods	Kamauff (2010)
Primary	Operations (quality)	Confirming that the goods, semi-finished products, and purchased goods conform to the specifications and the BOM.	Kamauff (2010)
Primary	Outbound logistics	Shipping the goods to the customer	Wang and Koh (2010)

TABLE 3 | Firm infrastructure and its purpose.

Infrastructure	Purpose	Literature Sources
Environmental sensors	To measure ambient conditions of the factory system (e.g., power consumption, temperature)	Kalsoom et al. (2020) Lian et al. (2013)
Mechanical assets	Machine tools, with varying degrees of automation and data generation capability	Mori et al. (2019)
Machine sensors	To generate telemetry data from machines as per Level 0 ISA-95	Mehta et al. (2018)
PLC	Sensing and manipulation level of the ISA-95 model	Galloway and Hancke (2013)
SCADA/HMI/DCS	Monitoring and control of systems	Galloway and Hancke (2013)
Cloud	Internet based, on-demand scalable computing resource (typically for data storage, processing and analytics)	Tan and Labastida (2021)
Computers	On-premises computing resource (typically used for real-time data process and analysis)	Tan and Labastida (2021)
Network	Arrangement of connections between assets to transfer data and share resources	Galloway and Hancke (2013)

networking via smart products can build close customer relationships and create service ecosystems that offer business potential (Breschi, 2017). In manufacturing, this type of change is described as servitization, which is being driven by digitalization and is seen as a promising transformation from a product-centric understanding of industry. Nevertheless, the question arises of how to continue to exploit previous competitive advantages. It is likely that tangible goods will continue to be a component in offerings (Porter and Heppelmann 2015). Hybrid service bundles tend to better meet customer needs and create competitive advantages (Anderson, West and Harrison, 2021). Product development will therefore remain an important pillar. To this end, it is also important to align production sites in the best possible way for the transformation towards hybrid offerings. The factory environment comprises numerous key components related to process automation, such as telemetry sensors, programmable logic controllers (PLC), Supervisory control and

data acquisition (SCADA), Human-machine interfaces (HMI), and Distributed control systems (DCS). The integration of new digital technologies into these traditional infrastructure components is described in **Table 3**, based on the ANSI/ISA-95 standards (ANSI, 2008).

Roles Within a Smart Factory Environment

Smart factories and Industry 4.0 have brought new and changed job profiles and competencies into manufacturing industry (Pejic-Bach, 2020). These can be conceptualized as roles that are understood as "distinct technologically separable, value-added activities undertaken by firms or individuals" (Kambil and Short, 1994, p. 10). In multi-actor settings, actors can take on different roles depending on the situation, which is why a differentiation of roles, instead of actors is used in this paper (Ekman et al., 2016; Anke et al., 2020). The roles within the smart factory environment have been structured based on Porter's value

TABLE 4 | Typical roles within the design and development phase (beginning of life) focused departments.

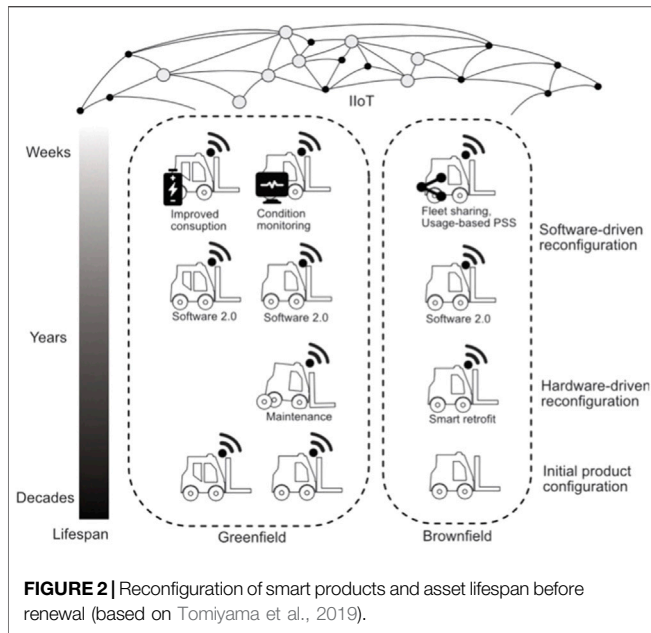| ACT	Description	Outlook			Literature Sources
		Operational	Tactical	Strategic	
Customer and Target 'Users'	Target Customer of the Value Proposition; Informs Projects		x	x	Poeppelbuss et al. (2021)
System integrator	Install and support ICT systems and develop technical concept	x	x		Poeppelbuss et al. (2021)
Digital Innovator	Facilitate creation of ideas and design of business model	x	x		Poeppelbuss et al. (2021)
Hardware supplier	Supplying sensors and other hardware components	x			Anke et al. (2020)
OEM	Manufacturing physical assets (e.g., machines, parts)	x	x	x	Anke et al. (2020)
UI/UX specialist	Development of HMI and designing front-end	x			Anke et al. (2020)
Data analyst	Data engineering and implementing big data solutions	x	x		Anke et al. (2020)
Smart product designer	Product management and prototype and test	x			Pejic-Bach et al. (2020)
Customer satisfaction manager	Adapt business processes to the needs of the customer	x	x	x	Pejic-Bach et al. (2020)

TABLE 5 | Typical roles within production (middle of life) focused departments within a firm.

Role	Description	Outlook			Literature Sources
		Operational	Tactical	Strategic	
Finance manager	Ensure cost control Deliver financial reports Review Asset Renewal		X	X	Kamauff (2010)
Information and communications technology (ICT)	Install and support ICT systems at lowest cost	X	X		Dewett and Jones (2001)
Product development	Design new products Generate BOM Transfer new BOMs to production		X	X	Olson, Walker and Ruekert (1995)
Operations manager	Lead the operations/production To lead the operations strategy		X	X	Kamauff (2010)
PLC Programmer	Provide complementary automation and develop automated systems	X	X		Benešová and Tupa (2017)
Robot Programmer	Remove heavy physical labor by programming industrial robots	X	X		Benešová and Tupa (2017)
Production supervisor/planner	Lead the shift Manage the production plan Deal with short-term production problems on a tactical basis	X	X		Kamauff (2010)
					Lowe (1993)
Machine operators	Operate the machines according to the plan	X			Kamauff (2010)
Maintenance (Smart Factory)	To plan and execute maintenance (electric and mechanic) to support operations	X	X	X	Jerman (2020)
Maintenance (ICT system)	To plan and execute maintenance To keep ICT technologies running	X	X	X	Jerman (2020)
Quality and safety	To oversee quality and safety of the production To lead root cause analysis	X	X		Kamauff (2010)
Cyber security	Secure systems e.g., against hacker attacks		X	X	Benešová and Tupa (2017)
Continual implement/lean	To trouble-shoot quality issues in production To identify operational improvements	X	X		Kamauff (2010)
Procurement manager	To purchase the production BOMs according to operational plans To purchase infrastructure according to specifications	X	X		Kamauff (2010)
Data analyst	Processing information from data for optimization and management	X	X	X	Benešová and Tupa (2017)
Logistics manager	To manage the inventory of raw materials To manage the inventory of subsystems To manage the shipping of goods to customers	X	X	X	Kamauff (2010)

chain (Porter, 1985) and are described in **Table 4** for the design and development phase and **Table 5** for the operational phase of the PLM. The descriptions that each role takes, and their outlook, has been based on the literature. The outlook has been established from the breakdown between operational, tactical, and strategic thinking in a manufacturing environment according to Momme (2002), as this provides insights into their approach towards their role.

On reviewing the different roles, clearly defined 'tribes' of stakeholders emerge, arising from their different backgrounds

FIGURE 2 | Reconfiguration of smart products and asset lifespan before renewal (based on Tomiyama et al., 2019).

and outlooks. Firstly the 'Traditional Production' tribe, such stakeholders are found mainly in sectors like engineering and manufacturing that follow more conservative stage-gate thinking with emphasis on iterative changes. Then the 'Disruptive tribe', these people are found mainly in information technology and internet-based organizations. They follow management approaches such as agile development, with an emphasis on incremental innovation with shorter change cycles via minimum viable products, resulting in a more cyclical and collaborative approach, which is more conducive to innovation. Meanwhile, traditional tribes follow waterfall and stage-gate methods, where change is addressed in more sequential steps. With regards to their respective experience, manufacturing heavy industries in physics, engineering, and other physical sciences dominate traditional stakeholders. Strategic long-term thinking is vital in this field. Meanwhile, disruptive stakeholders are in the information technology and digital sectors, where regulations or corporate governance rules are still nascent and some risk can be taken. Traditional stakeholders and their organizations deal with long lead times, strong intellectual property protection with extended quality analysis and release cycles. Meanwhile, disruptive industries follow a more agile, open-source approach, with a "perpetual beta" and fast corrective patching mindset. These general differences across stakeholders are a key consideration for lifecycle management, as this mismatch (and sometimes lack of awareness) of different intuitive perspectives can cause operational issues.

Asset Renewal Within a Factory

Asset renewal is the replacement (or refurbishment) of an existing asset or component with a new asset (e.g., new machine) capable of delivering the same level of service as the existing asset (NAMS

Group, 2006). The asset renewal process should, in general terms, be closely related to the asset depreciation (Vangermeersch, 1971; Sigidov et al., 2016) and maintenance strategies (Kelly, 2006). The rate of asset depreciation should match the cost of asset renewal in the medium term to ensure the same level of performance from the system. The asset depreciation should be based on the estimate of useful life (or the asset's lifespan). The asset depreciation period may be considered within an accounting environment and provides the framework for asset renewal within a factory (or a smart factory). The rate of depreciation can be impacted by the component's lifespan and the maintenance strategy applied (i.e., preventative or predictive, repair or replace etc.). Within asset renewal the concept of obsolescence needs to be integrated, as obsolescence is often closely associated with innovation and technology maturity (Burns, 2010).

Besides mechanical asset renewal, the establishment of smart products creates the possibility of post-production reconfiguration (Abramovici et al., 2017). Products that have been delivered to a customer can be modified through smart retrofitting (Jaspert et al., 2021), but also through the continuous adaptation of software modules (Tomiyama et al., 2019), and ongoing 'over the air' updates to firmware (Nilsson and Larson, 2008). Such integrated views of asset renewal and reconfiguration enables new value creation in greenfield and brownfield factories. Understanding the smart factory or smart service systems as changing systems—whose use phase in the life cycle can be extended continuously through constant updates and reconfiguration—can have a significant impact on the 10Rs (Kirchherr et al., 2017) in the context of the circular economy. The increased integration of various asset classes, from long-lived mechanical components to short-lived software products, results in a complex network that must be managed. **Figure 2** shows the different reconfiguration options with asset lifespans. It is notable that with a shift to newer digital technologies, there is a corresponding decrease in the lifespan, becoming more pronounced as the technology separates from the traditional production environment.

As such, **Table 6** provides an overview of different asset classes within a smart factory environment based on the literature and on a Japanese government database (NIES, n.d.). To distinguish asset classes, we used the layers introduced in section 3.1.

A SYSTEMS-BASED FRAMEWORK FOR ASSET LIFE MANAGEMENT

Our contribution covers various facets of asset management in the implementation of smart products and product-service systems within the smart factory setting. As a contribution to research, the main areas considered were: asset lifecycle management, product lifecycle design, and the new role of the nested lifecycle manager.

Asset lifecycle management gives a detailed perspective on the lifecycles of different technologies and how they are related to innovation cycles. Assets with different innovation cycles (fast vs mature) should be considered distinctly in asset and lifecycle

TABLE 6 | Examples of asset classes in a smart factory.

Layer	Asset Class	Examples	Typical Average Lifespan	Asset Renewal				Literature Sources
				Maintain	Repair	Refurbish	Replace	
Physical	Infrastructure	Building	100 years	X	X	X		Cooper et al. (2014)
	Production system	Industrial equipment	16 years	X	X	X		Vendrell-Herrero (2021)
		Plant for manufacturing	31	X	X	X		NIES, (n.d.)
	Mechanical assets	Bearings/seals	3–5 years				X	Budris and Bloch (2021)
		Servo motor	1-2 years				X	Park et al. (2018)
		Pumps and compressors	19 years	X	X	X		NIES, (2021)
Sensor	Machine sensors	Retrofit sensor (sealed batteries)	5 years				X	AWS (2021)
	Electronic components	Microprocessor relay	6–12 years				X	Kleman and Moyer (2017)
Connectivity, data and cloud intelligence	PLC	Automotive industry	20 years				X	PMMI Media Group (2014)
	Connectivity	Router/switches	5 years				X	Rassier (2017)
	Cloud	Storage	3–5 years				X	Rassier (2017)
		Analytics	1–5 years				X	Rassier (2017)
Application	SCADA/DCS	Manufacturing plant control	10–15 years		X	X	X	Fiero (2019)
	Comput-ers	SCADA system	5–10 years		X	X	X	Winsystems (2018)
	HMI	Interfaces	10 years					Honeywell Building Technologies (2021)

management and require different tools and processes. For the installed base, a field that often receives little attention, we provide a new perspective that enables further research, less oriented to OEM considerations but with a focus on the operational phase. In general, life cycles and lifespan are a poorly considered field of research. As other researchers from related fields have noted, this perspective can provide exciting insights that may be helpful in explaining existing challenges in the context of Industry 4.0 (Vendrell-Herrero et al., 2021).

A systems-based approach requires us to first consider the entire system by describing the boundary conditions before considering the subsystems (Blanchard, Fabrycky and Fabrycky, 1990). Within such a system it is then possible to consider the lifespan incongruences that have been identified in **Section 3**, around which it is now possible to consider the actors and their expectations that come from their individual roles. These shed light on the paradox that competing lifespans can provide when considering asset life management in a smart factory environment.

In asset life management within the smart factory, responsible personnel should ensure that the products are suitably designed (Bakker, et al., 2014). According to Bakker, et al. (2014), products with short innovation cycles and immature technologies should be as easy to replace (and recycle) as possible. Plant components with long lifespans and mature technologies, on the other hand, should be designed for a long service life, with minimal use of materials, and be easy to maintain. The findings are summarized in **Table 7**. However, as described in **Table 6**, there are (sub) system components, e.g., bearings, seals, and car tires, that are considered consumable in nature, even though the technology may be considered mature.

Within the context of systems engineering (supporting with system boundaries) and the asset life management of the smart factory, the development of a framework becomes clearer when considering the literature findings. The first aspect is that the smart factory is a complex system that consists of many different actors with different perspectives, based on their individual and collective contexts. Here there is a clear difference when we consider a greenfield or a brownfield smart factory. The purpose of the factory remains to produce products efficiently, however over its lifespan the production will vary based on market, technology, and management changes (Lei, 2017; Mantravadi et al., 2022; Benotsmane et al., 2019).

The lifespan of a product or asset describes the expected duration of the object's performance as planned (Vendrell-Herrero, 2021). In comparison, the lifecycle describes the lifespan in more detail, including the stages beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL); this concept provides the option of iteration, meaning that EOL activities can lead to a new BOL phase. Therefore, lifecycle management can be described as an activity to either reach or exceed the expected lifespan of a product or an asset. When considering or defining a system with many individual components and subsystems, then lifecycle management activities on the individual asset level, the application allows the lifespan concept to be applied. The application of either the lifecycle or lifespan concept can depend on the technological maturity of the component or the relative importance of the component within the system for value creation or destruction. The approach taken for the maintenance and asset management of complex systems is described by Kelly (2006), where the trade-offs between different approaches and the

TABLE 7 | Impact of innovation cycle velocity on technology lifecycles and lifespans.

	Mature Technology	**Developing Technology**
Innovation cycles	Sedate innovation	Rapid innovation
Lifespan	7–100	<7 years
Examples	Skeleton/housing	Batteries
	Infrastructure	UI/HMI
	Mechanical components	Microcontroller
Preferred design	Longer product life	Remanufacture
	Repairability	Recycling
	Refurbishment	Modular (Wulfsberg et al., 2013)
	Modular (Wulfsberg et al., 2013)	

need to focus on the system and subsystems is considered. Also, it is clear that the BOL lifespan assumptions are design assumptions and that during the MOL phase these may need to be adapted. This approach to systems management also considers the obsolescence aspects, e.g., when a supplier stops producing a subsystem component and a firm needs to deal with the challenges it creates for long-term asset management.

The concept of digitally-enabled PSS can be applied to a smart factory because such a factory has all the main components related to such PSS, which are products, services, and digital technologies interacting with the purpose of value creation. Such a digitally-enabled PSS can become very complex, having many actors and products with different lifespans. The challenge of such a system orchestrator can be first, modelling the system and identifying system drivers for value creation and destruction. Second, establishing appropriate metrics for decision making from a systems perspective, and third, continuously evolving and adapting the system. The lifecycle management framework proposed in this paper aims to address the challenges stemming from continuously and sustainably evolving the digitally enabled product-service system.

There is clear interaction between the actors, and the various roles that they take, and the smart factory; yet each has different perspectives and different time horizons that they consider. This has been seen by considering the three horizons of operational, tactical, and strategic decision-making according to Momme (2002). Overlying this are the individual norms from each profession, which are not in alignment and are driven in part by the rhythm of their different professions, and in part by the norms of the technologies. The integrations between the different actors and the dominance of each actor depends on the position within the lifecycle (e.g., BOL, MOL, or EOL). The complexity is increased when considering the perspective of the asset owner and the supplier, as the factory itself may be in the MOL phase, yet the new machines that are being integrated into the factory are a new design and therefore at the late BOL phase.

The operational factory environment is dynamic (Benotsmane et al., 2019), yet the expectation of the operations manager is to maintain and standardize, and in doing so, optimize efficiency within a quality window (Romero et al., 2016). Processes to manage the mechanical, electrical and control system maintenance within a factory have become part of normal practices. The maintenance team understands the need for and the timing of maintenance since the machines themselves are of a

mature technology. What is new in a smart factory is the integration of IoT technologies where technologies are less matured and development cycles significantly shortened.

The systems engineering (Kossiakoff 2014) approach to mechatronic systems has been well described (e.g., in the V-model) and many firms today develop such systems using traditional product development processes. Often these have been based on stage gate-like processes with clearly defined cycles. IoT-technologies are less mature and are on shorter lifecycles today, with much shorter development cycles and are often developed on more agile development processes. This creates a paradox in the development of technical solutions for smart factories, as it is necessary to understand these two approaches to innovation and lifecycle management. In an operational factory, the integration of these different lifecycles provides the potential for additional challenges as operations and maintenance managers understand the mechatronic systems and the lifecycles and equipment lifespans (Vendrell-Herrero, 2021; NIES, n.d.). They therefore face the challenge of having to adapt to the higher velocity of change with IoT technologies and the shorter lifespans they offer. Furthermore, the actors who deal with mechatronic systems in their roles are different to those who deal with the IoT technologies, often with a data science or information systems background.

Based on the differences seen in the literature of the lifecycles and the lifespans of equipment and the difference of the actors within a smart factory environment, the framework in **Figure 3** has been developed.

Rather than considering only the system and the relevant subsystem of the different asset classes that constitute a production system, the framework integrates the perspective of the various actors and the asset mix within the smart factory. For the actors, it allows the decision-making horizons to be described visually and integrated into the Systems Engineering use case descriptions. The individual actor's outlook drives expectations and norms, and a significant part comes from their decision-making horizons that are often considered 'operational, tactical or strategic'. Additionally, the management team's skillset within a factory environment is traditional, whereas the new skills needed for smart factories come from Industry 4 (Tomiyama et al., 2019). This creates challenges, as the working norms can create misunderstandings. Using a framework that describes these over the lifecycle of the factory and its subsystems will help managers identify why and where collaboration between different people
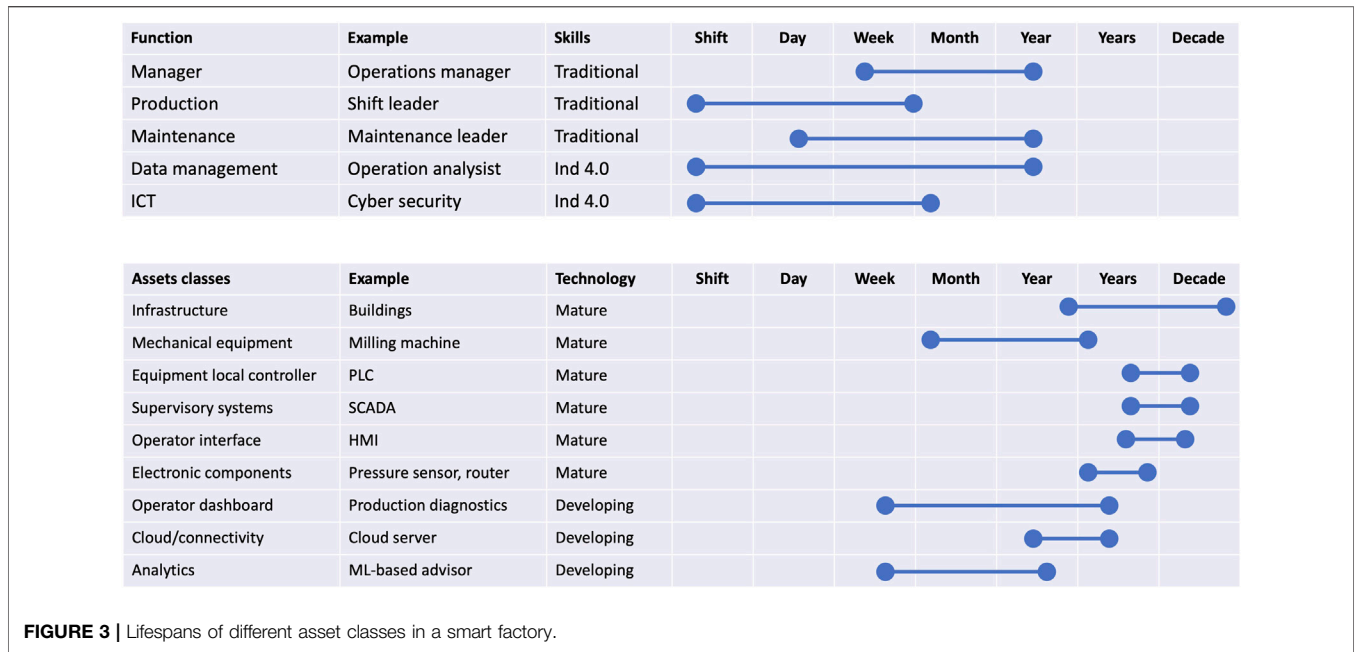
Function	Example	Skills	Shift	Day	Week	Month	Year	Years	Decade
Manager	Operations manager	Traditional			●——	——	●		
Production	Shift leader	Traditional	●——	——	——	●			
Maintenance	Maintenance leader	Traditional			●——	——	●		
Data management	Operation analysist	Ind 4.0	●——	——	——	——	●		
ICT	Cyber security	Ind 4.0	●——	——	——	●			

Assets classes	Example	Technology	Shift	Day	Week	Month	Year	Years	Decade
Infrastructure	Buildings	Mature						●——	●
Mechanical equipment	Milling machine	Mature				●——	●		
Equipment local controller	PLC	Mature						●—	●
Supervisory systems	SCADA	Mature						●—	●
Operator interface	HMI	Mature						●—	●
Electronic components	Pressure sensor, router	Mature					●—	●	
Operator dashboard	Production diagnostics	Developing			●——	——	●		
Cloud/connectivity	Cloud server	Developing				●——	——	●	
Analytics	ML-based advisor	Developing			●——	——	●		

FIGURE 3 | Lifespans of different asset classes in a smart factory.

may create difficulties due to different outlooks or training. Moving to consider the various asset classes, finance experts can provide insights into the replacement cycles, along with the Japanese database; alternatively, personal experience may be used to provide an initial view of lifespans. Nevertheless, an assessment of lifespan must be made with any capital investment, as finance will need to apply the appropriate depreciation rate to the new assets. For reliable asset management, it is crucial to understand and manage the lifecycle of important subsystems. With the integration of Industry four technologies, the lifespans have reduced due to rapid changes in technology as standards are established. The framework here is generic and would help to describe the individual assets and their subsystems. The visual approach here supports identifying possible nested lifecycles created due to the different levels of maturity or innovation in a particular system or subsystem.

Theoretical Implications

From a theoretical perspective, the concept of nested lifecycles provides an interesting viewpoint for asset management and the PLM research community in the context of a smart factory. This study further establishes the gap that the existing literature does not clearly distinguish between product lifecycle and product lifespan management concepts. By introducing the notion of nested lifecycles, this study argues that from a systems perspective, an asset's lifecycle can be modeled as a nested structure of subsystem lifecycles where the lifespan of those subsystems can also vary. In line with Wellsandt et al. (2019), we also argue that researchers should consider integrating the nesting concept in the Lifecycle Modeling Language. Furthermore, this study provides a framework that will help researchers to develop and analyze case studies based around a specific asset from the system's perspective by identifying the nested lifecycles resulting from different levels of maturity and innovation.

Managerial Implications

At present, the asset management focus within industry is based around ISO 55001 (Ma et al, 2014), which considers an asset's value, environmental and social costs, risk, quality of service, and performance. Core asset decision-making frameworks need to be extended to incorporate "nested lifecycle management". The perspectives of the various actors who are directly or indirectly involved in the management, operation, maintenance, or support of a smart factory need to be considered when designing a smart factory. This can be done visually and should consider actors who are outside the factory's production area, as Industry 4.0 approaches demand a vertical and horizontal integration of information flows. The addition of the different assets provides an asset-focused view of the factory. It provides an understanding of the typical asset relational cycles based on the expected operational lifespans of systems and subsystems. The integration of some Industry 4-based components within a traditional factory environment can lead to misalignments of expectations between different actors due to their backgrounds and experiences. This may also shed some light on the expectations of obsolescence within the system. The asset visual should be completed for the whole of the factory. Another area of concern is the lack of clear demarcation of operational responsibilities that follow the adoption of newer technologies. Such responsibilities need to be clearly defined throughout the organization. Typically, the responsibility for Asset Management overlaps between Quality and Operations functions (Parra et al., 2021). A new role should be created to support nested asset lifecycles, taking a more holistic view of the entire factory as a system and supporting the integration of the different stakeholder perspectives, ensuring that lifecycles or lifespan issues are a key consideration with asset strategy.

This has a direct impact on the second field of smart product development, which should consider the lifespan of technologies

in the design at an early stage to simplify asset management in the smart factory. Here, it is interesting to look at this in the same way as Bakker et al. (2014) see product lifecycle design. Companies should incorporate suitable lifecycle models and design decisions into development at an early stage. For new technologies and applications, innovation cycles are so short that the establishment of long lifespans does not make economic sense or is not yet technologically possible (e.g., batteries). In this case, however, it is important that these components have no influence on the parts and subsystems of a PSS that otherwise have a long lifespan (e.g., housing). It must be possible to simply renew, replace and recycle developing technologies within the PSS. Otherwise, there is a risk that the expected positive effects of digitalization and PSS on sustainability will turn into the opposite, resulting in rebound effects (Kjaer et al., 2018; 2019). This brings us to the third area, namely the question of personnel and the required skills of engaged actors. Asset lifespan consideration could make it important to establish new roles. So far, the focus has been strongly on digital skills and a change of job profiles in the context of Industry 4.0 (Jerman et al., 2020; Pejic-Bach et al., 2020). In previous work, the topic of lifespan management is underrepresented, and we propose, for example, the establishment of a nested lifecycle manager. Here, it would be necessary to clarify who can take on such a role or what skills they need. A Smart Factory is a dynamic system that is subject to ongoing changes and optimizations. A governance approach should be adopted comprising the key function stakeholders to oversee and manage proposed changes to the factory system, from asset beginning of life to renewal.

CONCLUSION AND RECOMMENDATIONS

Much of the literature on product life cycle management is from the manufacturer's perspective. However, in a Smart Factory, the distinctions of the supplier break down, as many different systems and subsystems may be represented. Furthermore, many different perspectives are represented within the factory environment with varying outlooks. For these reasons, we propose that it may be necessary for a new nested lifecycle management task to be included in the asset lifecycle and product lifecycle design. To support this, we

have developed a framework based on the integrative literature that visually combines the outlooks of different actors and the lifespan of various assets, systems, and subsystems.

The framework requires testing and further refinement, and this paper aimed to develop a framework based on published theory, which has been fulfilled. Additionally, the tasks around managing what we have called 'nested lifecycles' need to be further described. This role needs to integrate asset lifecycle management and lifecycle design perspectives.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SW (lead author) with contributions in all sections. ME with contributions in all sections. MA contributed to the overall concept, the introduction, the literature review, and the discussion. OS with contributions to the methodology and discussion. JP with contributions to the abstract and the conclusions. MK contributed to theoretical and managerial implication sections and PLM-related discussions throughout the paper.

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