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Midlife upgrade of capital equipment: A servitization-enabled, value-adding alternative to traditional equipment replacement strategies

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ABSTRACT

Fast-paced technology lifecycles continuously increase the uncertainty of decision-making processes when it comes to acquisition of new technological innovations. This is especially true in case of technology acquisitions by means of equipment replacement that is often capital intensive and time consuming. The midlife upgrade strategy, building on manufacturing servitization and product-service system (PSS) business models, presents a promising alternative to traditional equipment replacement. Midlife upgrades describe the extension of capital equipment's remaining useful life by means of upgrading components, sub-systems or the like in response to certain triggers from users, environment, or market. However, the concept of midlife upgrade has thus far been discussed primarily from a theoretical perspective in literature. The state of the art lacks empirical evidence regarding the potential and outcome of successful midlife upgrades. In this paper, our objective is to empirically investigate the potential of midlife upgrade of capital equipment as a value-adding alternative to traditional equipment replacement in the context of servitization. To this end, first we develop a replacement decision framework based on the influencing factors and motivations behind equipment replacement. Then we present five case studies of capital equipment that have been upgraded during their middle of life to perform beyond their initial design specification. These case studies are analyzed based on the replacement decision framework with the goal of understanding whether the established influencing factors and motivations behind traditional equipment replacement are also applicable to capital equipment midlife upgrades and if so, to what extent. Our findings indicate that midlife upgrades have the potential to effectively postpone replacement while extending the remaining useful life of capital equipment and thereby facilitate the implementation of the circular economy. Our findings also suggest that midlife upgrades indeed present a value-adding alternative to traditional equipment replacement from the perspectives of both users and manufacturers, especially when provisioned with a servitized PSS business model.

Introduction

Many firms are pivoting towards more service-oriented business models. This process is generally referred to as servitization [1,2]. Servitization is the phenomenon of manufacturing firms developing value proposition by incorporating additional services [3] in order to attain a competitive edge in the market [4]. Ren & Gregory [5] defined servitization as a 'change process', where manufacturing companies adopt service orientation by developing new and better services with the aim to fulfil customers' needs, attain competitive edges, and enhance overall firm performance. Alternatively, Baines et al. [6] described servitization as the innovation of organizational capabilities required to shift from selling products to selling Product Service Systems (PSS). The term of PSS was first introduced by Goedkoop [7], who defined it as "system of products, services, networks of players and supporting infrastructure that continuously strives to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models".

Servitization and PSS are strongly tied to Product Lifecycle Management (PLM), as information exchange/access across and within lifecycle phases is crucial ([8,9]). There are two main perspectives on product lifecycles. One is frequently employed in the business (strategic management/marketing) domain and

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focuses mainly on the lifecycles of industries, product generations, etc. [10,11]. While the other is mainly utilized in the engineering domain and allows for a more product-oriented perspective that divides the product lifecycle in three distinct phases: Beginning of Life (BOL), Middle of Life (MOL), and End of Life (MOL) (see Fig. 1). The BOL comprises the ideation and creation of the product (design, manufacturing, assembly, etc.), MOL covers the whole usage of the product but also service/maintenance and other operations, while EOL focuses on the remanufacturing, recycling, and disposal [12]. The three-phase model is often used when it comes to item-level coverage and closed-loop PLM [13].

The MOL phase is currently the main focus area of servitization as it is during this period where a PSS delivers the most value to the user. Active management of assets through the MOL in a PSS setting brings forth new opportunities for manufacturers and other stakeholders [14,15]. By extending the value offering through MOL services and ultimately creating a PSS, the users and manufacturers of PSS are tied more closely together and additional revenue streams are created ([3,6]). One such value adding MOL service strategy gaining traction in the literature is midlife upgrade of PSS [16–20]. Midlife upgrade describes the process of improving the performance and functional capability of a PSS during its active usage period. Ultimately, it allows to extend the useful lifetime of a PSS by postponing replacement.

However, despite being a potentially value-adding MOL service strategy, concrete cases of successful midlife upgrades are currently not available in literature. In a recent systematic literature review, Khan et al. [16] reported that the concept of midlife upgrade has been treated primarily in a theoretical fashion in the PSS literature with rare evidence of any practical implementations and actual evaluations. Hence, it can be concluded that the state of the art lacks empirical evidence regarding the potential of midlife upgrade in the context of servitization. In order to address this gap, we aim to empirically investigate the potential of midlife upgrade as opposed to traditional equipment replacement. We want to explore whether the influencing factors and motivations behind equipment replacement are applicable to equipment upgrade as well. Additionally, we investigate to what extent midlife upgrade can be a value adding alternative to equipment replacement in the context of servitization. To this end, first we explore the available literature on equipment replacement in order to collect and understand the various influencing factors and motivations behind equipment replacement. As the literature on traditional equipment replacement is much more mature and developed compared to literature focused on the relatively new concept of midlife upgrade, we aim to investigate if we can use some of the proven and established findings in this new field. Building on that, we develop a novel equipment replacement decision framework based on the identified factors and motivations. To answer our main research question, whether the equipment replacement factors and motivations can be used to analyze and inform midlife upgrade decisions, we present five case studies of capital equipment that have been upgraded beyond their initial design specification. Our

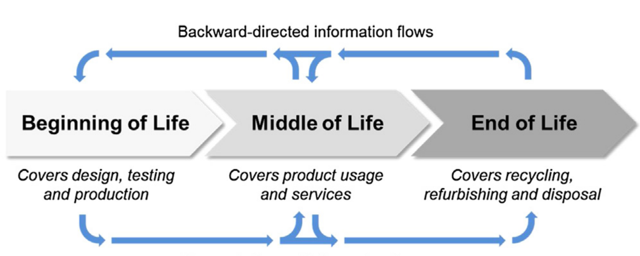

Fig. 1. Model of a product lifecycle and important information flows [73].

case studies are analyzed using our new framework to evaluate its usability in the context of midlife upgrades, as well as provide empirical insights on successful midlife upgrades for capital equipment to contribute to the literature of the field.

This paper is structured as follows: section two provides a brief background and in-depth problem description to motivate our research. In the next section, we describe our research methodology, structured around the four main steps we followed to answer our research question and close the research gap. In the fourth section, we present our novel equipment replacement decision framework, including a detailed list and description of all factors and motivations behind traditional equipment replacement decisions. Following, we present and analyze our five midlife upgrade case studies using our framework in section five and discuss the results and the limitations of this work in section six. Section seven concludes the paper and provides an outlook on further research.

Research background and problem justification

The strategic replacement of capital equipment is a routine phenomenon for most industrial enterprises and an essential topic in the management of capital assets [21]. Incorrect replacement decisions often cost far more than all the savings achieved in any other area of production and planning [22]. Equipment replacement regularly requires significant investment and can affect the profitability and competitiveness of an organization for the next several years. The importance of optimal replacement decisions is further substantiated by the fact that companies and other organizations in the United States alone spent $975 billion on capital equipment in 2016 [23], thus accounting for more than five percent of the annual GDP in the same year.

The need for new equipment is primarily motivated by either additional equipment that is required to meet an increased demand for a company's products or services, or the replacement of existing equipment [24]. The decision to replace existing equipment, in turn, can be largely attributed to two main reasons: (i) increased operating and maintenance (O&M) costs of the existing equipment, and (ii) the availability of technologically advanced equipment on the market. As capital equipment is generally utilized over time, it faces physical deterioration, which ultimately leads to increasing O&M costs and a decrease of the salvage value. Furthermore, technological progress leads to the emergence of newer equipment that operates more efficiently and often provides additional benefits [25].

The equipment replacement problem has been studied for nearly a century by researchers in the field of economics and operations research under different contexts [81]. Particularly, the influence of technological progress on replacement decisions has been studied extensively in the literature. Some valuable recent contributions worth mentioning include des-Bordes and Büyüktahtakın [26], Büyüktahtakın and Hartman [27], Hartman and Tan [81] as well as Yatsenko and Hritonenko [28]. This emphasis is not surprising considering the rapid development of technology that provides companies with many opportunities to improve their efficiency, product quality, and ultimately profit [29]. Furthermore, the importance of adopting advanced technologies in order to achieve and maintain a company's sustained competitive advantage has been established for a long time within the literature [30,31].

At the same time, the lifecycle of equipment is shrinking, at least partly caused by the fast-paced technology cycles [29]. What appears to be a rational equipment purchase may soon become obsolete [27]. As a result, it is increasingly difficult for decision makers in industry to confidently acquire new technological innovations by means of traditional equipment replacement, which is often very capital intensive and time consuming. A major factor is that the invested capital for a new equipment purchase might very well not be recovered by the time another advanced technology appears and renders is obsolete. Therefore, it becomes increasingly difficult for decision makers to justify yet another replacement [27]. Under these circumstances, midlife upgrades may have the potential to (i) keep the capital equipment up to date with the rapid technological advancements, and (ii) reduce the risk, financial and beyond, of equipment purchase. Midlife upgrades can effectively lead to postponing equipment replacement by extending its remaining useful life. Furthermore, servitization adds to these positive aspects by fostering a close relationship between the equipment manufacturers and users of the equipment.

Methodology

Given the exploratory nature and novelty of this research, a combination of literature review and case study approach is most applicable [32,33]. Therefore, we have employed the research method following two main activities (see Fig. 2): (1) developing an equipment replacement decision framework based on the motivation behind equipment replacement and related factors that are used to characterize these motivations through an in-depth literature review, and (2) applying our novel framework empirically, using several midlife upgrade case studies. The research objective is to understand whether the influencing factors and motivations behind traditional equipment replacement are also applicable to equipment midlife upgrades, and if so, to what extent. The results of these two activities enable us to understand the potential of a midlife upgrade strategy as a value-adding alternative to equipment replacement. Furthermore, by presenting empirically grounded case studies, we expand the current literature which lacks in this area.

Steps to develop the equipment replacement decision framework

In order to develop our novel equipment replacement decision framework, we investigated the available equipment replacement literature to identify the influencing factors and motivations behind traditional equipment replacement. To this end, we followed four steps to develop our new framework: (i) database selection and literature identification, (ii) screening identified literatures for relevancy, (iii) identifying the influencing factors and motivations behind traditional equipment replacement decisions based on the synthesis of relevant literature, and (iv) constructing our novel framework.

i In a *first step*, we selected Web of Science (WoS) as our primary database due to its comprehensive coverage of the focus area and its high-quality content. Following, we conducted a keyword search in WoS using the search string "(equipment or asset or machine) and (replacement or substitution or upgrade or modernization)". We have applied the keyword selection and initial screening criteria described in Ref. [16], which resulted in 872 papers as of December 2018.

ii In a *second step*, after reading the titles and in selected cases additionally the abstracts of all 872 papers, 794 papers were excluded as these papers primarily focused on repair, maintenance, spare parts replacement, or some other topics considered out of scope. This exclusion resulted in a consolidated sample of 78 papers. These papers were then read in full to carry out a detailed content-based selection, during which only those papers that explicitly discussed issues related to capital equipment replacement decisions were selected for our final analysis. This content-based selection carried out on the sample of 78 papers, allowed to exclude 47 additional papers. Furthermore, the database search was complemented by cross-referencing for further relevant publications, which led to a final list of 44 relevant papers as a basis for constructing of our framework.

iii In a *third step*, we have thoroughly read all of our selected papers while looking for potential influencing factors and motivations behind equipment replacement decisions. Whenever we were able to identify an influencing factor or replacement motive, we took note of it along with a short description and its references. This step resulted in set of replacement motivations and associated influencing factors that characterize those motivations.

iv In the *final step*, we have constructed our framework by carefully refining, categorizing, describing, and mapping the identified influencing factors within each of the equipment replacement motivations. For this step, we have also taken inputs from other PhD students and a post-doctoral researcher from our lab. Eventually we refined, categorized, and mapped the identified factors into the framework by a three-step iterative process.

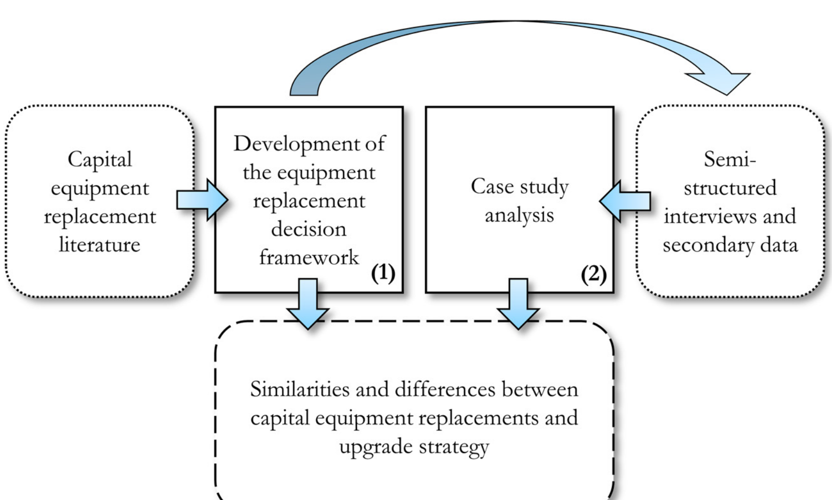

Fig. 2. Schematic of the methodological steps.

Case study selection and analysis

In a next step, we have selected and analyzed five different case studies on midlife upgrades to analyze the similarities and differences between capital equipment replacements and midlife upgrade decisions. The selected case studies cover the description of capital equipment midlife upgrades that have already been implemented in real life. The case studies were selected as they have the following traits in common: complex engineered products and their associated services, a long operational lifetime, and set in a Business-to-Business (B2B) environment. The data collection for the case studies included qualitative, semi-structured interviews, as well as secondary sources to augment the empirical data. To ensure the reliability and validity of data collection procedure, we developed a research protocol based on the equipment replacement decision framework. Additionally, the framework has provided a definite structure with a list of factors to be investigated and has been used as a guideline throughout our semi-structured case interviews. Analysing the case studies in a structured way based on the equipment replacement decision framework allowed us to derive insights that are valuable for both academics and industrial decision makers.

Equipment replacement decision framework

We have thoroughly reviewed the equipment replacement literature to identify the influencing factors and motivations for equipment replacement. Based on the identified replacement factors, we have developed a novel framework that provided the basis for our semi-structured interviews and subsequent analysis of the five case studies.

Factors that influence equipment replacement

Over time, equipment ages and it becomes increasingly expensive and sometimes even impossible to maintain the required level of performance (i.e., capacity or quality), leading to equipment replacement. Replacement decisions, in turn, depend on many different factors including both financial and non-financial measures. Following the methodology described in section 3, we have identified a comprehensive list of 40 different factors that were reported to influence replacement decisions. In Table 1, we have created a comprehensive list and briefly defined the identified factors, along with the references originally reporting them. Additionally, we have classified the various factors based on their definitions broadly into three categories: technical factors, economic or commercial factors, as well as regulatory factors. It should be noted that some of the factors are interdependent and may depend on the cumulative effect of several other factors. For example, some of the replacement models considered the overall O&M costs as a single factor, whereas other models have considered individual factors such as rate of failure, energy cost, labor cost, spare parts cost, lubrication cost, repair cost, etc. separately. Furthermore, potential risks are also important to consider beside the actual factors. For example, increased environmental risk may influence a replacement decision despite the fact that an actual event is yet to occur.

Motivation behind equipment replacement

Based on the synthesis of the relevant literature, we identified several equipment replacement rationales that can be consolidated into four basic motivations. The replacement of equipment is generally motivated or driven by (i) deterioration of the equipment currently owned, (ii) obsolescence of the existing equipment with

Table 1
Comprehensive list of factors that influence equipment replacement decisions.

Category	Factor		Brief description	References
Technical factors	Productivity factors	Availability or downtime	The actual time that the equipment is capable of production as a percentage of total planned production time.	[1], [6], [14], [15], [20], [28], [30]
		Productivity	The overall efficiency of the equipment. Usually measured in terms of the rate of output per unit of input.	[3], [11], [13], [14], [19]
		Rate of failure	Frequency of equipment breakdowns expressed in failures per unit of time.	[1], [3–7], [16], [31–32], [43]
		Reliability	The probability that the equipment will satisfactorily function when performing the intended tasks for a specified period of time.	[1], [3], [5], [19], [20], [29], [30–31]
		Scrap or rework rate	Percentage of failed assemblies or materials that are added into production but is not part of a finished product.	[14], [15]
		Throughput time	The amount of time it takes for a product to pass through the equipment.	[25], [42]
		Utilization rate	Utilization rate is the percentage of time an equipment spends doing the intended function.	[2], [3], [10], [11], [13–15], [18], [25], [29], [34]
	Obsolescence factors	Availability of mechanics	Availability of mechanics or technicians who have the technical knowledge to fix a failed equipment.	[41], [43]
		Availability of spare parts	Availability of spare parts, accessories and consumables.	[1], [3], [5], [20], [41]
		Future potential of technological progress	Further improvements of technology that could occur in the future, but those improvements may have a bearing on the current decision.	[16], [19]
		Incompatibility	Compatibility issues of an equipment with the other equipment in the production line.	[5], [6], [7], [41], [43]
		Technological progress	A process of invention and commercialization of new technologies that result in improved methods of producing goods.	[1–15], [17], [20], [25], [30], [34], [37], [39], [40–43]

Table 1 (*Continued*)

Category		Factor	Brief description	References
	Market factors	Product demand	Customer's willingness and ability to purchase a product at a given price.	[2], [10], [14], [15], [17], [18], [25], [34], [36]
		Product price	The amount of money that has to be paid to obtain a particular product.	[14], [15], [25]
		Product quality	The perception of the degree to which a specific product or service meets or exceeds the customer's expectations.	[10], [14], [15], [23], [25]
		Product variety or customizability	Refers to different product design and types aimed at meeting various customer needs	[14], [15]
	Others	Age	The length of time that an equipment has been in operation.	[2–4], [8–12], [14–17], [21], [29], [33–35], [37]
		Long term deterioration	Refers to the reduction in operational capability of an equipment due by wear and tear, erosion, fatigue, etc.	[1], [2], [26], [39]
	Regulatory factors	Cap-and-trade	An approach that sets emission limit for a group of corporations and allows them to trade their emission allowances among themselves.	[18]
		Carbon tax	A fee imposed on the burning of carbon-based fuels and depends on the carbon content of fossil fuels.	[18]
		Environmental issues / risks	Refers to the changes in law and policy regarding various environmental factors such as emission of carbon or other greenhouse gases.	[1], [3], [5], [18–21], [30], [38], [42], [44]
		Ergonomic efficiency	The ability of the equipment to reduce strain of the labors' body that would otherwise be caused by the manual.	[13]
		Safety or health issues	The issues related to the safety, health, and welfare of people who operate or work nearby the equipment.	[1], [3], [5], [7], [19], [20], [23], [29]
Economic or commercial factors	Cost factors	Energy cost	Refers to the cost of consumed energy by the equipment per unit operation time or per unit output.	[1], [3], [6], [7], [18], [42], [43]
		Fixed installation cost	The installation cost associated with the equipment replacement procedure.	[2], [5], [8], [17], [18], [34], [36], [37], [43]
		Floor space cost	The cost of space required for an equipment to perform its intended function.	[14], [15], [44]
		Holding cost or inventory cost	The cost of keeping an old equipment in the inventory before salvaging or disposing it.	[2], [12], [14], [17], [18], [40]
		Insurance cost	Cost to purchase equipment insurance, which covers expenses of the equipment incurred from various types of damages.	[2], [14], [15]
		Labor cost	Cost of labor hours needed by the equipment per unit operation time or per unit output.	[13], [14], [44]
		Operation and maintenance cost	The cost of operating labor, maintenance, materials and energy needed to guarantee that the equipment is available for production.	[2–4], [8–11], [16–18], [24], [29], [31], [33–36], [43]
		Purchase cost of new equipment or technology	Capital required to purchase a new equipment or adopt a new technology.	[2–5], [8–11], [16–18], [24], [25], [29], [34–37], [39]
		Staff training cost for new equipment	Cost to train the existing staff about how to operate the new equipment.	[3], [20–23], [28]
	Financial factors	Depreciation	A reduction in the value of an equipment due to long-term deterioration.	[4], [12], [16], [40]
		Discount rate	This rate is used to discount the future cash flow in order to find the Net Present Value (NPV) of that future cash flow.	[4], [6–7], [9–13], [16], [19], [24], [25], [29], [34–39], [43]
		Inflation	A general increase in the prices of goods and services over time or decrease in the purchasing value of money.	[4], [12], [16]
		Interest rate on invested capital	Refers to the cost charged by a lender to a borrower and is expressed as a percentage.	[4], [11], [12], [14], [16], [25]
		Payoff period	The length of time required to recover the purchase cost of an equipment.	[3]
		Tax concessions	Complete or partial monetary exemptions that reduce taxable income.	[4], [10], [12], [16]
	Others	Capital budget constraint	Available capital for long-term investment.	[2], [5], [13], [17], [18], [40]
		Salvage value	Estimated value of an equipment at the end of its useful life.	[2], [4], [8-11], [13-18], [24], [25], [29], [34–36], [38], [39]

[1] Hastings [52]; [2] des-Bordes & Büyüktahtakın [26]; [3] Zhang et al. [78]; [4] Mathew & Kennedy [22]; [5] Mellal et al. [60]; [6] Mercier & Labeau [62]; [7] Mercier [61]; [8] Yatsenko & Hritonenko [75]; [9] Yatsenko & Hritonenko [76]; [10] Rajagopalan [24]; [11] Rogers & Hartman [67]; [12] Koowattanatianchai & Charles [58]; [13] Jin & Kite-Powell [56]; [14] Chang [47]; [15] Meyer [63]; [16] Hartman [25]; [17] Büyüktahtakın & Hartman [27]; [18] Abdi & Taghipour [41]; [19] Apeland & Scarf [44]; [20] Sulaiman & Visser [72]; [21] Bollinger [46]; [22] Keating et al. [57]; [23] Dima & Man [50]; [24] Al-Chalabi et al. [43]; [25] Wang & Nguyen [29]; [26] Jain [55]; [27] Sindhuja [70]; [28] Micromain [65]; [29] Scarf & Hartman [69]; [30] Sandborn et al. [68]; [31] Mardin & Arai [59]; [32] Chen & Cheng [48]; [33] Yatsenko & Hritonenko [28]; [34] Hartman [51]; [35] Hritonenko & Yatsenko [53]; [36] Yatsenko & Hritonenko [74]; [37] Yatsenko & Hritonenko [77]; [38] Stutzman et al. [71]; [39] Nair & Hopp [66]; [40] Adkins & Paxson [42]; [41] Clavareau & Labeau [49]; [42] Aylen [45]; [43] Michel et al. [64]; [44] Hritonenko & Yatsenko [54].

respect to technological advances of new equipment available on the market, (iii) increase or decrease of the required capacity, and (iv) changes in law, policy, or regulation. Below, we briefly discuss the four main motivations along with the reasoning behind their classifications.

Deterioration

Equipment deteriorates with age due to regular usage and other factors such as wear and tear, erosion, and fatigue. Over time, they face increasing failure rates leading to higher O&M costs, lower productivity, unmet production schedules, reduced output quality, and decreasing salvage value. Furthermore, the health, safety, and environmental costs also increase along with more frequent breakdowns. Consequently, there comes a point at which it is no longer viable to continue operating the current equipment and a replacement is often the consequence.

Technological obsolescence

Technological obsolescence usually occurs when new equipment or technologies become available to supersede the currently operating model. It is generally preferred to use the newer one despite the fact that the older one is still in working condition. From the perspective of capital equipment, we have classified technological obsolescence into the following three types:

- *Functional obsolescence* occurs when the repair and maintenance of legacy equipment become difficult or impossible due to unavailability of spare parts, skilled maintenance personnel, and supporting technologies, thus making the equipment functionally obsolete. Furthermore, changes made in a production system may render a piece of equipment incompatible with other machines within the system which is another example of functional obsolescence.
- *Economic obsolescence* occurs when technological advancements enable newer equipment available on the market to operate more efficiently compared to current equipment. Adopting new technology may reduce the O&M costs, failure rate, rework rate, labor requirement, energy consumption, etc., which in turn decreases output price, thereby increasing the overall competitiveness. The replacement decision in this case depends on various factors, such as new equipment cost, discount rate, interest rate, tax concession, and differences in efficiency, reliability, and safety of existing and new equipment. The basic idea is to compare the cost-benefits of keeping the existing equipment versus replacing it with something better. It is also important to consider the evolution of technological improvements that may become available in the future, because those improvements may have a bearing on the decision at this point in time.
- *Market obsolescence* occurs when an equipment delivers less marketable output (products and/or services) compared to what an alternative equipment available on the market may produce, resulting in reduced profitability or utility of the firm. In this case, replacement decisions are driven by competitive advantage considerations instead of primarily cost savings. For instance, when faced with market obsolescence, it could be more profitable to replace the existing equipment even before the end of its economic life to take advantage of a technological breakthrough that allows the output to be: of better quality, greater variety, or delivered faster, which in turn may create additional demand and greater profit margin.

Changed capacity needs

Changes in market conditions often lead to sustained increase or decrease in output demand. This may in some cases justify an equipment replacement project in order to guarantee the required capacity needed to satisfy demand in an economic manner.

Changed regulation

Changes in law, policy, or regulation related to emission, work place safety, waste treatment, etc. can often lead to replacement of existing equipment that cannot conform to the updated rules. For example, carbon tax and cap-and-trade are two regulatory schemes that are used to restrict industrial emissions. The carbon tax imposes a fee on the burning of carbon-based fuels and the cap-and-trade program sets emission limit for a group of corporations and allows them to trade their emission allowances among themselves.

After illustrating both the 40 identified factors and four main motivations behind capital equipment replacements, we present the resulting equipment replacement decision framework in the next sub-section. The framework serves as the basis for our semi-structured interviews and the case study analysis and ultimately is used to discuss the applicability of traditional capital equipment replacement factors and motivations for midlife upgrade decisions. Again, with the goal in mind to understand if the relatively new field of midlife upgrade can profit from the established body of knowledge on traditional equipment replacement.

Equipment replacement decision framework

We have developed our equipment replacement decision framework in Table 2 by mapping the 40 identified factors in categories based on the four main motivations for equipment replacements. The mapping was done using the context of the available literature as well as independent mapping by three experts with a follow-up discussion. Our developed framework will help us to analyze the case studies in a structured way and to investigate whether the influencing factors and motivations behind equipment replacement are also applicable and valuable to understand the motivation behind equipment upgrade decisions. Furthermore, we believe it is a valuable tool for academics and managers faced with difficult replacement or upgrade decisions to approach this in a structured way.

Case studies

In this section we provide a brief overview of the five midlife upgrade case studies followed by a detailed analysis based on our new replacement decision framework. The case studies were chosen strategically to cover different industrial sectors (defense, transportation, and power) and resemble complex engineered products with long operational lives. It is important to mention that the data collection and analysis involved both primary (semi-structured interviews) and secondary data (academic literature, white papers, websites, etc.).

Brief description of the case studies

B52 strategic bomber

The B52 is the largest strategic bomber in the US Air Force (USAF) and although already over 60 years old, it remains in active service today. The operational life of the aircraft has been extended to almost 100 years with the current plan to remove the aircraft from active service in 2050. Since its introduction, there has been a continued programme of upgrades to the aircraft to maintain its operational readiness. These have come about for two different reasons: (i) changes to mission requirements; and, (ii) availability of new technologies. The missions for the B52 have significantly changed since 1952, when it was initially designed as a high-altitude bomber. Shortly after its introduction it was forced to

Table 2
Equipment replacement decision framework.

Replacement reasons	Intrinsic motivations				Extrinsic motivations				
	Deterioration				Technological obsolescence			Changed capacity needs	Changed regulation
	Increase in costs	Decrease in output quality	Declining resale value	Decrease in safety conditions	Functional obsolescence	Economic obsolescence	Market obsolescence		
Related influencing factors that characterize the replacement reason	Age	Long term deterioration	Age	Long term deterioration	Availability of maint. personnel	Capital budget constraint	Product customizability	Product demand	Cap-and-trade
	Availability or downtime	Reliability	Depreciation	Rate of failure	Availability of spare parts	Depreciation	Product demand	Productivity	Carbon tax
	Energy cost	Scrap or rework rate	Incompatibility	Reliability	Incompatibility	Discount rate	Product price	Scrap or rework rate	Environmental issues
	Floor space cost		Long term deterioration	Scrap or rework rate		Fixed installation cost	Product quality	Throughput time	Ergonomic issues
	Insurance cost		Salvage value			Future tech. progress	Product variety	Utilization rate	Safety or health
	Labor cost		Technological progress			Holding cost or inventory cost			
	Long term deterioration					Inflation			
	O&M cost					Interest rate on invested capital			
	Productivity					Payoff period			
	Rate of failure					Purchase cost of new equipment			
	Reliability					Salvage value			
	Scrap or rework rate					Staff training cost			
	Throughput time					Tax concessions			
	Utilization rate					Technological progress			

operate at lower levels to avoid detection. And at present, it has been operational in 'cyberspace' and in counter terror warfare, which required major changes compared to the original requirements from the aircraft that date back to the cold war. New strategic bomber systems have been developed that can be considered competition for the B52, namely the B2 and Valkyrie. However, they could not fully replace the B52 in its versatility and capability (e.g., delivery of payload). B52 also extended the USAF's overall capabilities by bringing specific features such as the stealth design of the B2 to the table. The capabilities of the aircraft have been upgraded continuously, in particular the communications systems and the weapons pods. The motive behind those upgrades was to maintain compatibility in one form or another with other active weapon systems. Noncompliance with these new technological requirements would directly lead to a reduction in operational effectiveness and trigger the need to replace the equipment.

Frame 9E gas turbine

Introduced in 1978, the Frame 9E from GE is a mature heavy-duty gas turbine, which is designed for applications where high reliability, ease of operation, and fuel flexibility are needed. It competes with other power generation technologies available on the market and has been installed in industrial applications (e.g., aluminium manufacturing) as well as pure power generation. With time the user requirements have changed, and the primary interest is not limited to output and efficiency anymore. For example, increasing volume of electricity from renewable sources has led to the need for mixed generation of electricity from the turbine and other renewable sources. In order to respond to the changing user requirements, GE has introduced numerous upgrade programs (hardware and/or software) for its large fleets of 9E that resulted in enhanced plant performance (increased output and efficiency), operational flexibility, increased maintenance interval, and durability. Much of the new technologies have been originally developed for aero gas turbines or from advanced technologies used in subsequent generations of GE's industrial gas turbines.

Wartsila's slow steaming upgrade

Slow steaming upgrades for heavy cargo ships are a prime example to understand the importance of midlife upgrades, specially, given the market dynamics of global shipping logistics. Until 2008, the shipping industry was the greatest beneficiary of globalization, moving more and more cargo around the globe at an ever-increasing pace. However, the economic recession changed the situation abruptly and the boom ended almost overnight. Overall decline in the demand of goods resulted in excessive shipping capacity and steep decline in shipping rates. This overcapacity coupled with increased fuel cost, shifted the mission of cargo ships form providing a faster mode of transportation to a more economical mode of transportation. In order to tackle this crisis, slow streaming became a reliable solution for trimming down shipping capacity and fuel cost simultaneously. Slow steaming refers to the traditional method applied in cargo ships to reduce liner speed as a way to lower operating costs by reducing fuel consumption. Wartsila, a Finnish corporation, has introduced a slow steaming upgrade kit in 2008 to enable ship owners to realize major savings in fuel consumption and thus costs through slow steaming their ships.

Table 3
Case study analysis according to equipment replacement framework.

	Deterioration	Obsolescence	Changed capacity needs	Changed regulation
B-52	■ Reliability and maintainability of the electronic countermeasure system were improved by upgrading two components that had high failure rates. ■ Several minor upgrades supported the maintenance aspects of the aircraft, e.g., reduction of time required for certain maintenance activities and inspections.	■ The communication system received major upgrade called CONECT, which linked the B-52 s with the USAF's current communications networks. This upgrade included new computer servers, data links, and a digital IT architecture that will serve as the foundation for future upgrades. ■ In accordance with the technological advancements, continuous upgrades of the electronic countermeasure systems ensured state of the art defensive capabilities against a variety of enemy threats. ■ The B52's weapon systems received several midlife upgrades. For example, the weapons bay upgrade enabled the airplane to carry sensitive 'smart bombs' internally, which previously could only be carried on the wings exposed to the (harsh) environment. This resulted not only in increased weapon payload capacity but also improved fuel efficiency (due to reduced drag). ■ The USAF suspects that the diminishing sources for spare parts will make current engines unsustainable by 2030. Therefore, the USAF has finally decided to upgrade the existing TF33 engines with Rolls-Royce's BR725 or GE's CF34-10 engines. This upgrade will improve the engine reliability and fuel efficiency (as well as the overall range).	■ The Big Belly upgrade allowed the B-52 to increase its bomb capacity for carpet bombings. ■ The installation of the underwing fuel tanks further increased B-52's fuel capacity and range.	■ The need for low-level operations raised safety issue, which was addressed by adding the electro-optical viewing system (EVS). The EVS provided real-time information to avoid hazardous terrain situations. ■ B-52 has been criticized for both the noise and emissions created by its TF-33 engine, which is soon to be replaced by a newer engine. (BR725 or CF34-10)
Frame 9E	■ The Dry Low NOx (DLN) combustion system upgrade helped to significantly extend the interval between maintenance outages. It resulted in increased availability and overall lower O&M costs.	■ Newly available technologies allowed the upgrade of selected components and integration of advanced software to enhance turbine performance, operation, and durability. ■ Advanced gas path upgrades helped to increase output, efficiency, and availability while reducing fuel consumption. Gas path upgrades also improved cooling and sealing of components that resulted in increased durability. ■ Implementation of the OpFlex intelligent control system allowed the operational flexibility needed for integrating electricity from renewable sources.	■ Within the power generation sector, capacity requirements vary due to several factors. The OpFlex solution helped to economically respond to changing power demands (peak firing) by reducing start time and fuel consumption during partial load conditions. ■ Four-stage turbine module upgrades resulted in a significantly increased power output with comparably low investment required.	■ The DLN combustion system upgrades helped to meet the increasingly strict regulatory requirements by reducing CO2 and NOx emissions.
Slow steaming	■ There was no intrinsic motivation behind the slow steaming upgrade. Operating cost increased due to external factors such as fuel price and diminishing demand following the 2008 financial crises.	■ The ships were originally designed to operate at full speed between ports to provide maximum capacity on the shipping routes. However, the significant reduction in global freight transportation made those ships economically obsolete. The objective of the slow steaming upgrade was to increase ships' productivity in terms of cost per unit weight per unit distance. The modification involved replacement of the original control system, optimization of the engine for the lower speed, and changes in the hull structure to reduce drag at lower speed. ■ This upgrade allowed the marine engines to operate at as low as 10% of their maximum power without additional operating restrictions.	■ The worldwide decline in the demand of goods resulted in excessive cargo shipping capacity and thereby sharp decline in shipping rates. The slow steaming upgrade helped to reduce the excess capacity by slowing the ship's speed while reducing its operating cost significantly.	■ Even though there were no regulatory requirements to reduce emission, the slow steaming upgrade significantly reduced fuel consumption and thereby carbon emissions.

Table 3 (*Continued*)

	Deterioration	Obsolescence	Changed capacity needs	Changed regulation
		■ Without this upgrade, continuous slow streaming would not be possible due to risk of engine fouling and excessive component temperatures when operating below 50% engine load.		
SCADA interface	■ The original hardware-based SCADA system interface was getting costlier and technically difficult to maintain. It was replaced with a digital HMI, which was lot easier and less costly to maintain.	■ The changes in the market started to favor flexible operation – something the power plants were not originally designed for. As the fluctuations in electricity demand increased, the existing SCADA system was failing to respond to the drastic changes in demand. The new HMI provided additional functionality and flexibility, which made it easier for the operators to perform both peak- and base-loading operations.	■ The actual changes in the required electricity generation capacity did not play direct role in this case. However, the real-time fluctuations in electricity demand, amplified by an increasing percentage of renewables in the power mix, was an issue this midlife upgrade addressed.	■ Regulatory factors did not directly influence the midlife upgrade decision in this case. Indirectly, the regulations influence the percentage of renewables in the power mix, which in turn made the increased flexibility necessary.
Metro rail	■ Internal deterioration of the wagons had taken place leading to increased O&M costs. Additionally, health and safety conditions were also considered below 'modern' standards and reflected the shortcomings of the original design.	■ Upgrade of the metro's traction system from DC to AC increased its reliability (in terms of distance traveled between failures) almost twenty times and reduced energy consumption by over 40%. ■ Train control and monitoring system was upgraded. ■ Other systems, such as passenger information system, security system (camera), fire detection system, ground-to-train communication system, etc. were upgraded to comply modern standards.	■ The use of AC powered trains allowed for faster and smoother acceleration and thereby increasing the effective capacity. ■ Improved reliability and availability of the trains also increased the effective capacity.	■ Changes to safety regulations required that door controllers be upgraded. ■ Some of the upgrades were driven by a desire to improve the overall environmental performance of the metro system.

Supervisory control and data acquisition (SCADA) interface upgrade for power plants

The move to deregulation in both power generation and supply in the UK provided power plants with many challenges; the most significant being increased competition. The focus of power generation moved to favor increased flexibility and responsiveness, rather than base-loading, whilst also managing plant component life, integrity, and efficiency. Additionally, generation output had to accurately match commercial contracts in order to avoid expensive financial losses. SCADA systems played a key role in helping plants achieve these goals. However, most of the existing SCADA systems were nearing the end of their useful life. The power plants themselves were around 20–25 years old with a total expected operational life of 40 years. The objective was to upgrade the SCADA systems in a cost-effective manner with no additional plant down time (other than a normal outage) resulting in reliable, long-lasting systems.

Metro rail upgrade

The upgrade of 47 trains allowed the São Paulo, Brazil metro to install state-of-the-art traction technology at a significantly lower cost than the option of buying new trains could realize. The upgrade operation was performed using standardized modular kits that could be easily installed. An inverter was added to the existing rolling stock allowing the replacement of unreliable or obsolete parts while keeping parts that are in good condition. The objective was to reduce operating costs while improving the reliability (in terms of distance traveled between failures) and safety during wet conditions.

Case study analysis

In this section we present the analysis of case study data collected from semi structured interviews. In Table 3 we individually present the upgrade motivations for each of the case studies and also summarize the overall findings across all five case studies.

In Table 3 we illustrate the motivation for midlife upgrade for each case study following our novel equipment replacement framework. We can observe that the equipment replacement framework seems to adequately reflect the motivations behind equipment midlife upgrades as well. In other words, there is a large overlap of factors that influence equipment replacement and midlife upgrade decisions. Especially, the upgrades performed on B-52 and Frame 9E could justify delayed replacement based on each type of replacement motivation identified in the previous section. Furthermore, the fact that all of the equipment of the case studies investigated in this paper continued to provide value (despite the changes in technology, market condition, and user requirement) to its users and remained competitive, indicates that midlife upgrade can be a value-adding alternative to capital equipment replacement.

Traditional PLM-thinking contains a 'phased out' period when the equipment is no longer manufactured and only supported for a limited period afterwards. Apparently minor sub-systems that are deemed 'obsolete' may have expensive consequences for the longer-term support of the overall equipment or lead to (expensive and time-consuming) reengineering of specific solutions. However, most of the equipment studied in this paper exceeded their initially planned design life with the equipment remaining in operation significantly longer than originally expected (B-52, Frame 9E, and metro rail). The original design life appears to be a conservative assessment, or best guess, based on the original design and user requirements. Many of the initially installed technologies (hardware and software) had to be replaced as they did not function as per user's requirements. New technologies became available later during the lifecycle, meaning the newly available technologies could increase the operational value beyond the original design.

In most of the cases, only few components of the equipment became obsolete for a number of reasons; however, it did not generally limit the equipment from continuing to be upgraded and in effect overcoming the apparent limitations. One important observation is that not all the changes made to the equipment were an 'upgrade', rather maybe an adaptation given the changed market conditions and user requirements (i.e., modification of ships' engines for slow steaming). Some of the changes were of minor nature with an effective 'like-for-like' exchange whereas others were based on subsystem exchanges or a major system redesign. On the other hand, not all of the upgrades were implemented by the original manufacturer of the equipment. Third-party organizations also provided upgrade services leading to equipment life extensions. We also observed that users' expected value or requirements of the equipment changed or evolved over time. Which is rather logical, as the real requirements and limitations of a system become much clearer during active use facing different expected and unexpected events. For example, the B-52 was designed for one particular role yet has successfully preformed many others. It has managed to remain relevant to the USAF under a continuous technological advancement, changing political environment, and operational theatre conditions. Equipment does not generally operate in isolation and mostly has a risk of substitution when it no-longer provides its user with (perceived) value. The market obsolescence does not apply to all of the equipment studied in our case studies, yet it best describes the motivations behind changes in expected value and/or user requirement. Changes in ownership or operational strategies could also provide triggers that cause changes in expected value. When considering new equipment costs, most often the total cost of ownership (TCO) model is applied. When making a major new investment decision, this is a good approach to take. However, once an asset is operational, marginal costs (and marginal benefits) come to overrule the TCO approach. The capital cost of the operational asset can be considered a 'sunk cost'. This was clearly seen in the metro train upgrade where the owner had limited funds. Furthermore, procurement of new equipment could have incurred additional costs or risks (e.g., retraining operators and maintenance personnel).

Discussion

The results of our case study analysis indicate that midlife upgrades have the potential to keep capital equipment up-to-date with technological advancements and competitive under changing market conditions. Consequently, midlife upgrades can effectively delay replacement and thus extend the remaining useful lifetime of capital equipment. The principle effect of midlife upgrades on a product's lifecycle is illustrated in Fig. 3.

However, extending equipment's remaining useful life via midlife upgrades may diminish manufacturers' business opportunity to earn revenue from new equipment sales. Furthermore, some manufacturers may think that the provision of midlife upgrades will cannibalize the next generation of equipment, rather than providing a secondary channel for their technologies and improving customer retention. Simons [34] proposes changes to the suppliers' business models to improve the value creation associated with equipment upgrades and to address some of the cannibalization concerns. The successful and sustainable implementation of a midlife upgrade strategy will require decoupling of manufacturers' business success from the sales volume of new equipment. This can be achieved through the servitization of manufacturers' business models (i.e., PSS), where the MOL phase responsibility is transferred to the manufacturer, while the users pay for the services and value provided by the equipment [35]. PSS business models enable the manufacturers to capture value and continuously generate profits throughout the extended equipment lifecycle – hence, the interest of longer lifetime and profits align. Furthermore, there is a potential synergy between a midlife upgrade strategy and result oriented PSS business models. For example, any midlife upgrade that results in an increased output will also increase manufacturer's revenue earning potential under output-based contracts. PSS business models additionally provide opportunities to maintain a sustained competitive advantage, lock-in consumers, and systematically retrieve EOL equipment for remanufacturing and recycling [16,79]. These characteristics of PSS business models help manufacturers to formulate the business case for the provision of midlife upgrades that improve equipment performance (e.g., increased productivity, safety, environmental, or new customer value proposition) during MOL. The topic has a close link to the asset management, which is needed to ensure that the equipment operates effectively over its whole operational life where new technologies are feed into the existing equipment at the subsystem level [36]. This approach to asset management and

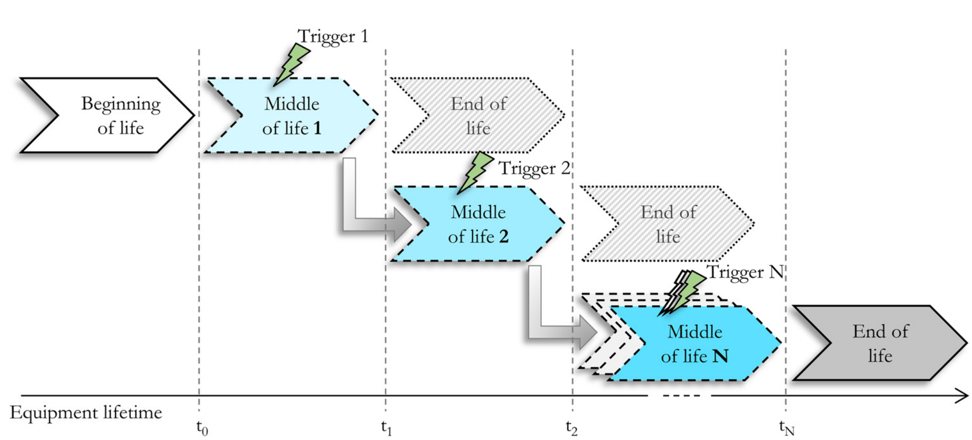

Fig. 3. Extension of equipment lifetime via midlife upgrades.

subsystem upgrades also lends itself to the implementation of the circular economy [34].

A key aspect we have to keep in mind is that no piece of equipment operates in isolation. In a narrow sense, the equipment operates synchronized with the associated services and the overall system, be it a power plant or an air squadron. This already implies the effect of interrelations and interconnectivity on the PSS. In a broader sense, when taking the competitive marketplace and political/governance aspects etc. into consideration, this is even more emphasised. Continuous changes in market conditions and user requirements demand adaptation, whether through an upgrade or replacement. For complex and often expensive systems, replacement is time-intensive (long planning horizon) and costly (both in terms of the replacement and in terms of the loss of output during the substantially longer replacement period), which are actually arguments for considering midlife upgrade as an alternative. The same stands true for rapid technological advances which significantly speeds up the cycle of when such upgrades are required and/or desired. The value stemming from a midlife upgrade is in line with the service dominant logic ([37,38]), in a sense that value originates from the user of the equipment and will change depending on the situation and the user's environment, objectives, and strategy. This confirms that the original PSS design needs to evolve over time in order to effectively maintain or improve the customer value. In general, all the cases in this study involved upgrades or modification of the subsystems, which is in line with the asset management approach [36]. With an upgrade or modification of a subsystem (product attribute) there are likely to be aspects of the service definitions that need to be adjusted.

When trying to generalize findings from our case study analysis, it becomes apparent that for complex technology-based PSS, the upgrade options and interfaces should be incorporated in the original PSS design process [39]. The ability to easily modify a system and incorporate technologies that might not even be invented yet will provide added value and additional revenue potential for the PSS stakeholders throughout the extended lifecycle. Novel approaches such as design for upgradability try to create awareness and a theoretical foundation for this changing mind-set. The fact that the lifecycles of PSS are not easily plannable adds additional complexity and thus additional challenges.

However, in most cases, challenges entail opportunity for the first movers who succeed in incorporating the new paradigm effectively and efficiently. From an asset management perspective, monitoring the portfolio is crucial to identify possible upgrade needs and/or opportunities. Viewing upgrades as opportunities is one way of delivering the value-added perspective to the customers and creating sustainable business models that replicate the new realities [40]. As a strategy, midlife upgrades give PSS providers a mechanism to market new technologies, where the accumulated margins maybe even higher than through the sale of new products [80]. Additional upgrade opportunities may stem from active management of the PSS lifecycle. The user and the PSS provider both should get value from the upgrades. The users are interested in the performance of the whole system rather than individual subsystems. The optimization of the system may provide possible upgrade opportunities at the subsystem level for the PSS providers. The performance may not be same compared to the newest product, but the expected cost-benefit should be higher compared to a total system replacement.

Understanding and facilitating the need to be able to change and/or upgrade a PSS based on the changing requirements of the user becomes a competitive advantage. Especially during the MOL, there are many factors that play a role in determining the opportunity and right time for an upgrade. Optimal upgrade timing will lock-in customers and shut-out competitors (for replacement and/or service/maintenance). Thus, creating effective entry barriers that are difficult to overcome for competitors. This can be determined by Internet of Things (IoT) based sensor networks, qualitative user feedback, and changes in the market or political environment. Gathering data from such a broad set of sources and subsequently extracting insights and knowledge from it will become a key factor of success for the manufactures of a complex PSS.

Given the general complexity of the PSS that are discussed here, additional tools and methods to manage this complexity is required. For example, the product avatar model [8], or the digital twin, provides the possibility to monitor, analyse, and interact with the equipment and the individual subsystems more directly and efficiently, and thus build a basis to innovate new solutions over the whole operational life of the asset. The equipment should be considered as a modular engineered system where new capabilities can be added later to provide the users with new opportunities. The new capabilities can be delivered as new physical technologies or as digital technologies. In B2B cases it is possible to build a lock-out strategy based on technology upgrades helping the PSS providers to remain ahead of competition. In the longer-term this may mean that new PSS development moves to the production of more modular designs that more closely align with customer value and reduce the impact of early retirement brought on by obsolescence. 'Trickle down' of new technologies into older products could then provide an additional route for technology exploitation. Other than providing a secondary market for newly developed technologies, midlife upgrades provide an opportunity to extend the user-provider relationships beyond a static PSS approach. To be successful, PSS providers need to understand the complex environment in which the equipment operates, how to increase the value stemming from the PSS, as well as how it can remain competitive compared to new market entrants. The use of the 'value in use' concept ([37,38]) may assist PSS providers with targeting these objectives.

When critically reflecting on the limitations of the presented research, selecting only case studies that successfully conducted midlife upgrades may present a certain bias. Including additional case studies of both successful and un-successful equipment replacement projects, as well as unsuccessful midlife upgrade projects might add additional insights on this complex topic. However, we believe that given the objective of this research, the chosen case studies support our conclusion that the main factors and motivations behind traditional equipment replacement and midlife upgrades are indeed shared. Another limitation of this work is that there are very few cases available where midlife upgrades were already planned during the design (BOL) phase and thus the full, theoretical potential of midlife upgrades can only be theorized at this point.

Conclusion

The objective of our research was to (i) contribute empirical evidence in form of case studies of successful midlife upgrades to the literature, and (ii) assess whether we can tap into the established literature on traditional equipment replacement to advance the emerging field of midlife upgrades and upgradability. By presenting and analyzing five different case studies we expand the available empirical evidence of successful midlife upgrades. We use these case studies to evaluate our newly developed framework and confirm that our collected and categorized factors and motivations behind traditional equipment replacement are valid for midlife upgrade decisions.

Overall, our findings suggest that midlife upgrades have the potential to effectively postpone replacement while extending remaining useful lifetime of capital equipment and thereby facilitate the implementation of the circular economy. Our findings also indicate that midlife upgrades indeed present a value-adding alternative to traditional equipment replacement from the perspectives of both users and manufacturers, especially when provisioned with a servitized PSS business model. A focus on the MOL phase allows PSS providers to create additional customer value and increase competitiveness. Successfully locking-out competition through value-adding midlife upgrades can provide potential benefits beyond directly measurable financial metrics/KPIs. The extended MOL period is increased beyond what was originally envisioned, and the user requirements may change substantially within that timeframe. In general, potential changes in technological advancement, political climate, or user preference are unknown and mostly unforeseen during the BOL periods, confirming the benefits of a more modular design that provides a higher degree of flexibility at the MOL stage. This can take different forms, e.g., embracing modular design and design for upgradability. This might involve higher initial cost for manufacturing and design, however, when taking the TCO (from the provider's view) into consideration, it will ultimately help to achieve the adaptability required and demanded by the users of complex technological products more economically. Based on this approach it is possible to then create new MOL strategies that provide continuous added-value to both PSS users and providers. In order for the PSS to remain valuable for the user, midlife upgrades must be designed and delivered that offer measurable (added) value. The value must be measurable within the user's own context and is therefore in line with the 'value in use' model from a service dominant logic perspective. The PSS provider may gain additional value as well through effects like, e.g., locking out competition by continuously upgrading the product, or receiving a share of the savings from efficiency gains.

In future, more research is needed to understand the principles of value creation during the MOL phase of PSS in order to better create value for both PSS users and providers. Future research should also explore how new business models (e.g., use/outcome-based contracts, or cradle-to-cradle models) can support the adoption of a midlife upgrade strategy. Another important challenge for future researchers is to incorporate the 'uncertainty of change required' in the design and manufacturing of complex technological products and capital equipment.

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References

[1] Vandermerwe, S., Rada, J., 1988, Servitization of Business: Adding Value by Adding Services. European Management Journal, 6/4: 314–324.
[2] Neely, A., 2009, Exploring the Financial Consequences of the Servitization of Manufacturing. Operations Management Research, 1/2: 103–118. http://dx.doi.org/10.1007/s12063-009-0015-5.
[3] Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Alcock, J.R., 2007, State-of-the-Art in Product-Service Systems. Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture, 221/10: 1543–1552.
[4] Porter, M.E., Heppelmann, J.E., 2014, How Smart, Connected Products are Transforming Competition. Harvard Business Review, 92/11: 64–88.
[5] Ren, G., Gregory, M., 2007, Servitization in Manufacturing Companies. Paper Presented at 16th Frontiers in Service Conference (San Francisco, CA), .
[6] Baines, T.S., Lightfoot, H.W., Benedettini, O., Kay, J.M., 2009, The Servitization of Manufacturing: A Review of Literature and Reflection on Future Challenges. Journal of Manufacturing Technology Management, 20/5: 547–567. http://dx.doi.org/10.1108/17410380910960984.
[7] Goedkoop, M., 1999, Product service systems. Ecological and economic basis..
[8] Wuest, T., Hribernik, K., Thoben, K.-D., 2015, Accessing Servitisation Potential of PLM Data by Applying the Product Avatar Concept. Production Planning & Control, 26/14–15: 1198–1218.
[9] El Kadiri, S., Grabot, B., Thoben, K.-D., Hribernik, K., Emmanouilidis, C., von Cieminski, G., Kiritsis, D., 2015, Current Trends on ICT Technologies for Enterprise Information Systems. Computers in Industry, 79:14–33.
[10] Levitt, T., 1965, Exploit the Product Lifecycle. Harvard Business Review, 43/6: 81–94.
[11] Tibben-Lembke, R.S., 2002, Life After Death: Reverse Logistics and the Product Life Cycle. International Journal of Physical Distribution & Logistics Management, 32/3: 223–244. http://dx.doi.org/10.1108/09600030210426548.
[12] Wuest, T., Nana, U.M.N., 2016, State-Based Representation of a Product's Middle of Life. International Journal of Product Lifecycle Management, 9/2: 108–138.
[13] Wellsandt, S., Nabati, E., Wuest, T., Hribernik, K., Thoben, K.-D., 2016, A Survey of Product Lifecycle Models: Towards Complex Products and Service Offers. International Journal of Product Lifecycle Management, 9/4: 353–390.
[14] Aurich, J.C., Fuchs, C., 2004, An Approach to Life Cycle Oriented Technical Service Design. CIRP Annals — Manufacturing Technology, 53/1: 151–154.
[15] Qu, M., Yu, S., Chen, D., Chu, J., Tian, B., 2016, State-of-the-Art of Design, Evaluation, and Operation Methodologies in Product Service Systems. Computers in Industry, 77/127: 1–14.
[16] Khan, M.A., Mittal, S., West, S., Wuest, T., 2018, Review on Upgradability—A Product Lifetime Extension Strategy in the Context of Product Service Systems. Journal of Cleaner Production, 204:1154–1168.
[17] Copani, G., Behnam, S., 2018, Remanufacturing with Upgrade PSS for New Sustainable Business Models. CIRP Journal of Manufacturing Science and Technology, . http://dx.doi.org/10.1016/j.cirpj.2018.10.005.
[18] Pialot, O., Millet, D., Bisiaux, J., 2017, "Upgradable PSS": Clarifying a New Concept of Sustainable Consumption/Production Based on Upgradablility. Journal of Cleaner Production, 141:538–550.
[19] West, S., Wuest, I.T., 2017, A Strategy for Midlife Upgrades to Provide Value for Both the Equipment Operator and the Supplier. Spring Servitization Conference (SSC 2017) (15–17 May, Luzerne, Switzerland), .
[20] Walsh, B. (2012, October). PSS for Product Life Extension Through Remanufacturing. Proceedings of the 2nd CIRP IPS2 Conference 2010; 14–15 April; Linköping; Sweden (No. 077, pp. 261–266). Linköping University Electronic Press.
[21] Van der Lei, T., 2012, Towards a Research Agenda for Strategic Engineering Asset Management. in Van der Lei TT., Herder PP., Wijnia YY., (Eds.) Asset Management. Springer, Dordrecht, pp. pp.169–172.
[22] Mathew, S., Kennedy, D., 2003, A Strategy for Optimal Equipment Replacement. Production Planning & Control, 14/6: 571–577.
[23] U.S. Census Bureau (2018, February 09). Annual Capital Expenditures: 2016. Retrieved from https://www.census.gov/library/publications/2018/econ/2016-aces-summary.html.
[24] Rajagopalan, S., 1998, Capacity Expansion and Equipment Replacement: A Unified Approach. Operations Research, 46/6: 846–857.
[25] Hartman, J., 2005, A Note on 'A Strategy for Optimal Equipment Replacement'. Production Planning & Control, 16/7: 733–739.
[26] des-Bordes, E., Büyüktahtakın, İ.E., 2017, Optimizing Capital Investments Under Technological Change and Deterioration: A Case Study on MRI Machine Replacement. The Engineering Economist, 62/2: 105–131.
[27] Büyüktahtakın, İ.E., Hartman, J.C., 2016, A Mixed-Integer Programming Approach to the Parallel Replacement Problem Under Technological Change. International Journal of Production Research, 54/3: 680–695.
[28] Yatsenko, Y., Hritonenko, N., 2009, Technological Breakthroughs and Asset Replacement. The Engineering Economist, 54/2: 81–100.
[29] Wang, K.J., Nguyen, P.H., 2017, Capacity Planning With Technology Replacement by Stochastic Dynamic Programming. European Journal of Operational Research, 260/2: 739–750.
[30] Porter, M.E., 1985, Technology and Competitive Advantage. Journal of Business Strategy, 5/3: 60–78.
[31] Frohman, A.L., 1982, Technology as a Competitive Weapon. Harvard Business Review, 60/1.
[32] Karlsson, C., 2009, Researching Operations Management. 1st ed. Routledge, New York, NY.
[33] Yin, R.K., 2009, Case Study Research: Design and Methods (Applied Social Research Methods).Sage, London and Singapore.
[34] Simons, M., 2017, Comparing Industrial Cluster Case to Define Upgrade Business Model for a Circular Economy. in Grösser SS., Reyes-Lecuona AA., Granholm GG., (Eds.) Dynamics of Long-Life Assets: From Technology Adaption to Upgrading the Business Model. Springer Nature, Cham, Switzerland , pp. pp.327–356.
[35] Manzini, E., Vezzoli, C., 2002, Product-Service Systems and Sustainability: Opportunities for Sustainable Solutions. UNEP-United Nations Environment Programme.
[36] Herder, P., Wijnia, Y., 2012, A Systems View on Infrastructure Asset Management. in Van der Lei TT., Herder PP., Wijnia YY., (Eds.) Asset Management. Springer, Dordrecht, pp. pp.31–46.
[37] Vargo, S.L., Lusch, R.F., 2004, Evolving to a New Dominant Logic for Marketing. Journal of Marketing, 68/1: 1–17.
[38] Vargo, S.L., Lusch, R.F., 2008, Service-Dominant Logic: Continuing the Evolution. Journal of the Academy of Marketing Science, 36/1: 1–10.
[39] Khan, M.A., Wuest, T., 2018, Towards a Framework to Design Upgradable Product Service Systems. Procedia CIRP, 78:400–405.
[40] Khan, M.A., Wuest, T., 2019, Upgradable Product-Service Systems: Implications for Business Model Components. Procedia CIRP, 80:768–773.
[41] Abdi, A., Taghipour, S., 2018, An Optimization Model for Fleet Management With Economic and Environmental Considerations, Under a Cap-and-Trade Market. Journal of Cleaner Production, 204:130–143.

[42] Adkins, R., Paxson, D., 2014, Stochastic Equipment Capital Budgeting With Technological Progress. European Financial Management, 20/5: 1031–1049.
[43] Al-Chalabi, H., Lundberg, J., Ahmadi, A., Jonsson, A., 2015, Case Study: Model for Economic Lifetime of Drilling Machines in the Swedish Mining Industry. The Engineering Economist, 60/2: 138–154.
[44] Apeland, S., Scarf, P.A., 2003, A Fully Subjective Approach to Capital Equipment Replacement. Journal of the Operational Research Society, 54/4: 371–378.
[45] Aylen, J., 2013, Stretch: How Innovation Continues Once Investment is Made. R&D Management, 43/3: 271–287.
[46] Bollinger, B., 2015, Green Technology Adoption: An Empirical Study of the Southern California Garment Cleaning Industry. Quantitative Marketing and Economics, 13/4: 319–358.
[47] Chang, P.T., 2005, Fuzzy Strategic Replacement Analysis. European Journal of Operational Research, 160/2: 532–559.
[48] Chen, M., Cheng, C.Y., 2007, Sensitivity Analysis for the Optimal Minimal Repair/Replacement Policies Under the Framework of Markov Decision Process. 2007 IEEE International Conference on Industrial Engineering and Engineering Management (December), pp.640–644. IEEE.
[49] Clavareau, J., Labeau, P.E., 2009, Maintenance and Replacement Policies Under Technological Obsolescence. Reliability Engineering & System Safety, 94/2: 370–381.
[50] Dima, I.C., Man, M., 2015, Models Used in the Management of Replacing Fixed Assets. Modelling and Simulation in Management, Springer, Cham: 355–375.
[51] Hartman, J.C., 2004, Multiple Asset Replacement Analysis Under Variable Utilization and Stochastic Demand. European Journal of Operational Research, 159/1: 145–165.
[52] Hastings, N.A., 2010, Physical Asset Management, vol. 2. Springer, London.
[53] Hritonenko, N., Yatsenko, Y., 2008, The Dynamics of Asset Lifetime Under Technological Change. Operations Research Letters, 36/5: 565–568.
[54] Hritonenko, N., Yatsenko, Y., 2012, Technological Modernization Under Resource Scarcity. Optimal Control Applications and Methods, 33/3: 249–262.
[55] Jain, M. (n.d.). Replacement of Equipment's: Reasons, Factors and Problems. Retrieved from http://www.yourarticlelibrary.com/industries/replacement-of-equipments-reasons-factors-and-problems/90640.
[56] Jin, D., Kite-Powell, H.L., 2000, Optimal Fleet Utilization and Replacement. Transportation Research Part E: Logistics and Transportation Review, 36/1: 3–20.
[57] Keating, E.G., Blickstein, I., Boito, M., Chandler, J., Peetz, D., 2014, Investigating the Desirability of Navy Aircraft Service Life Extension Programs. Defence and Peace Economics, 25/3: 271–280.
[58] Koowattanatianchai, N., Charles, M.B., 2015, An Extended Asset Replacement Model: Impacts of Taxation, Inflation and Technological Advancement on Optimal Asset Duration. INFOR: Information Systems and Operational Research, 53/4: 178–193.
[59] Mardin, F., Arai, T., 2012, Capital Equipment Replacement Under Technological Change. The Engineering Economist, 57/2: 119–129.
[60] Mellal, M.A., Adjerid, S., Benazzouz, D., Berrazouane, S., Williams, E.J., 2013, Optimal Policy for the Replacement of Industrial Systems Subject to Technological Obsolescence Using Genetic Algorithm. Acta Polytechnica Hungarica, 10/1: 197–208.
[61] Mercier, S., 2008, Optimal Replacement Policy for Obsolete Components With General Failure Rates. Applied Stochastic Models in Business and Industry, 24/3: 221–235.
[62] Mercier, S., Labeau, P.E., 2004, Optimal Replacement Policy for a Series System with Obsolescence. Applied Stochastic Models in Business and Industry, 20/1: 73–91.
[63] Meyer, B.C., 1993, Market Obsolescence and Strategic Replacement Models. The Engineering Economist, 38/3: 209–221.
[64] Michel, O., Labeau, P.E., Mercier, S., 2004, Monte Carlo Optimization of the Replacement Strategy of Components Subject to Technological Obsolescence. Probabilistic Safety Assessment and Management, Springer, London: 3098–3103.
[65] Micromain (2016, December 8). Asset Repair or Replace? Important Factors to Consider in Your Decision Making Process. Retrieved from https://www.micromain.com/asset-repair-or-replace/.
[66] Nair, S.K., Hopp, W.J., 1992, A Model for Equipment Replacement Due to Technological Obsolescence. European Journal of Operational Research, 63/2: 207–221.
[67] Rogers, J.L., Hartman, J.C., 2005, Equipment Replacement Under Continuous and Discontinuous Technological Change. IMA Journal of Management Mathematics, 16/1: 23–36.
[68] Sandborn, P.A., Herald, T.E., Houston, J., Singh, P., 2003, Optimum Technology Insertion into Systems Based on the Assessment of Viability. IEEE Transactions on Components and Packaging Technologies, 26/4: 734–738.
[69] Scarf, P.A., Hartman, J.C., 2008, Replacement of Capital Equipment. Complex System Maintenance Handbook, Springer, London: 287–319.
[70] Sindhuja, S. (n.d.). Replacement of Equipment's: Introduction, Reason and Factors. Retrieved from http://www.businessmanagementideas.com/industries/equipments/replacement-of-equipments-introduction-reason-and-factors/9876.
[71] Stutzman, S., Weiland, B., Preckel, P., Wetzstein, M., 2017, Optimal Replacement Policies for an Uncertain Rejuvenated Asset. International Journal of Production Economics, 185:21–33.
[72] Sulaiman, M.J., Visser, J.K., 2015, An Investigation into Technology Advancement for Switchgear at a Processing Plant. 9th WCEAM Research Papers, Springer, Cham: 307–319.
[73] Wellsandt, S., Hribernik, K., Thoben, K.-D., 2015, Sources and Characteristics of Information About Product Use. Procedia CIRP, 36:242–247.
[74] Yatsenko, Y., Hritonenko, N., 2010, Discrete–Continuous Analysis of Optimal Equipment Replacement. International Transactions in Operational Research, 17/5: 577–593.
[75] Yatsenko, Y., Hritonenko, N., 2015, Algorithms for Asset Replacement Under Limited Technological Forecast. International Journal of Production Economics, 160:26–33.
[76] Yatsenko, Y., Hritonenko, N., 2016, Asset Replacement Under Improving Operating and Capital Costs: A Practical Approach. International Journal of Production Research, 54/10: 2922–2933.
[77] Yatsenko, Y., Hritonenko, N., 2017, Machine Replacement Under Evolving Deterministic and Stochastic Costs. International Journal of Production Economics, 193:491–501.
[78] Zhang, Z.G., Liu, C.H., Zhao, Y.H., 2013, Investment Decision-Making Model and Application of Mining Equipment. Applied Mechanics and Materials, vol. 271. Trans Tech Publications. p. 1776–1779.
[79] Khan, M.A., Kalverkamp, M., Wuest, T., 2018, Cascade utilization during the end-of-life of product service systems: synergies and challenges. Cascade Use in Technologies, Springer Vieweg, Berlin, Heidelberg: 1–7.
[80] Mercer. 2003, Service in Mechanical Engineering – Unused Opportunities in the Service Business.Mercer Management Consulting, München.
[81] Hartman, J.C., Tan, C.H., 2014, Equipment replacement analysis: a literature review and directions for future research. The Engineering Economist, 59/2: 36–153.