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Exploring the role of digital servitization for sustainability: A framework for environmental and social impact

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A R T I C L E I N F O

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A B S T R A C T

In the manufacturing context, servitization emerges as a relevant path to improve sustainability. Notably, it can be applied to reconfigure industries' business models into circular ones, through multiple sustainable and circular strategies. Digital servitization, particularly, can enhance companies' sustainability along the products' lifecycle, optimizing design and operations through collected data and supporting decision-making for end-of-life activities.

Digitalization, servitization, and sustainability present promising synergies, nonetheless this topic requires more research. It is possible to observe a lack of understanding of the intersection of servitization, digitalization, and sustainability, and how they can be applied in the manufacturing context.

This paper aims to investigate the connection between digital technologies, services, and sustainable strategies. The objective is to identify and characterize the linkages between digital technologies, services, and environmental and social sustainable strategies in the context of servitization. Through the implementation of a systematic literature review, the paper proposes an analysis of the state-of-the-art, identifying main trends and investigating specific relevant digital technologies, services, and sustainable impacts. The authors then propose a framework which clarifies how services, enabled by specific digital technologies, can be leveraged in the context of manufacturing product service systems to implement social and environmental sustainability strategies. Finally, the paper highlights opportunities for future research based on existing identified gaps.

1. Introduction

Achieving sustainable development is a goal shared at a global level, as shown by Agenda (2030), which, through 17 goals, pursues sustainable development across three pillars: economic, social, and environmental (United Nations, 2015).

In the manufacturing context, the trend of servitization and the adoption of product service systems (PSS) emerge as promising approaches to improve sustainability. Servitization is the process of adding value to the corporate offering, the physical product, through services, adopting a customer-focused perspective (Vandermerwe and Rada, 1988). In the manufacturing context, a growing number of companies are choosing to couple the traditional physical offering with services (Mastrogiacomo et al., 2019). PSSs are defined as business models focused on the provision of a set of products and services, designed to be economically, environmentally, and socially sustainable, to fulfill customers' needs (Annarelli et al., 2016).

Servitization is recognized as a strategy to achieve not only economic sustainability, by increasing profit and competitiveness, but also social sustainability, offering opportunities to high-wage countries to protect employee positions and create new jobs, and environmental sustainability (Meier et al., 2010). PSSs involve activities, such as the reuse and recycling of products, maintenance services, leasing, sharing, and renting, which can positively impact environmental sustainability (Annarelli et al., 2016). Notably, servitization and circular economy (CE) are particularly coherent with PSSs, as they leverage similar principles. Servitization can reconfigure companies' business models to enable circular ones (M. Kim et al., 2023), offering multiple paths to achieve circularity (Kjaer et al., 2019). Nonetheless, not all servitized business models are environmentally superior (Ulaga and Kowalkowski, 2022) and they should be accordingly designed and implemented. By definition, PSS is not a circular business model, but it aims to achieve similar goals to those of circular business models (Antikainen et al., 2018).

Servitization has also been increasingly studied and applied in

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conjunction with digitalization, in a trend called digital servitization (Paschou et al., 2020). Digitalization and servitization have a potential mutual reinforcement: digitalization enables servitization for manufacturers and servitization offers opportunities for the creation and monetization of digital-based offerings (Pirola et al., 2020).

Wu & Pi (2023) suggest that digital technologies capabilities and PSSs are required to facilitate the development of CE business models. Digital servitization can provide companies with opportunities to improve their environmental performances (Ulaga and Kowalkowski, 2022). It can enhance sustainability along the whole lifecycle: leveraging collected data to optimize the design, improve resource usage, optimize operations, and support decision-making for end-of-life (EoL) activities (S. A. Wiesner et al., 2023).

Thus, the intersection between digitalization, servitization, and sustainability presents promising synergies and the relevance of digital sustainable servitization is recognized by the literature. While the economic and financial sustainability of PSSs has been thoroughly analyzed (e.g. (Benedettini, 2024; Kohtamäki et al., 2020; Korkeamäki et al., 2021)), more investigation on the intersection between digitalization, servitization, and environmental and social sustainability – from now on referred as sustainability-is required.

According to Antikainen et al. (2018), there is still a gap related to the investigation of opportunities in the integration of PSS, digitalization, and circular economy. Indeed, as studied by Zhang et al. (2022), the research on digital PSS and sustainable PSS is in the exploratory stage and it is still immature. There is a lack of understanding of the intersection of servitization, digitalization, and sustainability, and how they can be applied in the manufacturing context (Hallstedt et al., 2020). More research is needed on the sustainability impact of digital PSS and the role of sustainability in specific business models (Kohtamäki et al., 2019). Additionally, Atif et al. (2021) ask for the investigation of the role and impact of specific digital technologies concerning servitized business models and specific CE practices. Finally, Q. Zhou et al. (2024) argue that digital servitization is not always sustainable, and ask for future research to explore sustainable servitization in the digital era, to investigate the role and impact of digital technologies for sustainable servitization, and to understand the sustainable opportunities of digital servitization.

Answering these calls, the paper aims to investigate the connection between digital technologies, services, and sustainable strategies. The objective is to assess and analyze the current state-of-the-art on sustainable and digital servitization in the manufacturing context. Based on that, it aims to identify the enabling technologies, the most common services, and the most relevant environmental and social sustainable strategies achievable through digital PSS, and the linkages among them.

In particular, the research questions guiding this work are RQ1: "Which is the state of the art in the context of digital sustainable servitization in manufacturing?" and RQ2: "Which are, in the context of servitization in manufacturing, the linkages between the most relevant digital technologies, services, and environmental and social sustainability strategies?"

This work implements a systematic literature review (SLR) analyzing all relevant papers on the intersection between PSS, digital technologies, and sustainability. It proposes an analysis of the state-of-the-art elucidating current gaps and future research opportunities. Then, a framework illustrating the linkages between digital technologies, services, and sustainable strategies is proposed based on the evidence from the literature.

In section 3 the methodology applied is explicated, in section 4 the results of the analysis and the current state-of-the-art are proposed, section 5 presents the proposed framework and future opportunities for research, finally, section 6 summarizes the findings of the paper.

2. Theoretical background

2.1. Servitization, PSS, and digital servitization

Servitization is the transformational process in which a company shifts from product-centric to service-centric business models; nonetheless, the transformation can take place in a continuum, in which companies' service orientation increases as service elements are more central to the offering (Kowalkowski et al., 2017). The transition involves a transformation of the business model, encompassing, to varying degrees, elements such as value proposition, revenue structure, resources, and customer and network relations (Adrodegari and Saccani, 2017).

Servitization has been increasingly adopted in manufacturing (Mastrogiacomo et al., 2019), where companies appear to focus more on warranty, maintenance, consultation, and technical support, while the relevance of advanced services is not yet recognized (Kozłowska, 2020), even though the more ambitious service strategies are those that could provide the greatest benefits (Mathieu, 2001).

Companies have moved towards servitization strategies to gain defensive and offensive benefits, affecting both providers and customers. The former consists of the improvement in business efficiencies, including cost savings and financial predictability; while the latter includes the improvement in business competitiveness (Baines and Shi, 2015).

Even though the terms servitization and PSS are often used interchangeably in the literature (Q. Zhou et al., 2024; Atif, 2023a); servitization describes the transition process above explicated, while PSSs are integrated offerings of products and services, which Annarelli et al. (2016) defined as *"a business model focused towards the provision of a marketable set of products and services, designed to be economically, socially and environmentally sustainable, with the final aim of fulfilling customers' needs"*. PSS offerings can be categorized into three main clusters: product-oriented, in which the offering centers products to which supporting services are added; use-oriented, in which the provider sells the usage of the product while retaining its ownership and result-oriented, in which the providers and clients agree on a result to be delivered (Tukker, 2004).

Notably, PSSs are increasingly adopted and implemented by leveraging digital technologies as they are significant enablers of servitization (Minaya et al., 2024). Digitalization and servitization present potential mutual reinforcements: digitalization enables manufacturers' servitization while servitization concurrently enables the development and monetization of digital-based offerings (Pirola et al., 2020).

The convergence of servitization and digital technologies is a recent and fast-growing research topic in literature (Brissaud et al., 2022; Paschou et al., 2020), and has been studied under the name of digital servitization (Bortoluzzi et al., 2022).

Digital servitization can be defined as the transition from pure product to smart PSS (Kohtamäki et al., 2020), and it implies the development or enhancement of services through digital technologies (Paschou et al., 2020).

Moreover, digital servitization enables new business model opportunities and value creation for providers and customers (Minaya et al., 2024). In particular, digital technologies such as the Internet of Things (IoT) enable the collection of data to be leveraged in digital PSSs (Ardolino et al., 2018) and allow companies to differentiate the offering and improve quality and customer involvement (Sassanelli and Pacheco, 2024). Digital servitization can be applied to improve personalization and to enable continuous improvement of the offering (Bortoluzzi et al., 2022; Chen et al., 2021; Favoretto et al., 2022; Matsas et al., 2017) as well as improving operative efficiency, by allowing monitoring and optimization activities to minimize downtimes and reducing operational costs (Raddats et al., 2022). It enhances the relationship between providers and users through increased collaboration and transparency (Chen et al., 2021; Ciasullo et al., 2021; Le-Dain et al., 2023).

2.2. Digital servitization and sustainability

Servitization is considered a relevant strategy to achieve social and environmental sustainability (J. Zhang et al., 2021; Q. Zhou et al., 2024). PSSs can be applied to enhance sustainability through improved resource utilization, by increasing the lifetime of products and services, intensifying usage and incentivizing better resource utilization and EoL management, and through increased innovation generating sustainability effects (Reim et al., 2015).

In particular, servitization can be linked to CE strategies, Kjaer et al. (2018) investigate how PSS can be applied to reduce the utilization of resources coherently with CE principles. The providers can support and improve user operations through services such as monitoring, training, maintenance, repair, and upgrades. Take-back/EoL management strategies can be applied to increase the reuse, remanufacturing, and recycling of PSSs. New business models, such as sharing configurations and functional results can decrease resource production and consumption and dematerialize offerings.

Nonetheless, PSSs are not sustainable by default and different PSS configurations could achieve different sustainability implications (Tukker, 2004). Several assessments of PSSs' impact (such as (Martin et al., 2021; W. Zhang et al., 2018)) show that the environmental impact of PSSs is highly influenced by their configurations, and it could increase compared to the traditional alternatives. Thus, PSSs should be developed and adopted accordingly (Michelini et al., 2017; Tukker, 2015), for example, by including environmental considerations in pricing strategies (Saccani et al., 2024). Additionally, while non-digital servitization appears to have a limited positive impact on environmental and other non-financial performances; digital servitization is a strong contributor (Vaillant and Lafuente, 2024).

Therefore, as manufacturers are increasingly leveraging digital technologies in the delivery of their integrated service offerings (Raddats et al., 2022) and digitalization shows cross-fertilization opportunities with sustainability (Lichtenthaler, 2021), digital servitization can be leveraged by companies to achieve business advantage while contributing to a more sustainable society (Hallstedt et al., 2020).

Digital servitization offers multiple opportunities to improve the sustainability of PSSs, enabling and incentivizing resource-efficient operations (Grahn, 2022; Paschou et al., 2020). Digital servitization can reduce resource usage and enable circular systems, while also fostering the development of green smart products and circular manufacturing (Schiavone et al., 2022).

Digital servitization allows data collection along the lifecycle of products to improve product design, reduce resource consumption during usage, improve decision-making, and enable EoL management (Alcayaga et al., 2019; Bressanelli et al., 2024; Paiola et al., 2021). It can enable the extension of product lifespan, achieving improved resource efficiency and closed-loop, coherently with circular economy principles (Zheng et al., 2019a).

3. Methodology

To address the research objective, thus identifying the role of digital technologies, services, and sustainable strategies in the context of servitization in manufacturing companies, this paper applies a SLR coherent with Snyder (2019). Through this review process, the authors identified and analyzed how digital technologies are implemented to deploy PSSs to achieve improved environmental and social impact. While analyzing the papers, the digital technologies, services, and sustainable practices have been clustered to facilitate the analysis of the state-of-the-art.

The collection of papers ended on the December 23, 2024 and has been implemented by querying Scopus and Web of Science databases as described below.

3.1. Keywords' selection

The keywords used to query the scientific databases have been selected to investigate the intersection of the three thematic clusters: digitalization, servitization, and sustainability (additionally considering the circular perspective).

Sustainability, circularity, and green have been selected to cover the theme of environmental and social sustainability. Particularly, the concept of circular economy is coherent with PSSs, and "green" is often associated with environmental sustainability, thus they have been selected to identify relevant publications.

The keywords related to PSS have been selected to include the most common and encompassing declinations of the concepts of servitization and PSS. Additionally, the keywords have been adapted from previous SLRs such as H. Li et al. (2024), to capture publications related to servitization in manufacturing. The keywords related to digitalization have been selected to encompass the more general definition of the trend, without focusing on specific technologies. Notably, Industry 4.0 and Industry 5.0 keywords have been selected to include publications related to the industrial field. Keywords related to manufacturing have not been selected to avoid excluding relevant publications, which may not explicitly mention the concept, but could be relevant to meet the research objective.

The final query used is: *(sustainab* OR circular* OR green*) AND (pss OR "product service" OR "product service system" OR serviti*ation OR "product-service") AND (digital* OR smart OR digiti*ation OR "Industry 4.0" OR "I4.0" OR "Industry 5.0" OR "I5.0")*

3.2. Eligibility criteria

The research has been conducted by collecting the documents available through Scopus and Web of Science, selecting only those available in English. The authors eliminated duplicated papers and then proceeded with a first screening based on the title and abstract, Fig. 1. The final screening was conducted by analyzing the documents' full texts. The exclusion criteria that guided the selection can be summarized as follows.

- The document does not study the topic of servitization, digitalization, and environmental/social sustainability. Many papers only mention one of these themes or analyze them separately, not investigating their intersection. Only papers focusing specifically on the intersection of the three themes have been included.
- The document is not focused on manufacturing and cannot be applied to manufacturing.

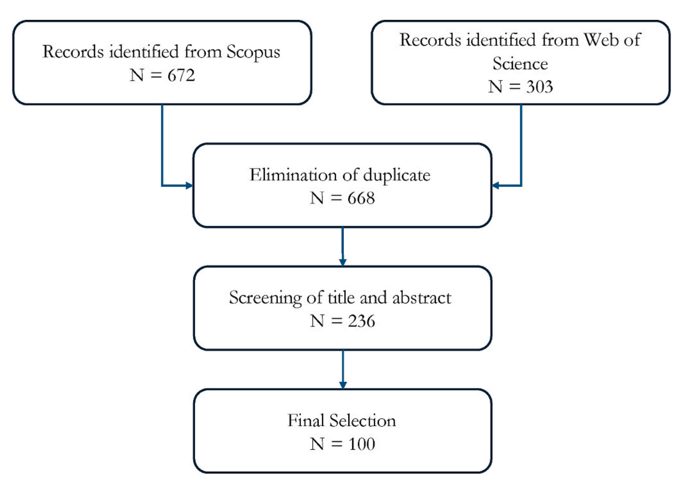

Fig. 1. Selection process.

- The document does not focus on sustainability from a social and/or environmental perspective, as stated above, economic sustainability has not been investigated in this contribution.

4. Literature review results

4.1. Quantitative analysis

The final pool of papers has been analyzed according to multiple quantitative dimensions.

It is possible to observe in Fig. 2 that the theme of digital sustainable servitization is quite recent, with the first publication in 2016, a conference paper. The topic has gained growing attention; notably, in 2023, 23 papers have been published.

The publications are quite scattered, in Fig. 3 Journal (light blue) and Conferences (dark blue) sources with at least 3 publications are shown. It is possible to observe that *Journal of Cleaner Production* and *Sustainability* are the most common sources of literature on the theme, with 25% of publications.

VOSViewer has been applied to map the geographical distribution of the publications, as shown in Table 1, by isolating the countries with more than 5 publications. Germany, China, Sweden, and Italy have a primary role in the field of digital sustainable servitization with a higher number of publications. By analyzing the number of citations, Italy, Finland, and China are the most mentioned. Coherently, the most cited authors, with more than 3 contributions, are from Italy, Sweden, China, and Singapore, particularly from the University of Brescia (Italy), University of Vaasa (Sweden), Northwestern Polytechnical University (China) and Nanyang Technological University (Singapore).

From a methodological perspective, 31% of the contributions are heavily theory-based (SLR, literature reviews, bibliometric analysis, framework development with no implementations); 16% of the contributions apply surveys and database investigations as the main methodology or as the final validation of proposed artifacts, 53% of the contributions involve the industrial perspective, through case-study, interviews, workshops, presentation of industrial projects or use case applications of developed artifacts.

Finally, the documents have been analyzed considering the investigated market dimension, business-to-business (B2B) or business-to-customer (B2C). Literature prevalently does not focus on a specific market and the findings can mostly be applied both to B2B and B2C markets. Nonetheless, the selected documents often present use cases or involve the contribution of experts in specific industrial markets, 54% have no explicit or specific focus, while 35% of publications present B2B case studies and application cases or focus on the B2B dimension, and 11% of publications involve the B2C market.

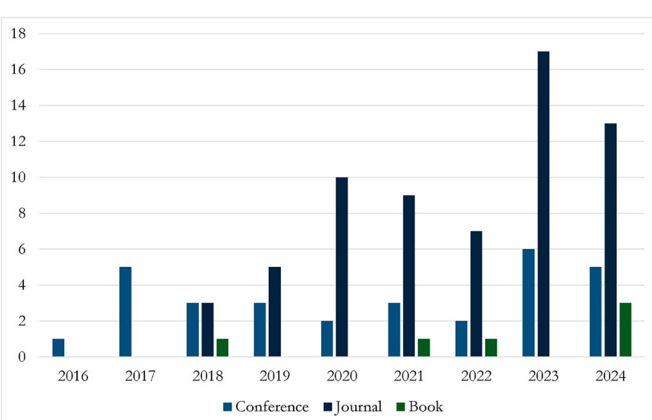

Fig. 2. Publishing year.

4.2. Qualitative analysis

Literature has been analyzed according to common focuses and themes. The topics are not mutually exclusive, given that several papers presented multiple focuses and themes.

While all the contributions analyze to a certain degree the intersection of servitization, digitalization, and sustainability, it is possible to observe that most of the literature adopts a heavily **technological perspective** of digital and sustainable PSS, specifically investigating the role of technology in enabling PSS and less prominently analyzing the sustainability dimension.

The literature heavily investigates the role of digital technologies for PSS, proposing technical solutions (e.g. (Ren et al., 2022; Walk et al., 2023; N. Wang et al., 2020)); data frameworks (e.g. (X. Li et al., 2021)) and identifying opportunities to leverage specific technologies such as big data (Ren et al., 2019), cloud manufacturing (Charro and Schaefer, 2018), digital twin (Timperi et al., 2023), and IoT (Basirati et al., 2019). Digital technologies are **clearly recognized as an enabler of circularity and sustainability in PSSs by the literature**, even though many papers don't go into detail on which sustainable impact has been achieved and how.

The explicit focus on the **sustainability dimension** is not as common and it appears to be a less investigated topic of analysis. Particularly, **social sustainability** is investigated in 29% of papers, in which it is often only mentioned and it is mostly not explained how the implementation of PSS could improve social sustainability.

Most papers analyzing sustainability focus on **specific activities** (such as remanufacturing (Fofou et al., 2021; Kerin and Pham, 2020)), **business models and PSS configurations,** and **methodologies** to support digital sustainable servitization.

Most proposed business models have a specific focus, such as prescriptive maintenance (Martín et al., 2021), waste collection (Elia et al., 2016), and equipment sharing (Ren et al., 2022). Other papers focus on specific elements of the business model, in particular the role of technologies concerning circular business models (e.g. (Bressanelli et al., 2018; Neligan et al., 2023; Prakash and Ambedkar, 2022)).

The literature proposes tools and methodologies that center on the **design** (Arioli et al., 2023; F. A. Halstenberg et al., 2019; Lugnet et al., 2020; Riedelsheimer et al., 2021; Song et al., 2021) and **assessment** ((Liu et al., 2020; Z. Wang et al., 2020)) of digital and sustainable servitization. Few attention has been given to the lack of achievement of sustainability, such as rebound effects, which may impede sustainability potential (Kjaer et al., 2018), and to the role of digital technologies both as mitigators and drivers.

Finally, it is relevant to observe that a high number of papers propose **state-of-the-art investigations, bibliometric analysis and future research directions** related to specific elements of digital and sustainable PSS such as servitization in general (Chen et al., 2022; Kohlbeck et al., 2023; Ulaga and Kowalkowski, 2022; C. Zhou and Song, 2021), the role of big data (Ren et al., 2019) and 3D printing (Chaney et al., 2021) and LCA for servitization (Kruschke et al., 2023). Given the time distribution of the papers, which are quite recent, it is possible to conclude that the research directions are currently being set and investigated. The literature is currently trying to structure knowledge related to digital sustainable servitization and to identify and propose research opportunities.

4.3. Digital technologies, services and opportunities for sustainability

4.3.1. Digital technologies

The relevance of digital technologies for servitization is widely recognized, Fig. 4. Information technologies play a critical role in the development of smart services (Alcayaga et al., 2019). Moreover, technologies are usually not used individually, but combined, leveraging and complementing the offered opportunities. To implement digital and sustainable PSSs, all key technologies should be integrated and applied

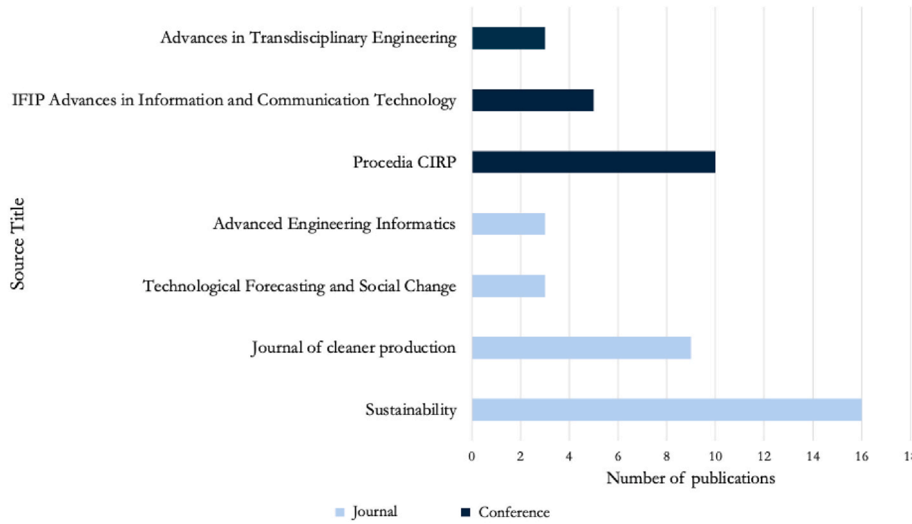

Fig. 3. Source title.

Table 1
Country distribution.

Country	Contributions	Citations
Italy	16	1079
Finland	7	870
China	21	801
Sweden	18	731
United Kingdom	9	561
United States	6	526
Singapore	7	475
Germany	19	464
France	9	448
Austria	6	335
Spain	5	169
Hong Kong	5	168

to operation and decision-making throughout the whole lifecycle (Ren et al., 2019). In this section, the technologies mentioned in the papers and their role in sustainable servitization are analyzed.

One of the most common technologies investigated in the literature is the **Internet of Things (IoT),** which is mentioned in **54% of the investigated publications**. This technology is one of the most mentioned in connection with PSSs, as it is considered an enabler of functionalities required by other technologies. IoT enables the collection of data, both product-sensed and user-generated (X. Li et al., 2021). Companies can monitor the products and their status and can gain knowledge related to the customers' usage (Bressanelli et al., 2018). The functionalities enabled by IoT are coherent with the circular economy, which requires the monitoring and control of products along their lifecycle (Han et al., 2023). Indeed, in the literature, IoT is particularly recognized for its role in collecting data for monitoring purposes (eg. (Arioli et al., 2023; Bag et al., 2024; Elia et al., 2016; González Chávez, Unamuno, et al., 2023; Nag et al., 2022; X. Zhang et al., 2022)). IoT-enabled remote access allows tracking, visualizing, and analyzing performances, thus guiding activities to increase efficiency (Paiola et al., 2021). Furthermore, IoT facilitates the development of PSSs, enables continuous tracking of product data, reduces operating costs, and supports the expansion of the service offering (Alcayaga et al., 2019).

Strictly connected to IoT is the high focus of literature on **data, big data, and data analytics,** which are mentioned by **66% of publications**, often in conjunction with IoT**.** The adoption of IoT brings an increasing amount of collected data, allowing continuous production improvement and the implementation of closed-loop lifecycles (Basirati et al., 2019). The relevance of data for servitization is clear, as the introduction of additional services becomes easier the more data are available (Neligan et al., 2023) and the availability of data allows the

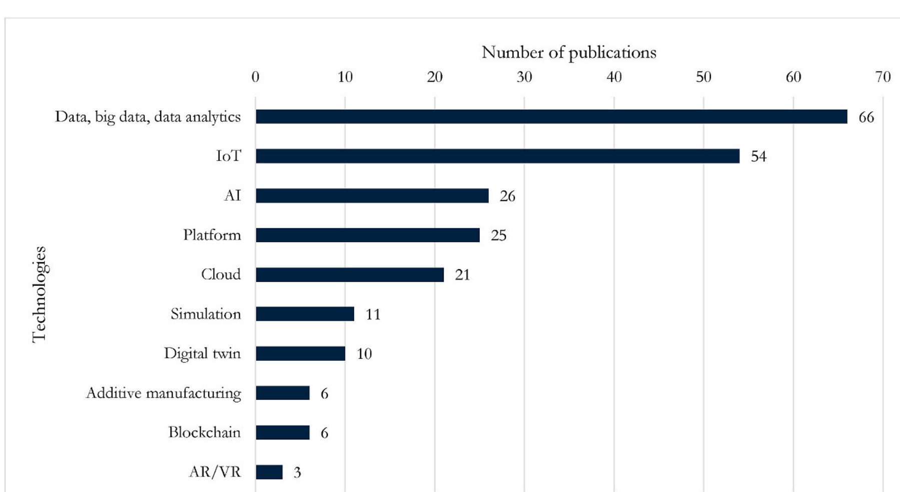

Fig. 4. Digital technologies distribution.

implementation of new services (Gonzalez Chavez et al., 2021).

Data and analytics techniques are critical digital enablers of improved decision-making (Atif, 2023b; Bressanelli et al., 2018). By sharing data along all lifecycle stages, it will be possible to implement more reliable decisions (Ren et al., 2019). The analysis of data allows the identification of required changes in the business model to optimize activities and reduce inefficiencies, thus the sustainability gains are affected by the reliability and validity of the collected data (Langley, 2022).

The literature, particularly, highlights the role of IoT and the analysis of collected data for activities' optimization. Data collected during the use phase can be applied to enable services and guide their provision, such as improving scheduling services according to production efficiency (Marilungo et al., 2017) and real customer needs (Elia et al., 2016). These technologies can also support avoiding extra repair, improving maintenance (Isaksson et al., 2018), and optimizing and increasing the efficiency of users' operations (de la Calle et al., 2021). Additionally, they could influence the design and improvement of future products (Charro and Schaefer, 2018) and drive EoL management services, facilitating reverse logistic planning and the selection of the most appropriate recovery strategy, guiding timely recovery decisions (Ren et al., 2019). The collection and analysis of data can also be implemented by PSS providers to offer guidance in reducing incidents by predicting them (Martín et al., 2021) and proposing dedicated training, based on the most common failures and identified knowledge gaps (Arioli et al., 2023)

IoT and data analysis have a role also in customer relationships, as they enable services that may increase the willingness to pay for PSSs (Pirola et al., 2020).

A technology related to data analytics is **artificial intelligence**, mentioned in **26% of papers**, which is identified as an enabler of new services and process optimization. According to Sjödin et al. (2023), artificial intelligence can enable two kinds of business models: augmentation (optimization) and automation business models. Indeed, AI can enable activities for PSS management (Stoll et al., 2023). AI is recognized as an opportunity to facilitate and improve data-driven analysis and decision-making (Han et al., 2023; Nicoletti and Appolloni, 2023; Sjödin et al., 2023). It enables the monitoring and optimization of activities, notably maintenance (Martín et al., 2021; Ren et al., 2022; Stoll et al., 2023), and of critical KPIs such as energy consumption (Sassanelli et al., 2022) and PSS lifecycle parameters related to sustainability (Abdoli and Bahramimianrood, 2023).

Walk et al. (2023) investigate the analysis of components combining computer vision and artificial intelligence analysis, to establish the foundation for result-oriented PSSs. These technologies are applied to propose services addressed at the machinery users to understand the wear state of components to improve operations and enable EoL decision-making (improvement in the design and the machining processes, remanufacturing, and recycling decisions).

Cloud technologies are investigated in **21% of the literature**. Cloud technologies enable the integration of data among the PSS stakeholders (Atif, 2023b). High focus has been given to cloud platforms for servitization (Arioli et al., 2023; Han et al., 2023; Landolfi et al., 2019; Ren et al., 2019). **Platforms** appear to have a relevant role in the literature related to sustainable and digital PSS, **25%** of publications mention platforms with different applications and objectives.

Platforms are becoming more relevant in the industry, as they ensure security and allow connectivity and data collection (Langley, 2022). Platforms can enhance the usage, maintenance, and upgrade of services (Atif, 2023b). Zheng et al. (2019) propose two categories of digital platforms for digital PSS: product-dependent, in which modularized services (such as monitoring and control) related to the physical product are offered, and product-independent, in which modularized e-services, not connected with the physical product, are provided. The investigated literature highly focuses on the earlier category: platforms strictly connected to physical products.

In the initial stage of the PSS lifecycle, platforms can be used to facilitate the collaboration for the design and development of PSSs, by collecting personalized requirements (Y. Chang et al., 2023; Matsas et al., 2017).

In the usage phase, platforms for PSS acquire different roles and applications. One relevant application of platforms is the monitoring of product performances and relevant information (Arioli et al., 2023; Paiola et al., 2021). Platforms can be also used to manage the energy consumption of the products (Sassanelli et al., 2022).

Furthermore, platforms can enable access to remote and shared resources (Charro and Schaefer, 2018; González Chávez, Despeisse, et al., 2023; Grahn, 2022; Landolfi et al., 2019; Paiola et al., 2021), thus potentially increasing the utilization of idle resources (Grahn, 2022), both tangible and intangible. This application of platforms is often related to cloud manufacturing and manufacturing-as-a-service, interconnected with additive manufacturing and blockchain for resource sharing (e.g. (Charro and Schaefer, 2018; Landolfi et al., 2019). Finally, advanced condition monitoring and service platforms can enable smart EOL management (Meng et al., 2020)

Simulation techniques are recognized as relevant by the related literature, as they are investigated in **11%** of documents. They offer an opportunity to enable analysis of different scenarios guiding design choices and decision-making (Arioli et al., 2023; Sjödin et al., 2023). Simulation techniques are often studied in connection to **Digital Twins (DT), which are analyzed in 10% of publications.**

In PSSs, DTs are used to enable simulation and optimization of performances along the entire lifecycle and can be leveraged to select and enable more sustainable alternatives in design and service provision. According to Abdoli & Bahramimianrood (2023), DTs for servitization should mirror the system's entire lifecycle, including design alternatives, to realize sustainability targets. DTs can be used to incorporate BOL feedback from MOL and EOL to improve design and simulate different scenarios (Basirati et al., 2019). The role of DTs includes also monitoring and optimization of activities, increasing resource efficiency (Riedelsheimer et al., 2021; Timperi et al., 2023).

Two additional technologies are identified in the literature with specific applications: **additive manufacturing** and **blockchain**. In the context of digital and sustainable PSS, **additive manufacturing** is often connected to cloud manufacturing (Charro and Schaefer, 2018) and customization (Chaney et al., 2021). It enables customization services while producing locally, closer to clients, with less raw material (Chaney et al., 2021), thus reducing transportation and resource consumption.

Blockchain technology is recognized as relevant in establishing trust mechanisms to resolve the data security problem, and it is particularly relevant for PSSs based on resource sharing (Landolfi et al., 2019; Ren et al., 2022).

Finally, **augmented and virtual reality (AR/VR)** are scarcely considered by the literature, mostly connected to supporting operators' activities and enhancing training (Gonzalez Chavez et al., 2021).

4.3.2. Services

The investigated literature proposes multiple services to be implemented with the support of digital technologies to improve sustainability, Fig. 5.

It is relevant to notice that the services identified in the literature are related to more product-oriented PSSs. This literature review aims to investigate the context of manufacturing PSS, thus most literature proposes the integration of services into the traditional product offering.

Several services are centered on the design and improvement of the offering, based on customers' needs and requests, such as **design improvement, customization, co-design, updates, and upgrades**. These services are recognized as relevant in the literature and are proposed by **31%** of papers. In PSSs, the provider is involved along the lifecycle of the physical product, thus capturing relevant information on the functioning of the offering, and can improve its design to match users' expectations. The data collected along the product's lifecycle can

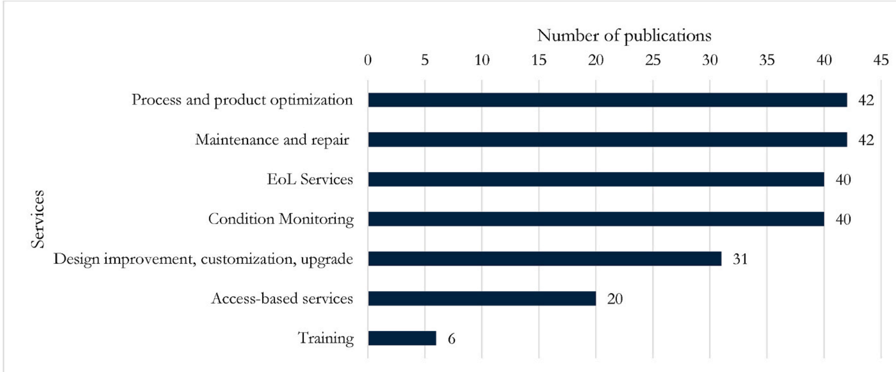

Fig. 5. Service distribution.

be integrated to lead to improvements and innovations in products (Ren et al., 2019).

These services, such as smart re-design and reconfiguration (X. Li et al., 2021; Walk et al., 2023; Zheng et al., 2019b), enable the ability to meet new client's needs and requirements which may emerge during the utilization of PSSs. The possibility to improve the design, upgrade it, and customize it, following the evolution of the context in which the PSS is immersed, allows to increase the offering's lifespan. Many papers investigate services of design improvement and product upgrade based on collected information (Gonzalez Chavez et al., 2021; Ren et al., 2019; Walk et al., 2023; X. Zhang et al., 2022). Customization can also facilitate the reuse of PSS, by adapting the same product to different users' requirements (Alcayaga and Hansen, 2024).

Moreover, customization as a service is proposed in the literature also in conjunction with specific technologies. Matsas et al. (2017) propose a platform that can enable the configuration and the consequent customization of the offering. Additive manufacturing can offer an opportunity for customization (Chaney et al., 2021). It is relevant to notice that the customization of the product-service offerings, selecting the most appropriate service configuration to answer specific customer needs, enables the implementation of specific services and related impact, as shown in Y. Chang et al. (2023). Timperi et al. (2023) investigate the role of DT in enhancing PSS, considering also design activities, as they allow customers to participate in building the most appropriate configuration to meet their needs. Moreover, DT-enabled design services can take into account sustainability targets and requirements.

One of the most common services identified in the literature is related to **condition monitoring (40% of papers)**. Monitoring services allow to assess performances (Zheng et al., 2019b), and to offer more insights on the process and the improvement opportunities (Walk et al., 2023). Moreover, the services can include the reporting of operations through dashboards and graphic features (Paiola et al., 2021; Sassanelli et al., 2022). Condition monitoring allows access to historical and real-time data, thus enabling a series of activities such as preventing unexpected failures through periodic checks and spare parts optimization (Arioli et al., 2023).

Indeed, condition monitoring is used to offer clients, as well as providers, visibility of the product's status and, when the product is a production asset, the related production process, allowing **process and product optimization (42%)**.

The service of process optimization is one of the most common services mentioned in literature, and it encompasses many different activities, such as.

- Process efficiency (production, maintenance, scheduling etc.) (e.g. (Basirati et al., 2019; González Chávez, Unamuno, et al., 2023; Marilungo et al., 2017b; Nag et al., 2022; Paiola et al., 2021; Ren et al., 2019; Scholtysik et al., 2021; Walk et al., 2023))
- Energy management and usage (e.g. (González Chávez, Unamuno, et al., 2023; Paiola et al., 2021; Riedelsheimer et al., 2021; Sassanelli et al., 2022))
- Partners' coordination (e.g. (Alcayaga and Hansen, 2024))
- Spare parts and inventory management (e.g. (Arioli et al., 2023; Ren et al., 2019; Timperi et al., 2023))
- Material usage and waste reduction (e.g. (Bressanelli et al., 2018; Gonzalez Chavez et al., 2021; González Chávez, Unamuno, et al., 2023; Paiola et al., 2021; Ren et al., 2019; Timperi et al., 2023; N. Wang et al., 2020))

Another highly mentioned service is related to **maintenance (42%),** enhanced by data and condition monitoring. The offering of maintenance services, enabled by digitalization and by PSS business models, can increase the product lifecycle, in line with sustainability objectives.

The information collected along the life of the product can be applied in maintenance operations, improving them and reducing downtime (e.g. (Alcayaga et al., 2019; M. M. L. Chang et al., 2017; Isaksson et al., 2018; Nag et al., 2022; Timperi et al., 2023)).

In particular, the literature focuses on predictive maintenance (e.g (Alcayaga et al., 2019; Basirati et al., 2019; Basirati et al., 2019; Bressanelli et al., 2018; Ren et al., 2019; Sassanelli et al., 2022; Scholtysik et al., 2021; Stoll et al., 2023; Zheng et al., 2019b)), preventive maintenance (Bressanelli et al., 2018; Ren et al., 2022; N. Wang et al., 2020) and improved maintenance planning (Gonzalez Chavez et al., 2021; Ren et al., 2022; Timperi et al., 2023; X. Zhang et al., 2022).

The literature also proposes **access-based services (20%)**, which can be considered also distinct PSS configurations, often connected with use- or result-oriented PSS, in which the producer retains the ownership of the products and gives their access to multiple actors (e.g (Charro and Schaefer, 2018; Landolfi et al., 2019; Pirola et al., 2020; Ren et al., 2022; Ries et al., 2023; N. Wang et al., 2020; Wu and Pi, 2023)). In the literature, access-based services are often presented in conjunction with other services supporting the physical product, such as monitoring and maintenance. These PSS configurations can increase the involvement of producers in the product lifecycle, promoting improved control over the products' utilization and EoL (Fofou et al., 2021; Ren et al., 2022; N. Wang et al., 2020)

The literature also highlights that the provider of the PSS can offer **training** as a service **(6%).** Training can be enhanced by digital technologies. By analyzing the most common failures it can be possible to provide additional learning material (Charro and Schaefer, 2018) and training lessons to cover users' skills gaps (Arioli et al., 2023). Training could be included in the installation phase (Nag et al., 2022), or enabled by more advanced technologies, such as DTs (Timperi et al., 2023).

Finally, the literature identifies opportunities for servitization also in the **EoL (40%)** of physical products, proposing specific services related to the management of the physical asset at the end of the lifecycle.

The collection of data and the retained control that PSSs allow can enable the exploitation of MoL information to guide EoL decision-making (Kerin and Pham, 2020), for instance, to determine if a product is more suitable for repair or remanufacturing (Fofou et al., 2021).

Services similar to **remanufacturing and recycling** are common EoL services in the literature (e.g. (Alcayaga and Hansen, 2017; X. Li et al., 2020, 2021; Ren et al., 2019; Ries et al., 2023; Schiavone et al., 2022; Timperi et al., 2023)), and will be expanded in the subsequent chapter as they can also be considered sustainability strategies.

4.3.3. Sustainable strategies

The literature proposes multiple perspectives on how digital PSS can improve the sustainability of offerings, Fig. 6, both through specific sustainable strategies as well as consequences of different configurations of physical products and intangible services.

Mirroring the related service, many papers propose as a sustainable strategy **the optimization and improvement of products and processes (45%).** For what concerns the optimization of the characteristics of the integrated offering, this strategy encompasses the improvement and upgrade of design based on the functioning and customer requirements. Upgradability and reconfigurability are recognized as an opportunity to achieve more sustainable solutions (Pirola et al., 2020). Moreover, the possibility to improve design brings increased upgradability, improved resource utilization, reconfiguration, and reducing the resources implemented. Finally, the reconfiguration allows to expand the lifespan of PSSs through a limited number of components (X. Li et al., 2021). It counteracts obsolescence, thus expanding the lifecycle (F. Halstenberg et al., 2021).

The optimization can also include the operations involving the integrated offerings, thus it is possible, coherently with the previously presented service, to improve and optimize activities, for example increasing the success of maintenance.

Another sustainable strategy is the **lifecycle extension (22%)** of products. Indeed, by upgrading and changing products and components, PSSs' lifecycle can be extended (X. Li et al., 2020). Through the monitoring of the functioning of the PSS, it is possible to prevent failures and prolong the PSS's useful life (Arioli et al., 2023). Moreover, the implementation of services can maintain products in useable conditions for a longer time (Nag et al., 2022). The extension of the product lifecycle, through certain PSS business models, leads to reduced necessity for new physical products (Sjödin et al., 2023).

Another opportunity for increased environmental sustainability comes from the **reduction in transportation (7%).** It can be enabled by improving the activities through data analysis, thus reducing the necessity for travel (Elia et al., 2016; Han et al., 2023; Timperi et al., 2023), and by dematerializing services.

The reduction in transportation can be enabled also by strategies of **local production (6%)**, through additive manufacturing (Chaney et al., 2021) and distributed manufacturing (Charro and Schaefer, 2018). Local production can be considered also a social strategy, creating **local job opportunities** (N. Wang et al., 2020) and regional development (Ries et al., 2023). Furthermore, the literature proposes other sustainable strategies related to social sustainability, such as **increased health and safety (12%),** by reducing malfunction risks (Martín et al., 2021; Tabacco et al., 2024) and giving preventive measures for hazards (Feng et al., 2023; Martín et al., 2021), **job creation (7%), and upskilling and reskilling (6%)**, by leveraging opportunities such as training based on data collected through condition monitoring (Arioli et al., 2023).

One of the most common **(44%)** sustainable strategies identified in the literature is related to the **reduction of resource usage, both considering material and energy consumption.** This strategy is particularly coherent with servitization: implementing PSS to lower energy consumption, reduce material utilization, and reduce waste is both economically and environmentally convenient (Langley, 2022).

The reduction of resource consumption can be achieved through different activities, such as.

- Optimization of spare parts usage (e.g. (Arioli et al., 2023) (Ren et al., 2019; Timperi et al., 2023))
- Identification of wear state (e.g. (Walk et al., 2023))
- Resource sharing and increased equipment utilization rate (e.g. (Charro and Schaefer, 2018) (N. Wang et al., 2020; Ren et al., 2022))
- Optimization of the efficiency of users' processes (e.g. (Walk et al., 2023; Paiola et al., 2021; Martín et al., 2021; Sjödin et al., 2023; Zheng et al., 2019b))
- Design improvement (e.g. (Matsas et al., 2017) (Timperi et al., 2023))
- Optimization of consumable usage (e.g. (Walk et al., 2023) (Paiola et al., 2021))
- Improved production planning (e.g. (Zheng et al., 2019b) (Marilungo et al., 2017))

High focus has been given also to the technologies implemented in achieving the reduction of energy consumption such as platforms (Sassanelli et al., 2022), data analytics, AI (de la Calle et al., 2021; Sjödin

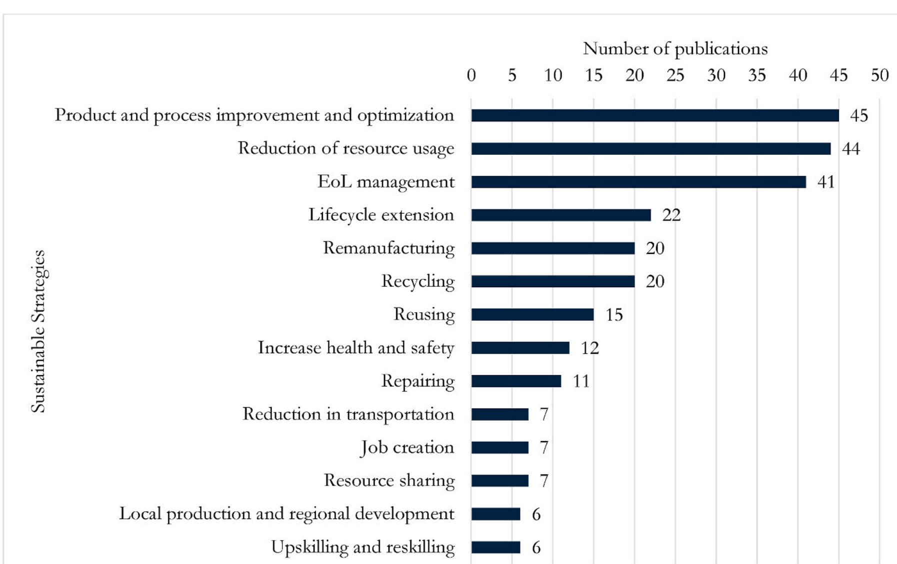

Fig. 6. Sustainable strategies distribution.

et al., 2023; Walk et al., 2023; Ren et al., 2019), and DTs (Riedelsheimer et al., 2021).

Resource sharing (7%) can be also considered a sustainable strategy. It can improve the equipment utilization rate, minimize resource consumption and negative environmental impact, and promote the resource integration of the entire manufacturing industry (N. Wang et al., 2020). It can also decrease the amount of products in circulation (Charro and Schaefer, 2018; Ren et al., 2022).

The literature highly focuses on **EoL activities and sustainable strategies (41%)**. The 9Rs are particularly present in the literature (e.g. (Schiavone et al., 2022)). For these activities, the increased control, intervention, and producer accountability enabled by servitization, together with the data collected through the lifecycle, are particularly relevant. The implementation of IoT enables access to real-time product information, which allows for the optimization of EoL activities, providing the status and location of products (Bressanelli et al., 2018).

The data collected by a digital PSS offers better decision-making opportunities, such as understanding, through data-carrying devices, which product is most suitable for repair or remanufacturing activities (Fofou et al., 2021) and guiding recovery activities (Meng et al., 2020; Ren et al., 2019; S. A. Wiesner et al., 2023). Other technologies of digital PSS can enable decision-making for EoL such as DT (Timperi et al., 2023).

The reusing of components or products is considered a viable sustainable strategy for digital PSS **(15%).** In the context of extended and retained ownership, the EoL responsibility of the offering falls on the provider (N. Wang et al., 2020), which has a high interest in expanding the lifecycle of the products by **reusing** them. According to Alcayaga et al. (2019), in this context, reuse can be closed-loop, which means that the products are reused for the same application, or open-loop, in which the products are reused for other applications.

Remanufacturing is highly mentioned in the literature **(20%).** The role of IoT, data, and the extended responsibility of producers are particularly relevant. Remanufacturing requires tracking, control, and analysis of the products' conditions and usage, which can be enabled by IoT (Basirati et al., 2019). The data collected can eliminate the uncertainties related to the activity (Alcayaga et al., 2019). As stated by Alcayaga et al. (2019), remanufacturing in servitization can be envisioned in two categories: closed-loop, in which remanufacturer and client have close relationships; or open-loop, which involves the sourcing of parts from different suppliers and brands.

Similar considerations can be made for **repairing (11%)**, enabled, as the other recovery strategies, by data and information collected along the lifecycle of products (Ren et al., 2019).

Finally, the last sustainability strategy identified in the literature is related to **recycling (20%).** According to Alcayaga et al. (2019), recycling can be closed-loop, proposed by a company working with specific recyclers; or open-loop, set up by municipalities and in which the recycled waste can be used for products with comparable, higher, or lower material quality. The role of technologies and control along the lifecycle is relevant also for this strategy, as the recycling process and the quality of product recycling can be improved through the collection of data (Zheng et al., 2019).

Many papers also propose **methodologies to assess the environmental impact** of digital PSS, such as LCA (F. Halstenberg et al., 2021; F. A. Halstenberg et al., 2019; Kruschke et al., 2023; Landolfi et al., 2019; Riedelsheimer et al., 2021; Walk et al., 2023), simple KPIs (Matsas et al., 2017) or new and dedicated methodologies (Liu et al., 2020; Song et al., 2021; Z. Wang et al., 2020). Moreover, it is relevant to notice that some papers in the literature do not clarify how digital servitization enables improved sustainability, and they appear to consider PSSs more sustainable by default.

5. Discussion

5.1. Framework

Based on the findings from the literature, the authors propose a framework (Fig. 7) aimed to clarify the linkages between digital technologies, services, and sustainability of PSS solutions. The framework highlights the connections and opportunities of leveraging technologies and services to improve the social and environmental sustainability of the integrated offering, in comparison to the traditional alternatives.

The framework aims to clarify the role of digital technologies, services, and sustainable strategies, and their connections. In particular, it offers a characterization of how, in the context of manufacturing, PSSs' services, enabled and empowered by specific digital technologies, can be offered to implement social and environmental sustainability strategies. The framework highlights the strategies and opportunities to achieve sustainable impact through specific digitally enabled services. In this chapter, specific paths to implement sustainable strategies are presented, as well as the role of the most relevant technologies for each service.

The technologies, services, and possible sustainable impacts have been extrapolated and rationalized from the literature, as well as the connections between them. It is relevant to notice the identification of two clusters of sustainability, one related to environmental sustainability and the other related to social sustainability, which represents an element of novelty in the literature, given the under-researched nature of social sustainability of PSSs. Additionally, the main three environmental strategies (lifecycle extension, reduced resource consumption, and improved closed-loop) are coherent with the circular economy value drivers proposed by the Ellen Macarthur Foundation (World Economic Forum & Ellen MacArthur Foundation, 2016).

It is important to notice that the most relevant technologies for specific services have been highlighted, nonetheless, digital technologies support and enhance each other and cannot considered as completely independent entities.

Customization and co-design, Fig. 8***,*** enable clients to adapt the PSSs to their specific needs. These services can be offered by leveraging **platforms and additive manufacturing**. Platforms enable the connection of clients to providers' physical assets and services. Additive manufacturing allows customers, by leveraging resources offered by the providers, such as specific 3D models, to adapt the physical products to their needs. Simulation techniques and DTs can be leveraged to select the most appropriate configuration, involving customers in building sustainable alternatives. Additionally, simulation and AR/VR can be used in customization and co-design services, supporting decision-making to optimize social and environmental sustainability, similarly to how they are being applied in traditional design activities (e.g. (Scurati et al., 2022; Wall et al., 2020)). These services can enable the **optimization of products and processes,** and the **extension of PSSs lifecycle,** by adapting the PSSs to specific customers' needs. Additionally, the implementation of advanced manufacturing for customization reduces the need for transportation, thus **reducing the related consumption and emissions** (Chaney et al., 2021). Moreover, these services empower decentralized production, thus potentially creating **job opportunities** in local communities. Finally, through specific customization of offerings, it is possible to improve the effectiveness of **reuse strategies**, by adapting the offering to the specific needs of the new client (Alcayaga and Hansen, 2024).

For example, Matsas et al. (2017) propose a platform that allows the configuration of PSS among different stakeholders, enabling customization and co-design, the platform enhances sustainability by enabling the collection of feedback and the inclusion of KPIs to guide design choices to enable optimal design and reduce resource consumption. Y. Chang et al. (2023) investigate multiple companies proposing customization in PSS; in the analyzed use cases the platforms to collect design requirements allow to reduce resource consumption, and the

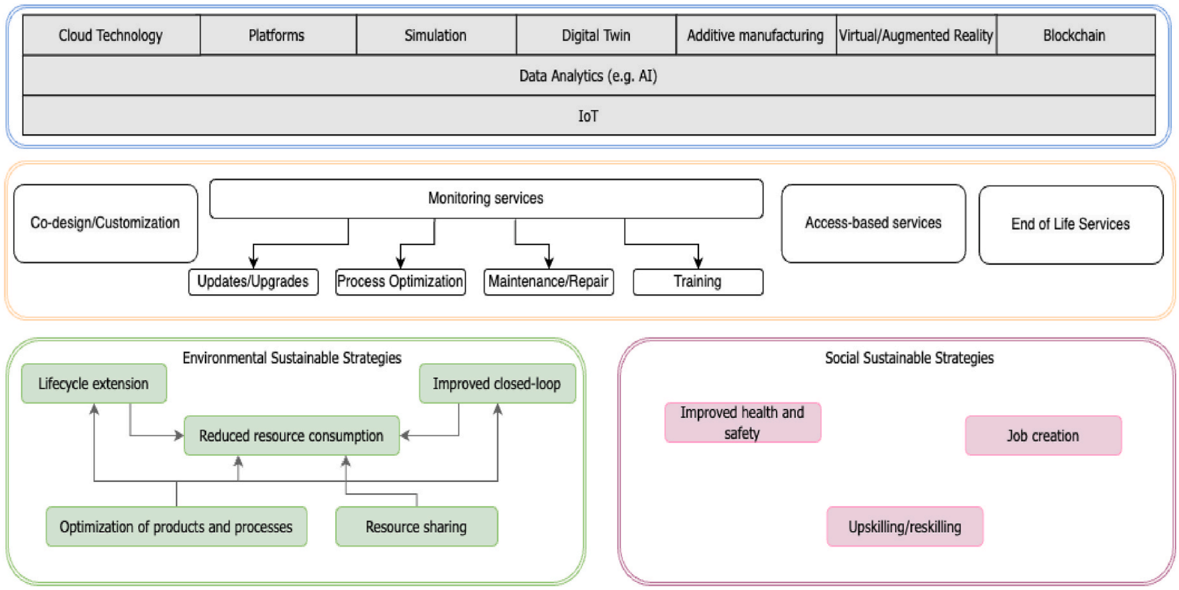

Fig. 7. Conceptual framework.

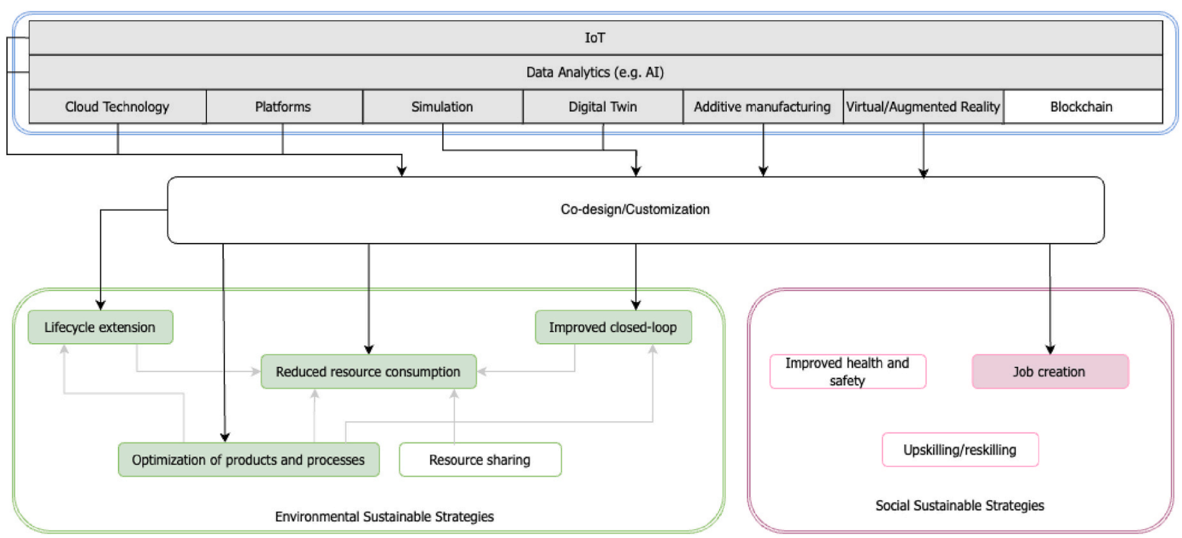

Fig. 8. Co-design/customization.

implementation of customization services increases job positions for qualified designers.

Monitoring services, Fig. 9***,*** are crucial to capturing relevant information, guiding decision-making, as well as enabling other services. These services are strictly connected to **IoT and data**, which enable the collection of information related to the asset's functioning, providing historical records and real-time visibility. **Platforms** can be leveraged to offer users access to the information, also through the support of reporting and customized dashboards. In more advanced configurations, product monitoring can be empowered by technologies of data analytics and computer visions enabling the identification of specific working states, based on pattern recognition (e.g. (Walk et al., 2023)). **DTs** can also be leveraged for product monitoring services. **Blockchain** can be used to support the exchange of data, increasing the security of the data transaction.

These services increase user awareness of the operating status of the product and can improve decision-making based on real-time and historical data. Enhanced decision-making can **decrease resource consumption**, such as energy and consumables, through **process optimization.** Furthermore, it can **extend the machine lifecycle,** and guide **recovery activities** in the EoL.

Finally, the monitoring services can increase the understanding of the products' functioning, predicting possible accidents and injuries, thus **improving the health and safety** of the operators.

For example, Arioli et al. (2023), investigate a platform enabling the monitoring of machines' parameters. The platform grants remote access to machine health status, potentially guiding additional services and activities to optimize consumption and extend useful life. The provision of real-time insights on energy consumption and related recommendations has been analyzed also by Malakhatka and Walbaum (2024) to foster more conscious customer usage.

Enabled by the monitoring services and data collection, the ***process optimization services,*** Fig. 10***,*** are valuable for improving sustainability. In these services, the PSS providers suggest or define parameters to optimize users' production processes and other related activities, such as procurement. The providers can leverage the unique knowledge of their products and the information related to customer usage. Thus, the optimization can be based on in-house knowledge as well as on

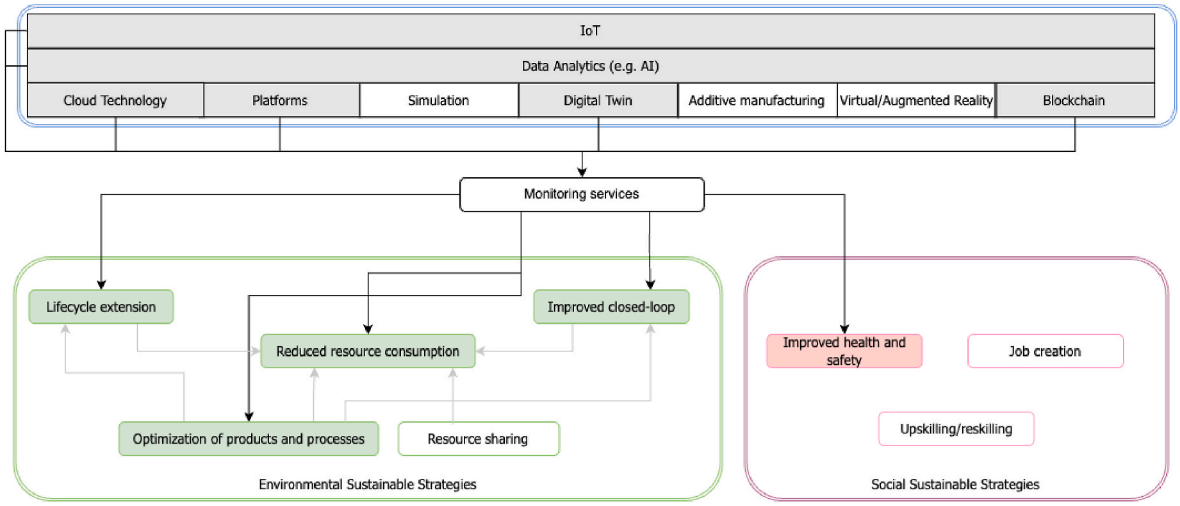

Fig. 9. Monitoring services.

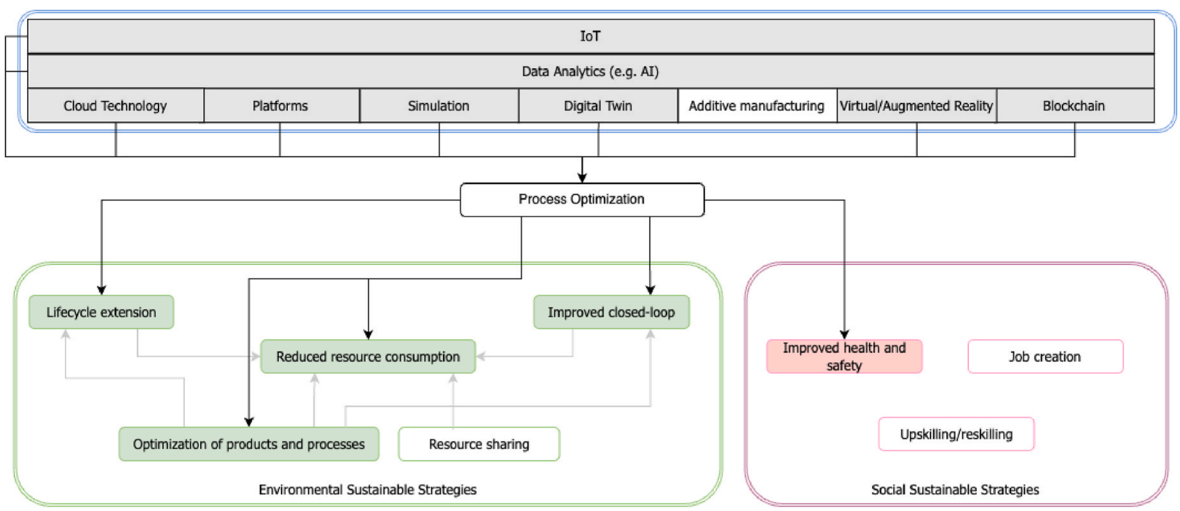

Fig. 10. Process optimization services.

anonymized and horizontal data coming from multiple users.

As stated above, the monitoring services and related technologies are enablers of optimization services. Technologies such as **cloud platforms** and **blockchain** facilitate data collection and create a point of communication between providers and users. From a technological perspective, this service is enabled **by IoT, data, and data analytics (also leveraging AI)** which are implemented to guide decision-making in the optimization activities. **DTs and simulation techniques** can also be applied to compare and select the best configuration of processes. **AR/VR** can enable optimization activities by guiding operators through a set of instructions based on optimal operations.

The sustainable opportunities offered by these services are coherent with those offered by monitoring services, in this case, the provider actively proposes or applies the optimization. Thus, the environmental opportunities include the **optimization of processes**, **improvement of resource consumption, extended lifecycle, and improvement of EoL activities.** From a social perspective, the optimization of processes can **improve the health and safety** of the operators.

For example, Walk et al. (2023) investigate the conjunct application of computer vision techniques and AI to improve, through PSSs, customers' machining processes, leveraging information on wear state to identify process improvement opportunities. Riedelsheimer et al. (2021) focus on a DT, implemented in the context of a PSS, leveraged to deploy optimization services, aimed at providing energy optimization recommendations to users.

Updates and Upgrades services***,*** Fig. 11***,*** imply that the provider adjusts, through new hardware and software, the offering to better answer customer needs and foster innovations. The technological enablers and sustainable implications are similar to those of process optimization services. In updates and upgrades services, it is the configuration of the offering that is innovated and improved. These services are also coherent with customization ones, but take place in the use phase of the PSSs, exploiting operative information. From a technological perspective, these services leverage the **connectivity of the physical products, data analytics, and simulation** to select the best offering improvement, based on customers' changing requirements and contexts. Cloud platforms can also be applied to propose updates and upgrades to customers. **Additive manufacturing** could also be implemented in this context, producing components in-house from producers' specifications, with environmental and social sustainability implications coherent to those of customization services, such as increased **job creation.** These services can improve **resource consumption**, and **extend the lifecycle** of the offering, reducing its obsolescence and the need to produce and buy completely new products.

For example, in the use case investigated by Bressanelli et al. (2018), PSSs' connectivity allows upgrades that extend the product lifespan and

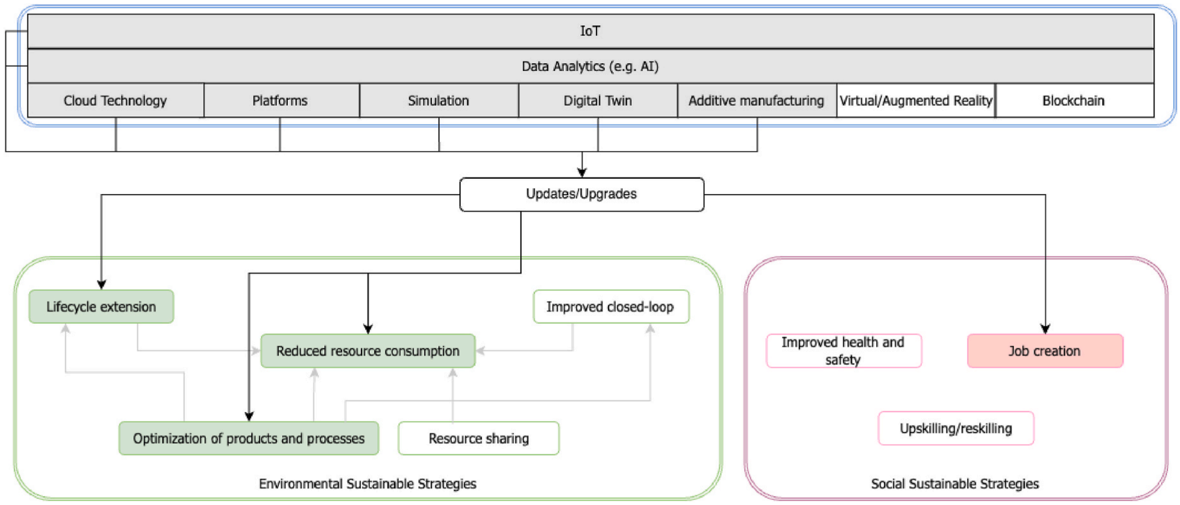

Fig. 11. Updates and Upgrades services.

improve the functioning of the PSSs regarding consumable utilization.

Maintenance and repairing services, Fig. 12***,*** can include several configurations, on-site and off-site, from planned to emergency-based. These services leverage **IoT** and **data analytics** to identify the most appropriate timeframe and define specific repair and maintenance activities. These services can use **cloud platforms** to enable operators access to provider's information and real-time data to carry on maintenance. Also, **DTs and simulation techniques** can be applied to improve the efficacy of the activities. The services can also leverage **AR/VR** technologies to guide on-site operators in the repairing and maintenance, thus dematerializing the activities and eliminating related transportation. These services can reduce the **consumption of resources**, by analyzing the most efficient timeframe and consumables required for the activity, as well as **extend the product lifecycle**, by keeping it functional for longer. They can also increase the **safety of the operators** by preventing accidents caused by malfunctions.

For example, S. Wiesner et al. (2022) highlight how machine data can be leveraged to offer maintenance services, such as preventive maintenance and optimized replacement of components. Additionally, the use case investigated by de la Calle et al. (2021) involves a digital PSS enabling the reduction of transportation and resource consumption through remote maintenance services and leveraging data to select the appropriate spare parts for the interventions.

Training services, Fig. 13***,*** can be enabled through the collection of data and product monitoring, thus **IoT and data analytics** technologies are required enablers. **Cloud platforms** offer an opportunity for providers to connect with users and share dedicated training material. Additional opportunities for enhanced training and reskilling are offered by **AR/VR** technologies which can increase the efficiency of training, potentially enhancing operators' **safety** (Cimini et al., 2023). Moreover, DT and simulation techniques could be used to train users in operating the PSS (Timperi et al., 2023). These services have a direct social impact: **upskilling and reskilling** workers to be able to carry on advanced and innovative operations. Furthermore, specific training activities and personalized instructions allow to increase the efficiency of processes, both day-to-day operations and repairing and maintenance activities, thus **reducing the utilization of resources** and **expanding product lifecycles**.

For example, Arioli et al. (2023) propose a platform that, by enabling the analysis of data related to frequent failure, potentially supports the provision of focused learning material and training sessions.

Access-based services, Fig. 14***,*** imply that the providers retain the ownership of the physical products and grant access to users through different configurations, in use- or result-oriented PSSs. These services and PSS configurations offer high opportunities to reduce environmental impact. They leverage **connectivity, blockchain, and platforms** to allow clients to access the products. They can also implement **additive manufacturing**.

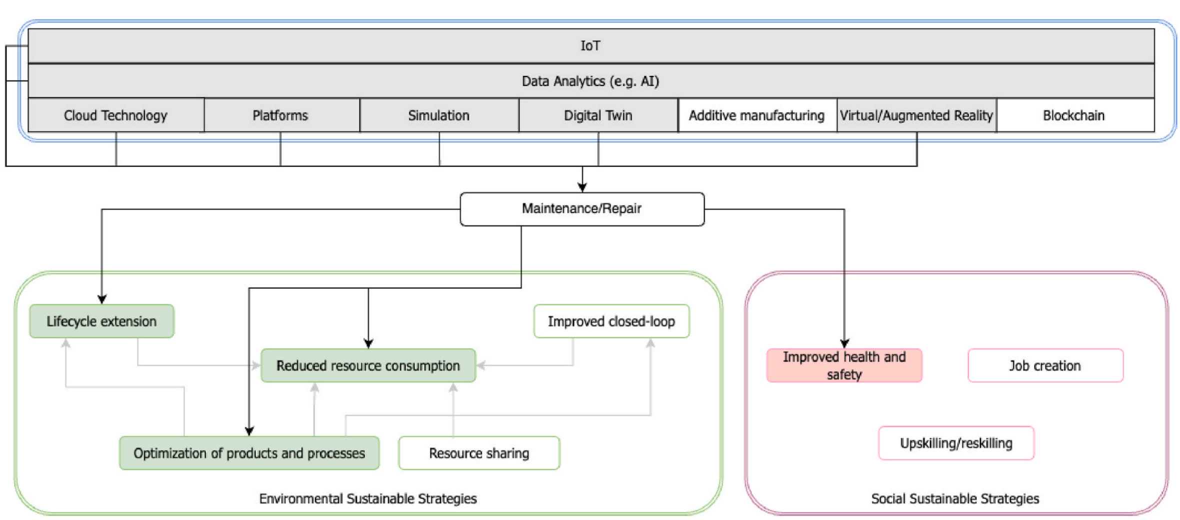

Fig. 12. Maintenance and repair.

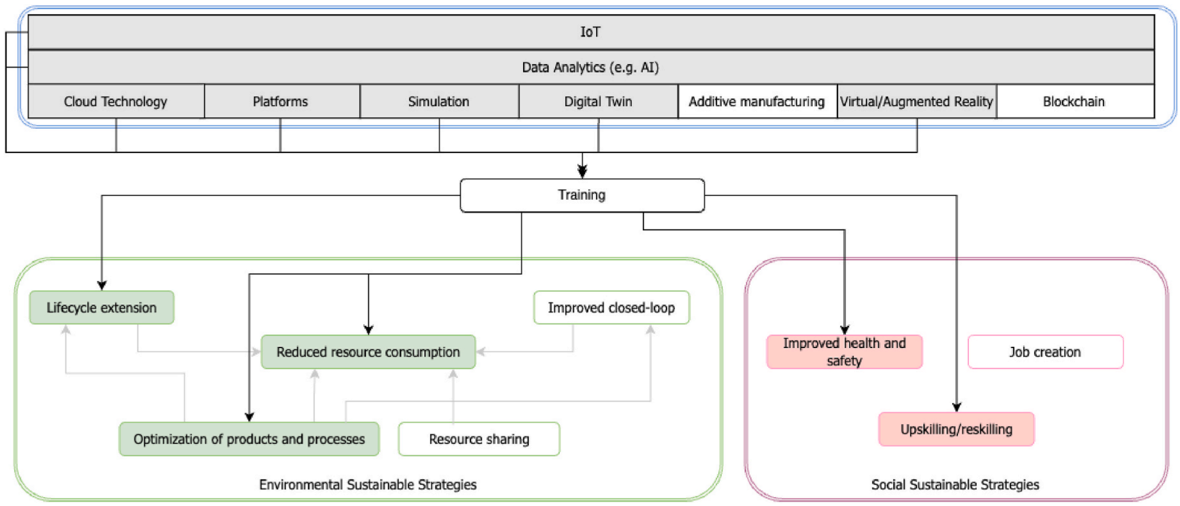

Fig. 13. Training.

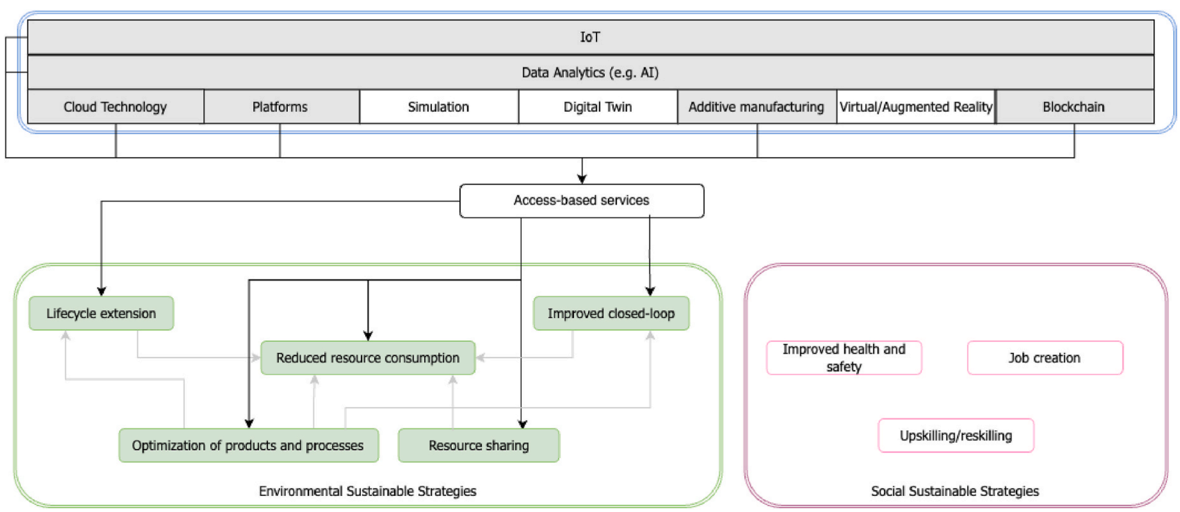

Fig. 14. Access-based services.

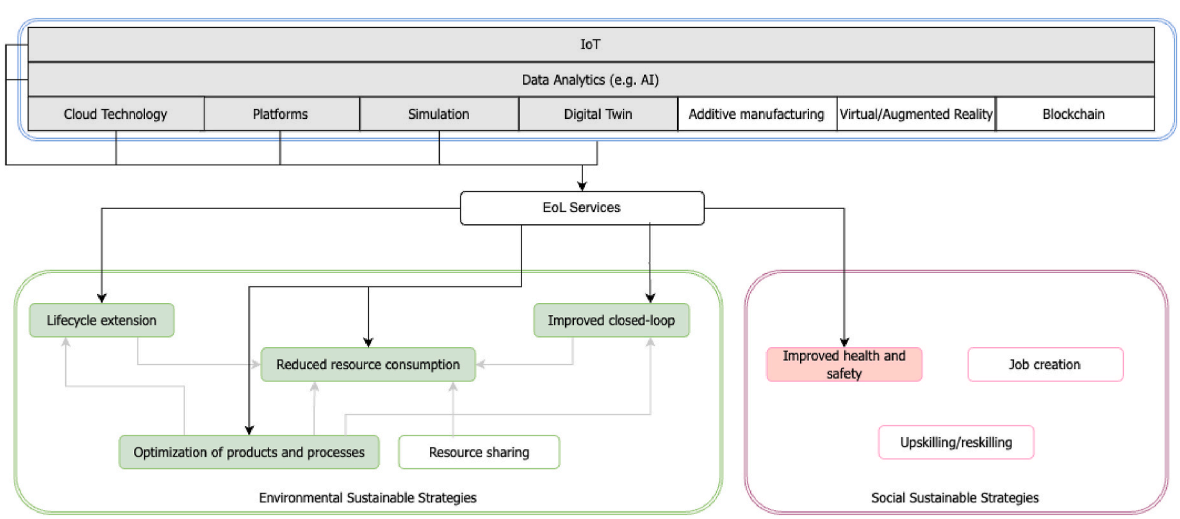

Fig. 15. EoL services.

Through these services, is possible to reduce the number of produced machines. This can be done by increasing the utilization rates of those already produced through the centralization of customers' production demand, thus **reducing the consumption of resources**. Moreover, the retained ownership pushes the providers to improve operational efficiency and to **extend the lifecycle** of the physical products, which is directly linked to their productivity. Moreover, these services incentivize **closing the loop,** by increasing the providers' control on the EoL stages and by making the reutilization of components more economically appealing.

For example, Landolfi et al. (2019) present a manufacturing-as-a-service platform, leveraging LCA, to share and access unused production capacity, thus focusing on the increase of utilization rate supported by environmental impact information. N. Wang et al. (2020) propose an access-based PSS that centers on CNC machines. The PSS configuration increases both the utilization rate of equipment and the provider's control of the machines. Therefore, the provider is facilitated and encouraged to improve maintenance activities and operations.

Finally, ***EoL services,*** Fig. 15***,*** include all the services related to the final phases of the offering lifecycle, such as remanufacturing, reuse, and recycling activities. **IoT and data analytics**, supported **by platforms and cloud technologies**, are critical technologies to enable these services. They provide data on the conditions and locations of physical products, recording their usage history, thus facilitating decision-making. **Simulation techniques and DTs** may enable the identification of the most appropriate recovery strategy.

These services can reduce **resource consumption.** By improving EoL activities and recirculating products, parts, and components, they can reduce the need to consume raw materials for production. Moreover, they are naturally coherent with **lifecycle extension** and **closed-loop strategies**.

The data analysis and the collected information can also **improve the execution of the recovery activities**, by improving the decision-making activities related to EoL and potentially optimizing the waste collection routes, reducing transportation. Additionally, coherently with maintenance and repair services, leveraging digital technologies to analyze the remaining lifecycle of products allows for retrieval and recovery of the products before possible malfunctions, consequently affecting the **safety of PSS users.**

For example, the use case analyzed by Bressanelli et al. (2018) deploys EoL services through IoT technologies. The technology enables real-time availability of information related to the condition and the location of the products, facilitating recovery activities as well as supporting the selection of the most appropriate EoL strategy and its subsequent implementation. Similarly, in Meng et al. (2020) a previously existing condition monitoring platform is leveraged to enable EoL decision-making, which allows the selection of the best recovery solution taking into account also environmental sustainability elements. Additionally, Elia et al. (2016) investigate how digital PSS can be leveraged in waste collection services to improve the selection of the waste collection route.

5.2. Gaps and future research opportunities

Based on the findings from the existing literature, the authors propose future research opportunities that are under-investigated and formulate exemplary research questions based on the gaps, Table 2.

The current state-of-the-art heavily analyzes the technical and technological perspective of digital sustainable servitization, investigating opportunities related to the implementation of specific digital technologies and proposing technical solutions. Nonetheless, certain digital technologies and their role in sustainable servitization are under-investigated such as **blockchain and AR/VR**. As explained in the developed framework, the latter can cover a relevant role in the use phase of PSSs and could be leveraged in **training activities**, another theme that is seldom analyzed in literature and can increase social sustainability.

Table 2
Exemplary research questions.

Future research opportunities	Exemplary Research Questions
Investigate the opportunities of achieving social and environmental sustainability of under-researched digital technologies such as blockchains and virtual and augmented reality	•Which are the opportunities to enhance the social and environmental sustainability of PSS by leveraging blockchain technology? •Which are the opportunities to enhance the social and environmental sustainability of PSS by leveraging virtual and augmented reality?
Investigate the opportunities to enhance the social sustainability of PSS through digitally enabled training services	•How can training services be applied to enhance social sustainability in digital PSS?
Investigate how specific digital PSS business models can enhance environmental and social sustainability	•Which are the different business model archetypes for digital and sustainable PSS? •Do different digital servitized business models have different social and environmental sustainable implications?
Investigate the opportunity to achieve TBL sustainable principles through digital PSS	•How do economic, social, and environmental sustainability interact in the context of digital PSS?
Investigate the rebound effects of digital PSS, focusing on the role of technology as a mitigator or driver of rebound effects	•Which are the main potential rebound effects of digital PSS? •How can digital technologies be implemented as a mitigator of rebound effects in PSS?
Investigate organizational resources, capabilities, and implementation paths to achieve sustainable digital servitization Develop tools to support manufacturers in building capabilities and resources to support sustainable digital servitization	•Which are the required capabilities to support digital sustainable servitization in manufacturing? •How can companies be supported in developing appropriate resources to implement sustainable digital servitization strategies? •Which are exemplary implementation paths of sustainable digital servitization?

Less focus has been given to **achievable sustainable impacts**. While the literature proposes the investigation of certain business models and digital PSS configurations for sustainability, future research should expand on this theme. One avenue of research is the proposal of digital and sustainable servitized business models and the analysis of the mechanisms capturing positive social and environmental impact as well as the required resources for their implementation.

The focus of the literature on **the TBL is scarce**, and little attention has been given to the interaction between the three pillars of sustainability, thus reducing the efficacy of the implementation of digital and sustainable PSSs. Moreover, the **social dimension is scarcely investigated**, and the mechanisms leading to improved social sustainability are often not clear. Thus, future research should focus on the analysis of the three pillars of sustainability, in particular investigating mechanisms to achieve TBL sustainability.

Additionally, the literature often assumes improved environmental sustainability against the traditional offering. PSSs are not always more sustainable than the traditional alternatives. Moreover, the implementation of digital technologies can be energy-consuming, and trade-offs should be investigated accordingly. Consequently, the topic of the **negative environmental impact of digital PSS** is under-researched, and scarce attention has been given to rebound effects.

The literature often focuses on PSS configurations, but few studies are dedicated to the transition of companies towards digital sustainable servitization; and themes such as the **main drivers, challenges, enablers, required organizational resources and capabilities, and possible implementation paths** are less researched. While methodologies to design PSSs and assess their impact could be identified, tools related to the companies' transition towards digital sustainable servitization, such as **maturity models and roadmapping methodologies** have been underexplored. Future research could focus on the investigation of required resources and paths for the transition of manufacturers, proposing specific supporting tools.

6. Conclusion

This study conducted a SLR to investigate the context of digital sustainable servitization in manufacturing. The paper aims to answer two research questions: RQ1*: "Which is the state of the art in the context of digital sustainable servitization in manufacturing?"* and RQ2: "*Which are, in the context of servitization in manufacturing, the linkages between the most relevant digital technologies, services, and environmental and social sustainability strategies?"*

Answering RQ1, the paper analyzes the state-of-the-art, identifying the main trends in the literature and highlighting the prevalence of the technological perspective against the sustainable one. Moreover, answering both RQ1 and RQ2, the contribution highlights the digital technologies, services, and sustainable impact studied by the existing literature, highlighting how digital technologies can be applied in PSSs to improve social and environmental impact.

Rationalizing the literature investigation's results, the paper proposes a framework clarifying the linkages between digital technologies, services, and social and environmental sustainability strategies, covering existing research gaps. In particular, the framework clarifies how services, enabled by specific digital technologies, can be leveraged in the context of servitization in manufacturing, to implement social and environmental sustainability strategies. Finally, the paper proposes gaps and related research opportunities based on the existing literature.

This research provides a meaningful contribution to the field of digital sustainable servitization, emphasizing and clarifying the role of specific digital technologies, services, and sustainable strategies. The research answers multiple calls asking for a deeper exploration of the intersection of the three elements of digitalization, servitization, and sustainability (e.g. (Antikainen et al., 2018; Atif et al., 2021; Q. Zhou et al., 2024)). Notably, this work addresses also the theme of social sustainability, underexplored by the literature (Ries et al., 2023).

From and theoretical perspective, the research offers an analysis of the current state-of-the-art, proposing main trends and possible gaps to be covered by future research. Based on the analysis, the paper highlights and investigates relevant digital technologies and services, as well as the social and environmental impacts achievable in manufacturing through the digital servitization paradigm. The paper then proposes a framework to illustrate specific connections between digital technologies, services, and sustainable strategies, which are often underexplored by existing publications.

The papers' contributions also present practical implications. Practitioners can leverage the findings of the research and apply the proposed framework in supporting the design and development of digital PSS to achieve social and environmental sustainability, through technologies and services usually applied for competitive and financial motivations. Moreover, the framework can guide practitioners in the identification of digital technologies and services to adopt to implement specific environmental and social strategies.

This contribution presents limitations that could be overcome by future research. First, the authors acknowledge the potential presence of bias which could influence the results of the analysis of the state-of-the-art. Second, the research develops a framework based on the findings of the literature; the investigation of the industrial context through a multi-case study could corroborate and complement the findings with the industrial perspective, suggesting additional linkages between the identified technologies, services, and sustainable strategies. Finally, even though a specific filter has not been applied, and access-based services have been included in the analysis and the framework, the framework has a product-centric focus which could be complemented by additional research focused on use- and result-oriented PSSs.

CRediT authorship contribution statement

Elena Beducci: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Federica Acerbi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Anna De Carolis:** Writing – review & editing, Validation, Supervision, Conceptualization. **Marco Taisch:** Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100269.

Data availability

No data was used for the research described in the article.

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