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A Systems Thinking Approach for Modelling Sustainability Impacts and Paradoxes of Product-Service Systems

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ABSTRACT

In recent decades, manufacturing companies have increasingly adopted product-service systems (PSSs) business models combining products and services. PSS solutions aim for greater sustainable performance across the triple bottom line (TBL) dimensions; however, the literature emphasises the significance of accurately assessing sustainability impacts because they may lead to unexpected negative effects. Given this, the study adopts systems thinking and an inductive approach, grounded in an in-depth case study, to investigate the dynamics of sustainability in PSS configurations. A causal model was developed using causal loop diagrams and integrating life cycle thinking and paradox theory to provide a systemic and comprehensive assessment of PSS sustainability. The findings reveal the key variables and feedback mechanisms underpinning TBL interdependencies in product-oriented PSS. Product-oriented services create sustainable value through asset availability, operational efficiency, and longevity, while simultaneously generating tensions related to service efforts, rebound effects, trade-offs, and hidden environmental and social costs.

1 | Introduction

For decades, manufacturing firms have adapted and transformed their businesses to address market competitiveness and sustainability concerns. An increasing number of manufacturing companies are selling combinations of products and services that upset the traditional product-centricity of this industry. This process is known as servitisation (Vandermerwe and Rada 1988) and has led to the development of product-service system (PSS) business models (Kurpiela and Teuteberg 2022).

PSSs extend the manufacturer's responsibility and internalise economic, environmental, and social factors that emerge during and after the product use phase, thus incorporating systems and life cycle thinking approaches (Evans et al. 2017) in the offerings to customers. PSS definitions emphasise the ability of these business models to generate benefits in all three dimensions of the Triple Bottom Line (TBL) of sustainability, that is, economic, environmental and social pillars (Elkington 2000), by generating higher profits thanks to a prolonged relationship with customers, by reducing resource consumption through optimising product utilisation while extending the product lifecycle, and by promoting competitive advantage (Alfarisi et al. 2023; Baines et al. 2009; Haase et al. 2017; Lee et al. 2012; Tukker 2004). However, the sustainability impacts of PSSs are still debated in the literature (Hao et al. 2021), with various issues being discussed, such as the 'service paradox' (Gebauer et al. 2005; Li et al. 2020) and 'rebound effects' (Guzzo and Pigosso 2024). Different sources of complexity may affect the misalignment between expected and achieved benefits, among which the change of ownership (Nyvall et al. 2023), the involvement of multiple stakeholders (Hirth et al. 2015), customer engagement (Xu et al. 2026) and customer behaviour (Muylaert et al. 2024) are the most frequently mentioned.

Since PSS sustainability is not inherent, they must be developed and assessed across their entire life cycle, as life cycle thinking is essential to guide sustainable value creation (Sarancic et al. 2023). Existing studies have investigated PSS sustainability and developed assessment methodologies, methods and tools, but a common and effective approach that supports PSS development and can guide PSS decisions (during the entire life cycle) considering sustainability dynamics is still missing (Moro et al. 2022; Sai et al. 2023; Sarancic et al. 2023) as well as practices for visualising the quantified value (Rabetino et al. 2017). Moreover, only a few methods exist for comprehensively assessing the sustainability of PSSs in the TBL (Arioli, Sala, et al. 2025), and the lack of interrelation between the three sustainability pillars is a well-known issue (Song et al. 2021). However, beyond the limitations of existing modelling approaches, the sustainability assessment of PSS is inherently characterised by feedback-driven interactions among environmental, economic, and social variables (Lee et al. 2012). These interactions generate non-linear and emergent behaviours that cannot be represented through linear equations or isolated pillar-based assessments. In this regard, the adoption of the system thinking approach is not merely a methodological alternative, but a necessary step to explicitly represent the causal structure underlying sustainability trade-offs and unintended consequences in PSS contexts. System thinking incorporates 'the ability to see the world as a complex system, to understand how everything is connected to everything else' (Sterman 2002) and, therefore, to identify relevant aspects and make long-term decisions consistent with the best interests of the involved stakeholders (Sterman 2002). It has been applied in existing studies for capturing the interrelation between TBL dimensions in complex scenarios and their resulting feedback dynamics (Avila-Choconta et al. 2026). Specifically, it has been applied in the PSS context for assessing the sustainability of such business models (Alfarisi et al. 2023; Gnoni et al. 2017; Laurenti et al. 2016; Lee et al. 2012) and also for investigating the service paradox and value co-creation in PSS (Li et al. 2020). However, comprehensive system thinking models are still lacking in the literature. Existing models often fail to capture all the TBL dimensions, unintended consequences (like the service paradox) via reinforcing and balancing loops, the perspectives of the different stakeholders of the PSS ecosystem, and life cycle services at a sufficient level of detail. Moreover, the available models require further improvements to be applicable across different manufacturing contexts (Gnoni et al. 2017; Lee et al. 2012; Wasserbaur et al. 2020), particularly in business-to-business (B2B) sectors.

Therefore, the objective of this paper is to investigate the systemic interdependencies between economic, environmental, and social sustainability outcomes in PSS and to identify the key variables and feedback mechanisms through which services create value and generate sustainability tensions across the ecosystem. Through this, we also aim to support companies in understanding the sustainable added value of their solutions from an ecosystem perspective, as well as their related tensions.

To address these objectives, the study investigates the following research questions (RQs):

RQ1. What are the key interdependencies between economic, environmental and social sustainability dimensions in product-oriented PSS?

RQ2. Which variables and feedback mechanisms drive sustainable value creation and sustainability tensions in product-oriented PSS?

RQ3. How can a systems thinking approach support sustainability-oriented decision-making in B2B manufacturing companies within PSS ecosystems?

To address the RQs, the study adopts an inductive, case-based approach, grounded in an in-depth analysis of a manufacturing company with a wide service portfolio and a strong conviction about the potential for servitisation to increase competitiveness and sustainability in the market. The study exploits a modelling tool typical of systems thinking that logically organises the key variables, their interactions, and their systemic effects: the Causal Loop Diagram (CLD) (Haraldsson 2004). The case study has been developed through the following steps:

1. Identifying the variables that constitute the business offerings, their relationships, interactions, tensions, and the effects on the sustainability of the services in the ecosystem (including also the case study customers), even those that are not directly or intuitively related to each other;
2. Aligning the involved services and associated business models with sustainability outcomes across economic-environmental-social dimensions.

By focusing on the theoretical understanding of the feedback mechanisms enabled by the use of CLD, this paper contributes to the growing body of literature that leverages systems thinking to address the complexity of sustainability in PSSs, specifically in the B2B context, taking into account simultaneously the TBL dimensions, the multi-actors perspective, and the most spread after-sales services that manufacturing companies offer in their business portfolio.

Theoretical generalisation of the model (Tsang 2014) is also proposed, supported by embedding empirical research literature in the development of the model, and interpreting the results obtained via a paradox lens (Lewis 2000). By integrating systems thinking with a paradox perspective, it becomes possible to emphasise that opposing forces inherent in dynamic and complex systems should not be examined in isolation (Schulte and Paris 2024). This is particularly relevant in the context of sustainability, where organisations are required to balance often conflicting social, environmental, and economic objectives (Van Der Byl and Slawinski 2015). As previously discussed, paradoxes are also present in the PSS literature. In this regard, paradox theory provides a suitable framework for examining both servitisation and sustainability from a holistic and systemic perspective (Van Der Byl and Slawinski 2015). Moreover, the application of a theoretical lens can enhance the explanatory power of research findings (Li et al. 2020).

We structure our article as follows. Section 2 reviews the literature on the concept of PSS, highlighting the link with sustainability, and provides the gaps in the literature and the motivation for this work. Section 3 describes the methodology used in the study. Section 4 reports the results driving the development of the conceptual model. Section 5 analysed and discussed the model while aiming for theoretical generalisation of the results. Section 6 concludes with implications for research and practice and directions for future research.

2 | Literature Background

2.1 | PSS and Sustainability

A PSS is defined as a bundle of products, services, actors and infrastructures designed and delivered to meet customer needs with lower environmental impact than traditional models (Mont 2002). The literature distinguishes three types according to the ownership of the product and the nature of provider and customer relationships of solutions (Gaiardelli et al. 2014): product-oriented PSS, where products are sold with supplementary services (e.g., maintenance, spare parts, training) and owned by customers; use-oriented PSS, such as rental or leasing, where the provider retains ownership and grants access; and result-oriented PSS, such as pay-per-use or outsourcing, where the focus is on delivering a result without a predefined product.

Product-oriented PSS are still the most common in manufacturing (Arioli, Pezzotta, et al. 2025) and represent an initial stage of servitisation toward performance-based models (Holgado and Macchi 2023). The PSS literature equally covers business-to-customer (B2C) and B2B settings in the manufacturing industry with the main difference that successfully implementing a PSS solution in a B2B manufacturing context requires a good understanding of customer needs and requirements regarding the asset and its performance (Holgado and Macchi 2023). Therefore, to create a situation in which both parties benefit, the PSS provider's gain and the customer demand must be connected (Meier et al. 2010). Customers' needs and requirements are usually related to better utilisation of the asset, higher performance, longer operation possibilities (Meier et al. 2010), and increasing sustainability (Meuer et al. 2020).

PSSs are often considered a promising approach to enhance sustainability in all TBL dimensions: PSSs may limit the depletion of natural resources and pollution emissions by extending, intensifying and optimising product use (Kjaer et al. 2019; Neramballi et al. 2020; Tukker 2004); PSSs can increase company revenues by adding services to the business portfolio and preserve costs by retaining the ownership in use- and result-oriented PSSs (Baines et al. 2009); PSSs can create new job positions and increase the health and safety (H&S) of workers and customers (Spadafora and Rapaccini 2024). However, environmental, economic and social benefits are not inherent to PSSs and must be intentionally designed (Roman et al. 2023).

The paradox lens is used in sustainability research, and quite recently, it has been applied in PSS research as well. Within this complex system, tensions arise due to the need for different customer relationships, organisational structures and approaches to innovation that can affect the success and performance of PSS. The most cited is the service paradox, which suggests that high investment in extending service business leads to increased service offerings and higher costs but does not yield expected higher returns (Gebauer et al. 2005). A systems approach and stronger theoretical foundations, for example, paradox theory, are suggested ways to advance knowledge on resolving the service paradox (Li et al. 2020). The paradox theory appears to explain the adverse PSS performance on the environment, which is also known as the 'rebound effects' of PSS models (Guzzo and Pigosso 2024). Measuring sustainability performance is not trivial because PSS models can lead to unintended consequences, reducing the overall sustainability benefits (Hahn and Pinkse 2022). By clarifying and defining the potential tensions before PSS implementation, it is possible to cope with the resulting paradoxes (González Chávez et al. 2021).

2.2 | System Thinking for Sustainability Assessment of PSSs

Alongside the definition and design of sustainable PSSs, increasing attention has been given to the assessment of PSS sustainability in the literature (Annarelli et al. 2016; Blüher et al. 2020; Kohlbeck et al. 2023; Pirola et al. 2020). Different methodologies, methods and tools for assessing the sustainability of PSS solutions have been proposed (Arioli, Sala, et al. 2025), but an exhaustive approach that can support decisions is still missing. Well-known methods (e.g., Life Cycle Assessment and Life Cycle Costing) focus on one sustainability pillar at a time; therefore, authors agree on the need to develop a more comprehensive assessment (Blüher et al. 2020; Doualle et al. 2020; Gnoni et al. 2017; Lee et al. 2012; Scafà et al. 2018) which should include the interdependencies among sustainability dimensions (Negri et al. 2016; Settanni et al. 2014; Song et al. 2021).

System Dynamics (SD) simulation, having its roots in the system thinking, has been suggested as a suitable means to address the above issues (Lee et al. 2012). There are already some SD works proposing PSS sustainability assessments in the literature, proposed in conferences (i.e., Gnoni et al. 2017; Legnani et al. 2010; Oh et al. 2021) and published in international journals (i.e., Abdelkafi et al. 2022; Alfarisi et al. 2023, 2024; Laurenti et al. 2016; Lee et al. 2012; Metic et al. 2024; Werrel et al. 2024). However, a deep analysis of these studies (as reported in Table 1) revealed different patterns:

1. Most of these studies focus on use-oriented PSSs (e.g., Alfarisi et al. 2023; Gnoni et al. 2017; Lee et al. 2012; Metic et al. 2024), not mentioning adaptability to other PSS typologies. Moreover, specific after-sales services are not always modelled, thus lacking details.
2. Few studies include social indicators (i.e., quality of life, inequality, health). The social dimension is often missing or underdeveloped, revealing a clear opportunity for further studies.
3. When more than one dimension of the TBL is considered in the modelling, no specific variables have been identified as connecting elements among the TBL dimensions (beyond the generic 'sales of PSS') (e.g., Alfarisi et al. 2023; Gnoni et al. 2017; Lee et al. 2012).
4. The models use mostly context-related variables, which makes it impossible to adapt the models to other manufacturing contexts and to different PSS types (e.g., Alfarisi et al. 2023; Gnoni et al. 2017; Lee et al. 2012). Thus, they

TABLE 1 | Analysis of previous works on PSS assessment for sustainability.

References	Study aim	Methodology	PSS type	TBL dimensions	TBL dependencies	Point-of-view (POV)	Paradoxes	Limitations
(Alfarisi et al. 2023)	The study intends to assess the implementation of PSS by considering the variable of "nurture" and analysing its contribution to the emergence of rebound effects that can impede the attainment of targeted sustainability goals	SD modelling with mixed methods case study	Use-oriented (car sharing)	All 3 TBL	Yes, environmental and social linked	PSS provider & environment	Yes, rebound effects via nurture	• Partial data use • Uncertain input • No policy
(Gnoni et al. 2017)	CLDs are used to show the main impacts of the changes involved in the transition from a traditional to a circular model (PSS) in the EEE sector	CLD modelling and case study	Use-oriented (leasing contracts)	All 3 TBL	Yes, TBL linked via PSS sales	Supply chain	Rebound effects just mentioned	• Qualitative modelling only • Application sector-specific • Lack of behavioural effects
(Laurenti et al. 2016)	The objective is to qualitatively analyse the unintended environmental consequences of improvement actions (PSS adoption) through CLDs	Causal Loop Diagrams (qualitative)	No specific PSS	All 3 TBL	Yes, TBL linked	PSS provider and customer	Yes, rebound effects central to modelling	• Qualitative modelling only • Lack of details
(Lee et al. 2012)	The authors propose SD and TBL to measure PSS for public bike system sustainability through a comprehensive view	SD modelling and case study	Use-oriented (bike sharing)	All 3 TBL	Yes, TBL linked via PSS sales	PSS provider & customer	Not discussed	• Estimations, uncertainty
(Alfarisi et al. 2024)	The study aims to develop a dynamic LCA of PSS implementation for quantifying environmental and economic performance through the use of SD	Design research methodology with a case study	Use-oriented (camera rental)	Economic, Environmental	Yes, but separate	PSS provider & environment	Yes, rebound effects via nurture	• No social • No policy
(Metic et al. 2024)	The authors aim to identify rebound effects via SD in the context of PSS oriented to use	Theory building and SD modelling	Use-oriented (dress rental)	Economic, Environmental	Yes, focused on REs	Market	Yes, rebound effects are central to the model	• No provider cost • No transport • No after-sales services • Lack of specific stakeholders
(Werrel et al. 2024)	Although the article does not explicitly state a single study objective, its purpose is to contribute to the discussion on evaluating the circularity of PSS	SD modelling with sce-nario/sensitivity analysis	CE PSS (repair, refurbish, etc.)	Environmental only	Not included	PSS provider	Not discussed	• No economic • No real data • Lack of behavioural effects

(Continues)

TABLE 1 | (Continued)

References	Study aim	Methodology	PSS type	TBL dimensions	TBL dependencies	Point-of-view (POV)	Paradoxes	Limitations
(Abdelkafi et al. 2022)	The main objective is to investigate why servitisation in the printer supply chain does not necessarily lead to the achievement of environmental sustainability goals through CLD models	In-depth case study	Servitisation	Environmental only	Not included	Customer	Not discussed	• No specific service, just servitisation
(Oh et al. 2021)	The authors present a systematic method to evaluate the economic sustainability of PSS business models using a SD modelling template	SD modelling with case study	Subscription-based	Economic only	Not included	Manufacturer	Not discussed	Not discussed
(Legnani et al. 2010)	The SD model has been developed to quantitatively simulate how the provision of PSS can affect the economic performance of a company	SD modelling and case study	Product-oriented PSS (preventive maintenance contracts)	Economic only	Not included	Manufacturer	Service paradox just mentioned	Not discussed

do not strike a balance between the generalisation and the details of the models.

5. Paradoxes are discussed in some cases, particularly rebound effects (e.g., Alfarisi et al. 2023, 2024; Laurenti et al. 2016; Metic et al. 2024), neglecting a specific discussion on the service paradox.

Moreover, it should be mentioned that studies using SD simulation usually need a large amount of data, which complicates quantifications and leads to many assumptions (Alfarisi et al. 2023; Lee et al. 2012; Metic et al. 2024; Werrel et al. 2024). On the other side, studies showing only CLDs are useful in understanding the dynamics within complex systems, such as PSS offerings, but still go broad and lack depth or quantification (e.g., Abdelkafi et al. 2022; Gnoni et al. 2017; Laurenti et al. 2016).

To address these literature gaps and improve the validity of the model in holistically assessing the sustainability of different PSS solutions, we benefit from the use of CLDs within a case study of a product-oriented PSS. The selected case, which involves a variety of integrated services, enables a comprehensive analysis across all TBL dimensions. CLD will support (i) adding qualitative variables for the often-neglected social dimension (e.g., satisfaction, health), (ii) mapping feedback loops linking TBL variables, (iii) showing unintended consequences via reinforcing/balancing loops, and finally (iv) using a structure-based reasoning to explore the systemic logic before proceeding to quantification.

3 | Methodology

The primary objective of this study is to support companies in the assessment of the TBL effects of their service offerings and business portfolio, taking into account the sustainability implications and systemic interaction of PSS. To achieve this, an inductive research approach grounded in an in-depth single case study has been adopted to enable the identification of key variables, relationships, and tensions characterising the PSS under investigation.

The case study, conducted within a manufacturing company operating in a B2B context, was selected to explore real-world complexity and generate insights rooted in practice. Indeed, the case study approach enables researchers to uncover deeper layers of reality, identifying mechanisms and the factors that link a cause to its assumed consequence (Yin 2012). This approach allowed us to gain insights into current practices and to develop a solid practice-informed foundation while seeking theoretical generalisation, where generalisation is defined as "general statement or proposition made by drawing an inference from observation of the particular" to other populations (Tsang 2014). The single case study contributes in terms of theoretical generalisation, that is, the development or refinement of theories that explain the mechanisms underlying certain phenomena (Tsang 2014). Through this inductive, case-based methodology, the study develops a practice-informed causal model that reflects the realities of PSS implementation, thereby contributing to a broader theoretical understanding.

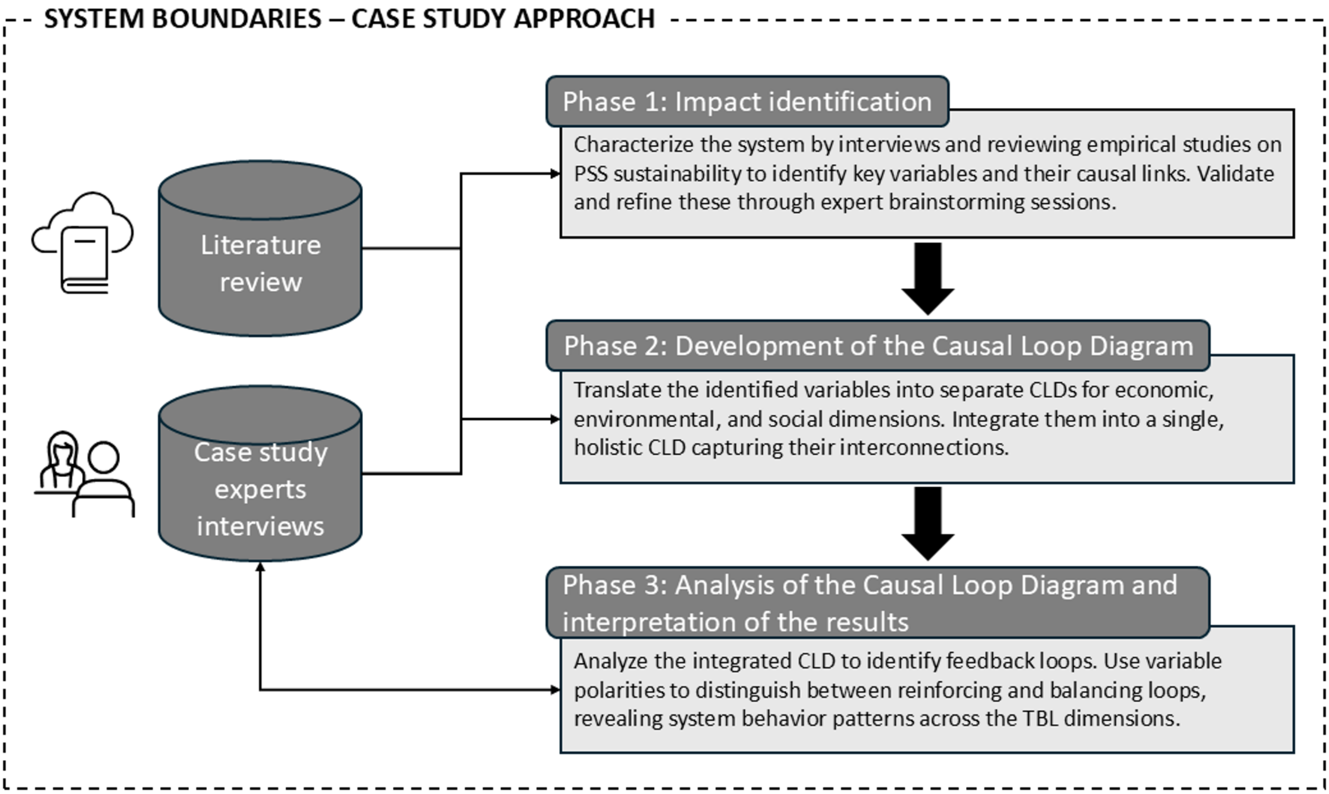

FIGURE 1 | Methodological approach.

To model and interpret the system dynamics, the CLD has been selected, a systems thinking modelling technique utilised to qualitatively explore variables and interrelationships of a system of interest (Haraldsson 2004). The CLD approach emphasises that everything in a system is connected while providing a comprehensive view of all relevant relationships on a single sheet and thus helping to gain a 'big picture' perspective and avoid seeing things in isolation (Williams and Hummelbrunner 2010).

The development of the CLDs followed Sterman's guidelines (Sterman 2002), including three main steps detailed in the next subsections. The overall picture of the methodology used in the study is reported in Figure 1. The CLD was developed by using the software VENSIM, which is particularly useful for identifying the feedback loops within the model.

3.1 | Case Study Background and Data Collection

As sustainability has become a worldwide issue, interest in sustainable manufacturing systems has increased significantly. Electricity and heat production are the largest contributors to global greenhouse gas emissions, followed by the transport and manufacturing sectors (Ritchie et al. 2020). This background is significant for a manufacturing company operating in the electrification sector wishing to become a leader in sustainable business strategy. For reasons of discretion, we refer to the company as Alpha. Alpha is a manufacturing company specialising in low-voltage (LV) and medium-voltage (MV) products that encompass solutions for the efficient management of electrical power across various industries. The company, to ensure this efficiency, offers a comprehensive service portfolio, including maintenance, training, and modernisation services in addition to both LV and MV electrical equipment.

The system boundaries were defined based on the selected case. Although PSSs involve multiple stakeholders, including product manufacturers, service providers, customers, business partners, and governments (Grueneisen et al. 2015; Hirth et al. 2015), this study focuses on the servitised manufacturer (SM) and the user (U), as the analysed manufacturer is also the service provider and the customer is the user of the provided asset.

Three types of product-oriented services have been included in the development of the holistic model: (i) care services, divided into reactive care services (including technical support and repair and spares and consumables) (PS1a) and proactive care services (including preventive and condition-based maintenance, installation and commissioning, and employee training) (PS1b), (ii) advisory services (including engineering and consultancy services, electrical system health check, and power system study) (PS2), and (iii) modernisation services (extensions, upgrades, replacements, retrofits, and other end of life services) (PS3). The case study drove this choice, strengthened by the consideration that product-oriented services are still the most offered by manufacturing companies, followed by result-oriented and use-oriented services (Arioli, Pezzotta, et al. 2025). Furthermore, product-oriented services guarantee to maintain asset performance and thus represent the first step of the servitisation process of manufacturing firms in B2B setting towards more complex performance-based services (Holgado and Macchi 2023). In this sense, they can be seen as scaffolding or a baseline for other PSS configurations.

3.2 | Phase 1: Impact Identification

As suggested by (Sterman 2002), CLD development began by defining the system under study, identifying key variables and their causal relationships ('+' for the same variation/direction impact and '−' for the opposite variation/direction impact).

The company's service portfolio was analysed through three interviews with service product managers, service sales managers, and the sustainability manager. During this phase, the company also provided us with secondary data, such as catalogues and sustainability reports. This was fundamental to understanding the offering better and collecting the variables that may impact the TBL dimensions. In parallel, a literature review (Grant and Booth 2009) focused on empirical studies exploring the sustainability of PSS solutions helped identify key impact variables and their relationships. These were refined through brainstorming with company experts from the service business unit and authors until consensus was reached. Results are described in Section 4.1.

3.3 | Phase 2: Development of the Causal Loop Diagram

All identified PSS impacts on TBL dimensions were translated into CLDs. A CLD consists of variables, displayed as texts, that are connected by arrows denoting the causal relationship among them and have polarities shown to indicate how the dependent variable (effect) changes when the independent variable (cause) changes (Haraldsson 2004). A positive link implies that an increase in the cause leads to an increase in the effect, and a decrease in the cause leads to a decrease in the effect. A negative link implies that an increase in the cause leads to a decrease in the effect, and a decrease in the cause leads to an increase in the effect. Additionally, in some cases, arrows were marked with a double line (//) indicating a delay in the expected effects' occurrence. Based on these relationships, one CLD was developed for each TBL dimension and then integrated into a final CLD capturing their interdependencies for a holistic sustainability assessment. All diagrams were validated with the authors and case study experts.

3.4 | Phase 3: Analysis of the Causal Loop Diagram and Interpretation of the Results

The final step consisted of analysing the developed CLD and identifying feedback loops. To do so, the reference behaviour pattern of the main sustainability indicators was useful in recognising the behaviour of the loop. The main loops (reinforcing and balancing) were identified based on the links between the variables and their polarities. Within a CLD, feedback loops are displayed with an identifier that can be positive (or reinforcing) or negative (or balancing). In reinforcing loops, the system behaves in the same direction, causing either systematic growth or decline, moving away from the equilibrium point. In balancing loops, the system is moved back to the equilibrium point (Haraldsson 2004). The identified feedback loops were then discussed with the case study experts, which helped to highlight the potential of the model as a supporting tool.

4 | Results

4.1 | Impact Identification

PSS sustainability assessment is multifaced due to the multidimensionality of PSS offerings and also the multidimensionality of sustainability, which includes economic, environmental and social aspects. To support the identification of service impacts on the TBL dimensions, the brainstorming sessions among authors and the case study experts were supported by a literature review on empirical studies which was used to analyse and describe the factors generating the impacts. All of the involved variables in generating the final sustainability impacts of the after-sales services PS1, PS2 and PS3 are summarised in Tables 2–4. The impact categories are also organised according to the user (U) and servitised manufacturer (SM) points of view (POV), indicating which organisation bears each specific impact. The tables also show their final polarity, + or −, that is, anticipating the increasing or decreasing nature, respectively, of the services' impact on sustainability detailed in Section 4.2. Appendix A (Tables A1–A3) presents three tables providing more details of how the three selected product-service offerings affect the TBL's impact categories.

The results show how, considering the economic dimension, after-sales services offered for LV and MV electrical equipment affect *costs* and *revenues*. In general, these product-oriented services are crucial to reducing the *cost of ownership* for the U. Since we are in a B2B setting, they are essential to preventing electrical equipment downtime and lost revenues and as a mechanism through which B2B customers can be helped to improve their productivity and revenues over time. This is verified with case study insights and supported by the literature (Blüher et al. 2020; Szwejczewski et al. 2015). Moreover, these product-oriented services are sources of increased revenues for the provider. *Energy consumption*, *material consumption*, *waste generation* and *CO_2 emissions* are representatives of the environmental dimension. Generally, product-oriented services lower the reported impact categories, although some exceptions will be detailed later in the study. PSS social impacts have received less attention than the other two dimensions of the TBL in the literature (Spadafora and Rapaccini 2024). However, we can observe that social indicators, such as *health and safety*, *staff development* and *job creation*, are affected by PSS adoption.

4.2 | Development of the Causal Loop Diagram

As mentioned earlier, all impacts were initially modelled in three separate CLDs, one for each TBL dimension. Each CLD model shows the three product-related services—care, advisory, and modernisation services. The linkages corresponding to these services are coloured differently and framed within the phases of the lifespan in which they are generated, namely Beginning of Life (BoL), Middle of Life (MoL), and End of Life (EoL).

TABLE 2 | List of variables affecting the economic sustainability impact categories involved by the adoption of after-sales services.

References	Involved variables	Impact category	POV	Polarity
(Holgado et al. 2020; Jasiulewicz-Kaczmarek et al. 2021; Mokhtari et al. 2012; Mourtzis et al. 2018; Szwejczewski et al. 2015; Xing et al. 2013)	Asset reliability; failure; unplanned downtime; asset availability; asset degradation; material efficiency; valuable operating time	Revenues	U	(+)
(Blüher et al. 2020; Bressanelli et al. 2018; Franciosi et al. 2020; Holgado et al. 2020; Kjaer et al. 2019; Mokhtari et al. 2012; Mourtzis et al. 2018; Pueo et al. 2019; Xing et al. 2013; Zhang et al. 2016)	Asset reliability; failure; unplanned downtime; costs of downtime; corrective maintenance demand; corrective maintenance costs; asset degradation; operating and maintenance cost; asset obsolescence; asset disposal; disposal cost	Costs		(−)
	Service purchase cost	Costs		(+)
(Szwejczewski et al. 2015)	Service sales	Revenues	SM	(+)
	Asset obsolescence; asset disposal; asset manufacturing; manufacturing cost	Costs		(−)
(Ho and Chang 2022)	Asset obsolescence; asset disposal; asset manufacturing; asset sales	Revenues		(−)
	Service cost	Costs		(+)

TABLE 3 | List of variables affecting the environmental sustainability impact categories involved by the adoption of after-sales services.

References	Involved variables	Impact category	POV	Polarity
(Aurich et al. 2006; Azcarate-Aguerre et al. 2022; Bressanelli et al. 2018; Franciosi et al. 2020; Holgado et al. 2020; Kjaer et al. 2019; Mourtzis et al. 2018; Pueo et al. 2019; Xing et al. 2013)	Asset reliability; failure; corrective maintenance demand; asset degradation; energy efficiency; energy consumption for asset use	Energy consumption	U	(−)
	Asset degradation; material efficiency; materials consumed for asset use	Material consumption		(−)
(Kjaer et al. 2019)	Asset degradation; material efficiency; wastes from asset use; asset obsolescence; asset disposal; wastes from asset disposal	Waste		(−)
(Glatt et al. 2019)	Energy consumed for service activities; materials consumed for service activities; waste from service activities	Energy consumption, material consumption, waste		(+)
(Franciosi et al. 2020)	Number of travels; fuel consumed for travels; energy consumed for software and/or hardware production	Energy consumption	SM	(+)
(Kjaer et al. 2019)	Raw material component supply	Material consumption		(+)
(Kjaer et al. 2019)	Wastes from software and/or hardware production	Waste		(+)
(Kjaer et al. 2019)	Asset degradation; Asset obsolescence; asset disposal; asset manufacturing; energy consumed for asset manufacturing; raw material component supply; wastes from asset manufacturing	Energy consumption, material consumption, waste		(−)

TABLE 4 | List of variables affecting the social sustainability impact categories involved by the adoption of after-sales services.

References	Involved variables	Impact category	POV	Polarity
(Franciosi et al. 2020; Holgado et al. 2020; Jasiulewicz-Kaczmarek et al. 2021)	Asset reliability; failure; asset degradation; material efficiency; asset obsolescence; energy efficiency; number of injuries	Health and safety	U	(+)
(Holgado et al. 2020)	Number of training activities	Staff development		(+)
(Schröter et al. 2012)	Number of service hours; job creation for the manufacturer	Job creation		(−)
	Number of travels	Health and safety	SM	(−)
(Abramovici et al. 2014; Schröter et al. 2012)	Number of service hours	Job creation		(+)
	Asset degradation; asset obsolescence; asset disposal; asset manufacturing; number of injuries for the asset manufacturing	Health and safety		(+)
	Asset degradation; asset obsolescence; asset disposal; asset manufacturing	Job creation		(−)

Figure 2 shows the economic CLD. Costs and revenues can be summarised into a final impact category—*profit margin*—which is used to represent the actual economic value of the service offerings of company Alpha. An increase in the profit margin can influence decisions of allocating more *incentives* (e.g., *budget*) to the source of profit, which was translated into *availability of resources* for the SM side. Product-oriented services providing value to users, for example, product lifecycle cost reductions or productivity increases, will increase their demand (Rabetino et al. 2017). This can be explained as customer loyalty, usually reflected in customer retention and repurchase intention and behaviour (Han et al. 2024).

Figures 3 and 4 show the environmental and social CLDs, respectively. CO2 equivalent emissions is the final impact category for the environmental model and is mediated by energy consumption, material extraction, and treatment of wastes. As multiple indicators can make interpreting the results difficult, it is good to rely on a well-known/common language to better reflect the comprehensive impact of PSS life cycle on the environment, the carbon emissions (Xiang et al. 2023). Satisfaction of the user is the final impact category for the social model. Generally, product-oriented services are crucial to ensure safety and customer satisfaction (Szwejczewski et al. 2015). Thus, satisfaction of the user was added to the social CLD, and it was directly linked to the health and safety variable (Kretschmar et al. 2023). The same was done for the workers on the SM side, triggering the satisfaction of workers and a consequent increase in the availability of resources due to less absenteeism (Gimenez et al. 2012; Kreye 2016). Here, the social performance gained through the adoption of product-oriented services constitutes the added value that can boost customer loyalty (Martínez León and Calvo-Amodio 2017) and thus the service demand.

At this point, the three models were integrated into a final model representing the holistic vision of the service offerings of company Alpha. The development of the general CLD involved adding new internal connections, establishing interrelationships, and introducing previously undefined nonlinearities (Haraldsson 2004). This process highlighted the existence of feedback loops between sustainability dimensions. Figure 5 shows a simplified CLD of the impacts of services on the TBL dimensions.

Considering the close interaction among TBL dimensions (Onat et al. 2016), we identified the key links that make these interrelations possible.

The economic and environmental dimensions are interrelated by the direct costs of the consumed resources, for example, materials and energy, which depend on the prices of the resources themselves, as well as their indirect/hidden costs, such as virtual prevention costs (Vogtländer et al. 2002) or shadow carbon costs (Azcarate-Aguerre et al. 2022) (named as *pollution prevention costs*). Minimising material and energy usage results in lowered costs (Jasiulewicz-Kaczmarek et al. 2021). In addition to environmental compliance costs, associated compliance expenses for H&S are also present (e.g., fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost) (Franciosi et al. 2020) (named as *social costs*). It is also recognised that improving employee H&S can achieve cost savings from less absenteeism and fewer industrial accidents (Gimenez et al. 2012). These specific costs are named *social costs*, following (Franciosi et al. 2017). These 'soft costs' are also incorporated into the CLD to present a comprehensive and systemic picture. The economic and social dimensions are connected by the link between the *satisfaction of the user* and *user revenues*. This was added because higher employee satisfaction can be associated with better productivity and firm performance (Krekel et al. 2019; Kurtz et al. 2025). The environmental and social dimensions are directly interrelated since the amount of pollution directly affects the human health status (Onat et al. 2016) or quality of life (Alfarisi et al. 2023).

The simplified complete CLD shows that the three sustainability dimensions interact and coexist simultaneously. The new links are represented with thick black arrows in Figure 5. By combining the three CLDs, we also observe how the sustainability performance of the services impacts demand. The connection between the SM's gains and U demand is highlighted, showing conditions for a win-win outcome for all involved. It is clear that a customer's

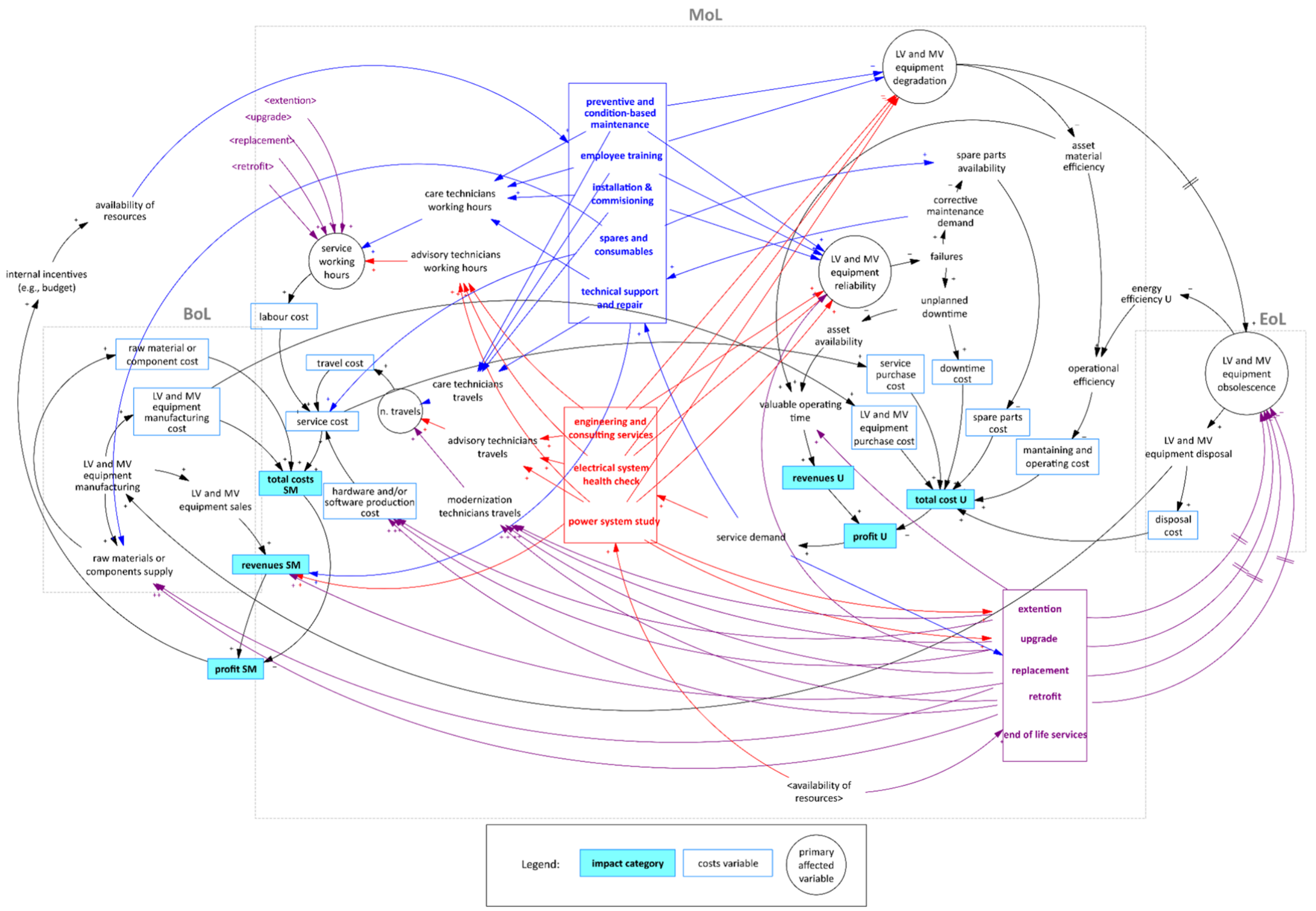

FIGURE 2 | CLD representing the impacts of product-oriented services (PS1a and PS1b care services, PS2 advisory services, and PS3 modernisation services) on the economic dimension of the TBL and the life cycle phase (i.e., BoL, MoL, EoL) when these impacts occur.

economic, environmental, and social performance can drive market value for the SM, expanding its customer base and scaling up service demand.

4.3 | Analysis of the Causal Loop Diagram: Feedback Loops

Finally, reinforcing and balancing loops were identified in the CLD. The loops were examined based on the type of service to help visualise and identify them. For this purpose, individual models featuring all TBL dimensions were created for each service type. This allowed observing that the TBL dimensions are influenced by both reinforcing and balancing loops caused by the service provision. The analysis of the individual loops identified the POV from which they were considered and an emerging thematic typology for the loops. In the remainder, we use the CLD representing the TBL impacts of PS1 as an example, while the complete analysis of all identified reinforcing and balancing loops across all service types is reported in Appendix B (Tables B1 and B2) and Appendix C (Tables C1 and C2).

Figure 6 depicts all the reinforcing loops aggregated and described in Table 5. We identified six reinforcing loop types: asset availability (R1a–R1d), operational efficiency (R2a–R2c), longevity (R3a–R3e), sustainability benefits (R4a–R4h), word of mouth (R5), and service profitability (R6). These loops demonstrate how service purchases by Alpha's customers enhance user value (efficiency, sustainability, and cost savings), and how service delivery by company Alpha improves provider outcomes (profits, customer attraction), highlighting the benefits for both parties in terms of environmental, economic, and social aspects.

Figure 7 shows the identified balancing loops for the same represented system, which were categorised in Table 6 in service efforts (B1a, B1b), service footprint (B2a–B2d), soft sustainable costs (B3a–B3f), and asset sales (B4). These loops illustrate how services negatively influence profits and costs for both parties, including the environmental and social dynamics.

5 | Discussion

Thanks to the use of the CLD, a systems thinking tool, this study identifies the main variables at the core of the interdependencies between TBL impacts and the effects on the TBL sustainability dimensions of different services in the ecosystem, even those that are not directly/intuitively related to each other. The tensions within each dimension and across dimensions are observable under the paradox lens via the identified balancing loops in the model. The following sections discuss our findings.

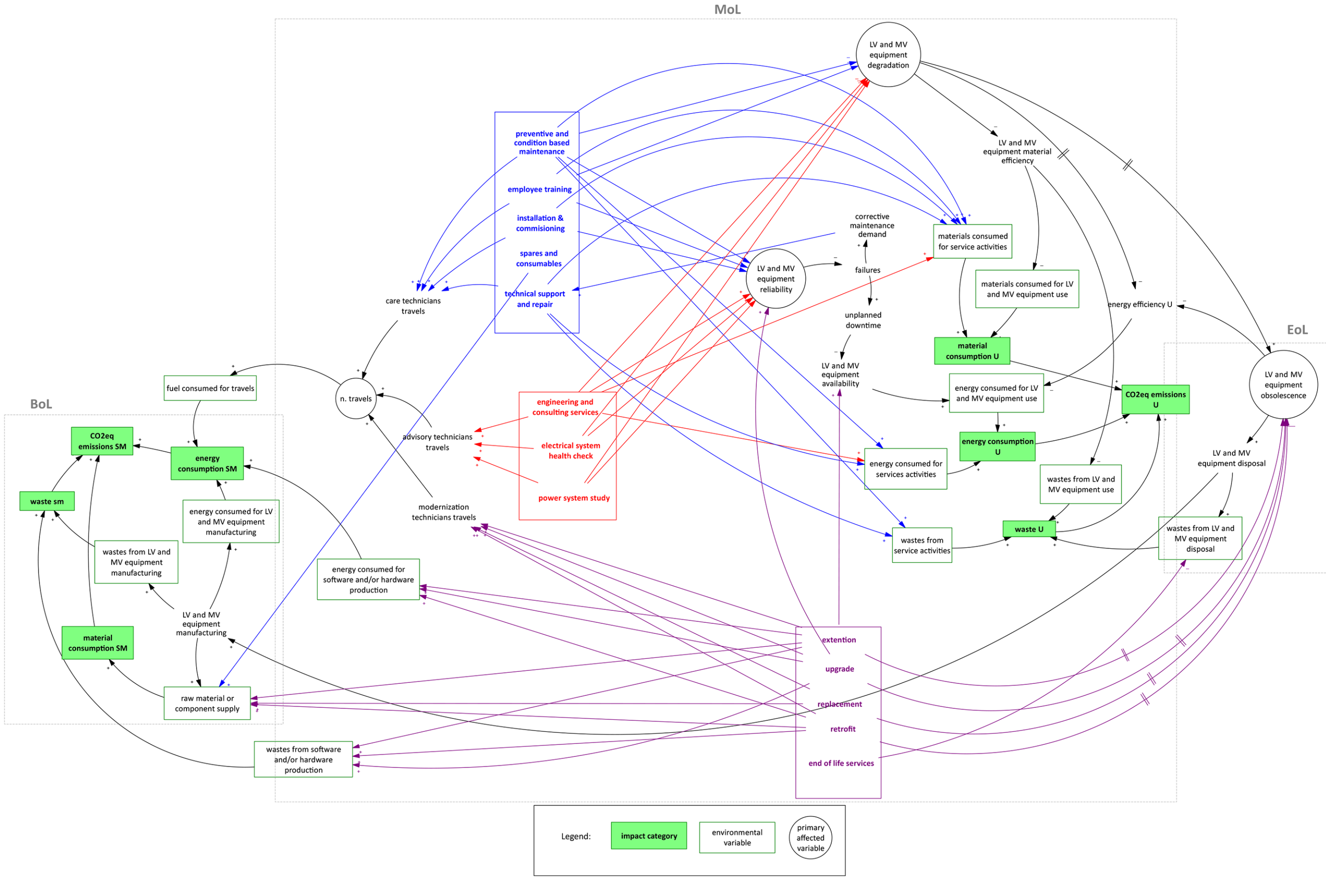

FIGURE 3 | CLD representing the impacts of product-oriented services (PS1a and PS1b care services, PS2 advisory services, and PS3 modernisation services) on the environmental dimension of the TBL and the life cycle phase (i.e., BoL, MoL, EoL) when these impacts occur.

5.1 | TBL Interdependencies

The identified interdependencies were traced back to three key *asset-related* variables that connect value creation in B2B services across life cycle phases: (1) asset *reliability*, (2) asset *degradation*, and (3) asset *obsolescence*. The reliability of LV and MV electrical equipment was identified as a key factor connecting user revenues, cost variables, environmental indicators, and user H&S. It influences the failure rate, asset availability, and valuable operating time for the user. LV and MV electrical equipment degradation was identified as the link between user revenues, environmental indicators, and user H&S due to its influence on material efficiency. LV and MV electrical equipment obsolescence links user energy consumption and H&S via energy efficiency, and connects SM revenues and cost variables with environmental and social indicators (i.e., H&S of employees and job creation) due to its indirect influence on the electrical equipment manufacturing variable.

The analysis of interdependencies also revealed four key *service-related* variables that should be considered in value-creation mechanisms for B2B services, as they have a direct impact on service costs and resources consumed or waste generated during service activities. These are (1) the *working hours* needed, (2) the *number of travels* needed, (3) the *resources (energy and materials) consumed* during the service activities and (4) the *waste* generated in delivering the service. Working hours affect manufacturer costs and job creation. Service travels impact manufacturer costs, energy consumption and employee H&S, linking economic, environmental, and social dimensions. Service activities consume natural resources and produce waste, both of which incur costs and act as connectors between environmental and economic dimensions. These variables are mainly responsible for lowering the overall sustainability benefits (service footprint balancing loops, B2a–B2d), except in the case of job creation, which benefits from increasing service working hours.

Finally, two *context-related* variables, that is, the soft costs, were identified: (1) the *pollution prevention cost* and (2) the *social cost*. Pollution prevention cost connects CO_2 equivalent emissions with total costs for both manufacturer and user. Similarly, social cost links H&S with the total costs. Both are highly dependent on the context in which companies operate, varying by product, sector or even country, as they reflect regulatory environmental and social costs. These variables enhance sustainable value in PSS configuration (soft sustainable benefits loops, R4a–R4h) but also cause tensions that drive balancing impacts on the TBL (soft sustainable cost loops, B3a–B3f). Since they are strictly related to the application context, the case study did not explore additional factors that may be involved in the generation of such hidden costs in depth. This also does not influence the generalisation of the model.

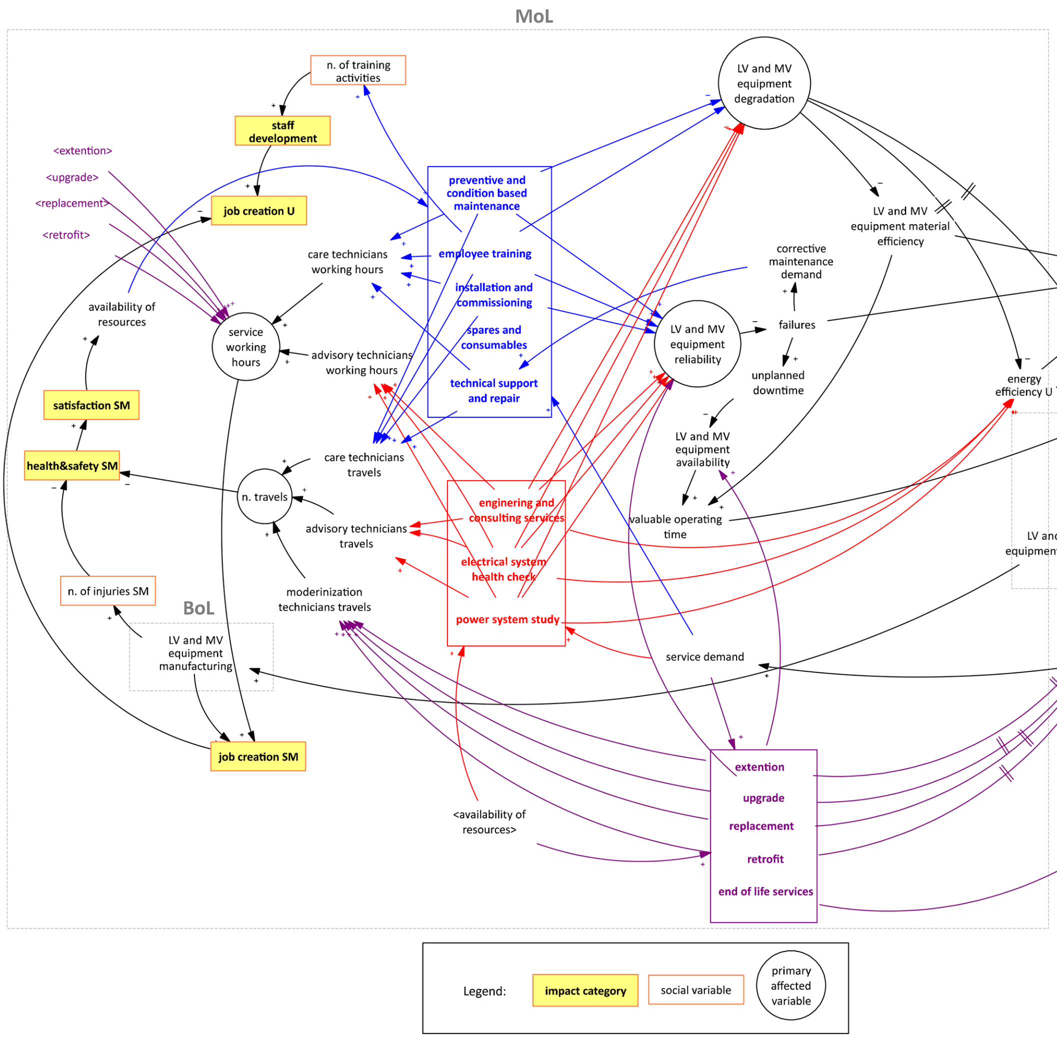

FIGURE 4 | CLD representing the impacts of product-oriented services (PS1a and PS1b care services, PS2 advisory services, and PS3 modernisation services) on the social dimension of the TBL and the life cycle phase (i.e., BoL, MoL, EoL) when these impacts occur.

5.2 | PSS TBL Dynamics: Added Value and Tensions Affecting Value Creation

Product-oriented services directly influence asset-related variables and are key drivers for guaranteeing asset availability, operational efficiency and longevity, as shown by the reinforcing loops (R1a–R1c, R2a–R2c, R3a–R3e). These loops illustrate how service adoption enhances PSS provider outcomes (e.g., profits, customer attraction) while delivering environmental, economic, and social benefits. Preventive maintenance, for instance, allows the SM to boost revenues, enhance asset availability and operational efficiency, extend asset life, and deliver better sustainability and cost savings—factors that help attract and retain customers. Among the reinforcing loops, both the user (B1a–B1c, B2a–B2c, R3a, R3b) and SM's (R3b–R3e) perspectives and central. Both parties benefit from the added sustainable value of product-oriented PSS, and the customer perspective is fundamental to ensuring greater diffusion and higher sustainability potential of the PSS offering. This shared value aligns with findings in the literature (e.g., Ruiz-Alba et al. 2024).

While asset availability is already recognised as an important indicator of value creation (Lay et al. 2009), operational efficiency and longevity are often credited only for their resource-saving role, especially for assets with long life cycles like machinery and equipment (Kjaer et al. 2019). Our findings suggest that all three—availability, operational efficiency, and longevity—are equally significant enablers of value creation in B2B settings, contributing to profit growth, social benefits, and resource and emissions reduction.

The model also reveals balancing loops illustrating how services can raise costs and lower profits for both manufacturer and user, reflecting environmental and social dynamics. It highlights PSS paradoxes suggested in the literature. For example, service efforts balancing loops (B1a and B1b) and asset sale losses balancing loop (B4) show how extending asset life can reduce revenues from asset sales. This is related to the service paradox and its underlying tensions: while services stabilise the company's revenues through recurring income over the product's life cycle, they also introduce higher costs and risks (Gebauer et al. 2005; Kohtamäki et al. 2020). The user viewpoint is key here, as it can influence the

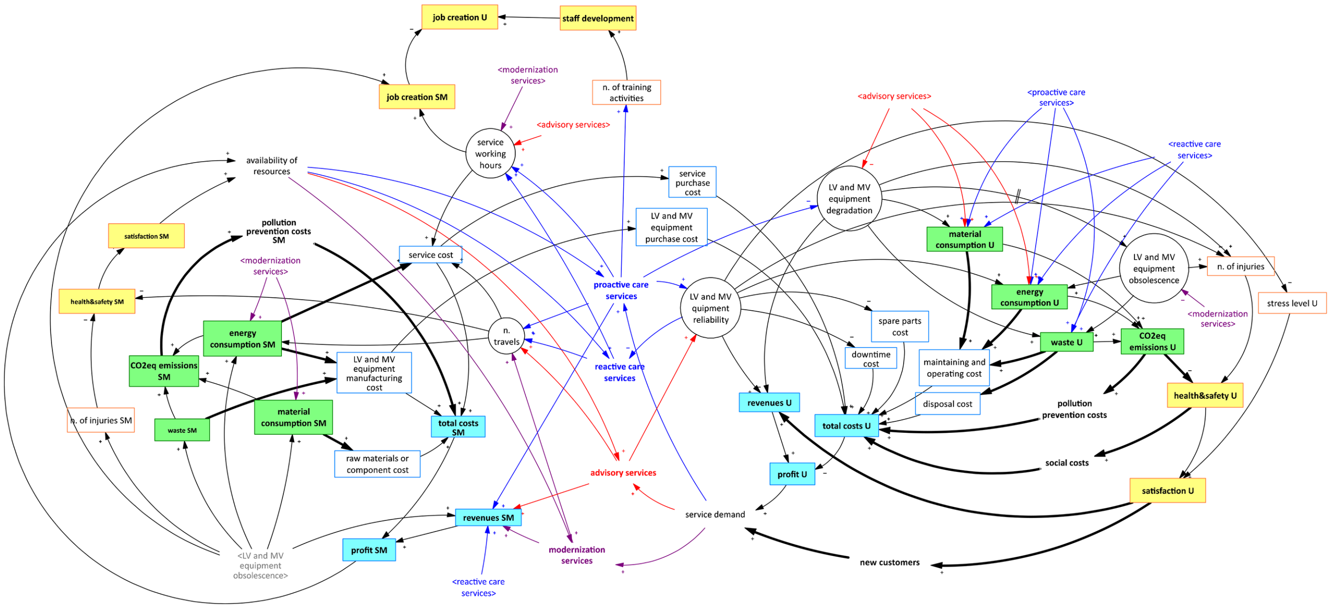

FIGURE 5 | Simplified CLD modelling the TBL impacts of product-oriented services (PS1a and PS1b care services, PS2 advisory services, and PS3 modernisation services). 'Shadow variables' represented as '<variable name>' replicate existing variables in the CLD to reduce overlapping links and enhance comprehension.

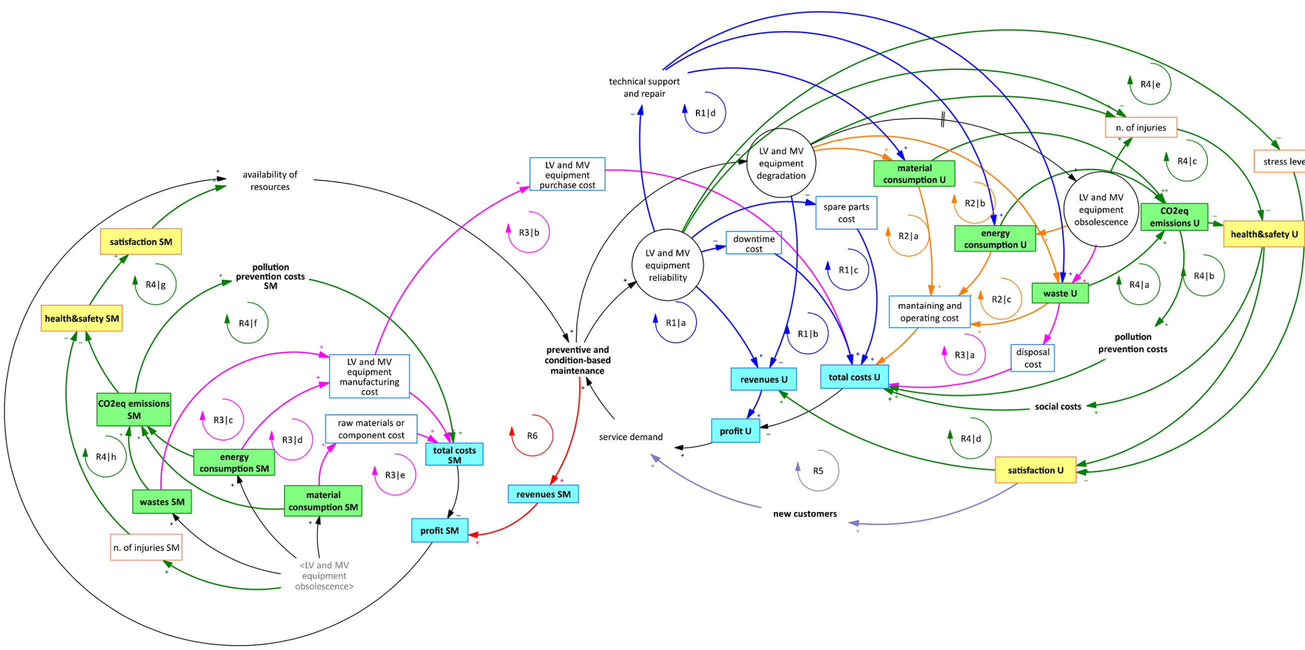

FIGURE 6 | Reinforcing loops representing systematic growth or decline of the TBL impacts of product-oriented services.

demand for services (B1b, B2a, B2b, B2c, B3a, B3b, and B3c) and thus impact the company's revenues. The SM must balance these risks, including higher service labour costs in PSS configurations. The model shows that resolving the service paradox depends on delivering real value to the customer, as reported by Vezzoli et al. (2015), for example, through innovative retrofit services that extend the asset life and improve their sustainability performance (Ho and Chang 2022). While this may reduce the asset replacement rate (Ho and Chang 2022), it does not fully undermine new components production or innovation. Customer loyalty, driven by profit, CO_2 equivalent emissions reduction, and satisfaction, is crucial to overcoming the service paradox.

The model also accounts for rebound effects (Kjaer et al. 2019). Offering services that lower customer costs and environmental impacts can drive up service demand, and since they are not zero-emission, this can increase the environmental footprint (service footprint balancing loops B2a—B2d). These rebound effects directly stem from added services/processes in the PSS configuration (Kjaer et al. 2018). It is worth highlighting that

TABLE 5 | Reinforcing loop typologies and descriptions.

Loop typology	Loop ID	POV	Loop description
Asset availability loops	R1a	U	They reinforce the added value for the asset user through improved asset *reliability* and decreased asset *degradation*, which help increase the *valuable operating time*, *productivity* and thus the *revenues of the user* (R1a). The loops also include decreasing the costs associated with unplanned *downtime* and other hidden *costs of corrective maintenance* (R1b, R1c, R1d).
	R1b	U	
	R1c	U	
	R1d	U	
Asset operational efficiency loops	R2a	U	They reinforce the added value for the asset user due to the increased *resource efficiency* of the asset during its use phase. Here, the moderating role of the services on asset *degradation* lowers the *resource consumption* during the use phase of the asset, directly decreasing *operating & maintenance costs* (R2a, R2b, R2c). We can observe how the introduction of product-oriented services generates the sustainability added value for the user.
	R2b	U	
	R2c	U	
Asset longevity loops	R3a	U	They describe the reinforcing effects of postponing asset *obsolescence* on the user (R3a, R3b) and provider *profits* (R3b, R3c, R3d, R3e) mediated by the provision of the services. As previously, within these loops, introducing the services lowers *resource consumption* and associated *costs* (i.e., the environmental and economic dimensions).
	R3b	SM, U	
	R3c	SM	
	R3d	SM	
	R3e	SM	
Soft sustainable benefits loops	R4a	U	They represent the reinforcing effects of avoided regulations on sustainability aspects (*CO_2 emissions* and *health and safety*), which lower both user and provider *costs* (R4a, R4b, R4c, R4f) and increase workers' *satisfaction* on *revenues* (R4d, R4e) and *availability of resources* (R4g, R4h). Within these loops, both the user and the servitised manufacturer perspectives are involved. Soft sustainable benefits loops simultaneously include the three dimensions of the TBL.
	R4b	U	
	R4c	U	
	R4d	U	
	R4e	U	
	R4f	SM	
	R4g	SM	
	R4h	SM	
Word of mouth loops	R5	U	They represent the reinforcing effect on service demand of the environmental and social benefits as a result of attracting new customers (R5).
Service profitability loops	R6	SM	They represent the reinforcing effect of the *sales of services* on *revenues* and *profits* for the PSS provider as a result of the adoption of PSS offerings (R6).

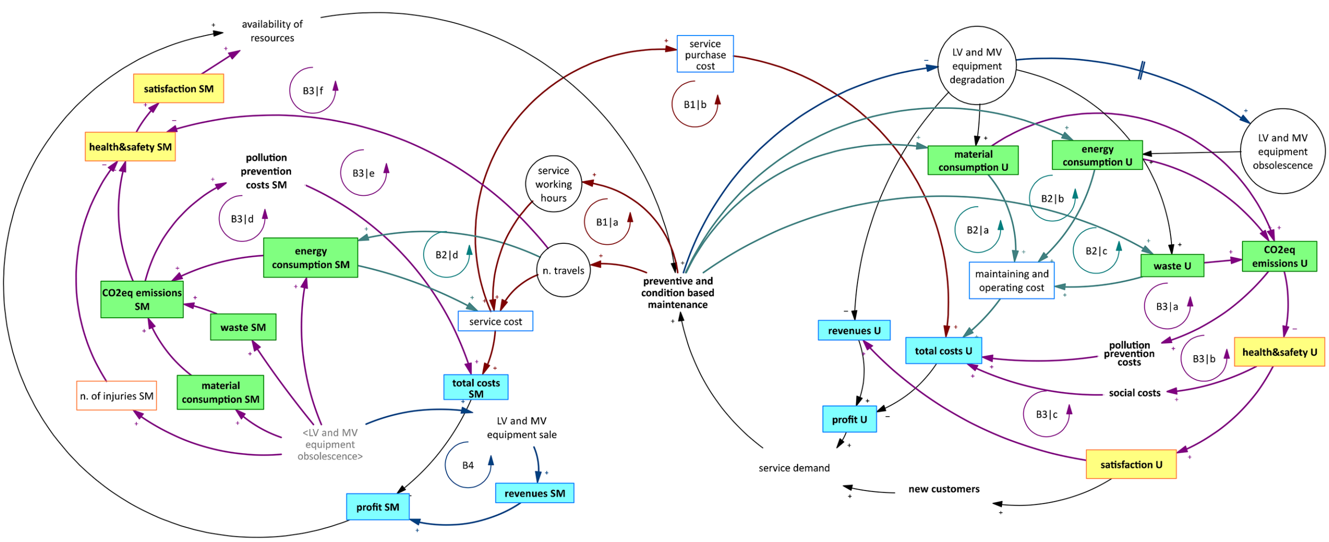

FIGURE 7 | Balancing loops representing side effects on the TBL impacts of product-oriented services.

rebound effects can be influenced by factors like lower product prices or user preferences and consumption behaviours (Guzzo and Pigosso 2024), but they are mainly studied in use-oriented and result-oriented PSS configurations (Alfarisi et al. 2023; Metic et al. 2024). Our study confirms and shows how rebound effects inevitably occur also with product-oriented services.

TABLE 6 | Balancing loop typologies and descriptions.

Loop typology	Loop ID	POV	Loop description
Service efforts loops	B1a	SM, U	They represent the balancing effect mediated by the services on the added economic value (i.e., profits) for both the servitised manufacturer (B1b) and the user (B1a) because of the direct increase in the service cost.
	B1b	SM	
Service footprint loops	B2a	U	They describe the decreasing effects of resources consumed and waste generated directly by services during their development and delivery. These effects affect the costs and profits of the user (B2a, B2b, B2c) and the serviced manufacturer (B2d).
	B2b	U	
	B2c	U	
	B2d	SM	
Soft sustainable cost loops	B3a	U	They represent the reducing effects of sustainability regulations (due to CO_2 *emissions* and *health and safety*) on both user (B3a, B3b) and provider (B3d) *costs*, as well as the effects of decreased workers' *satisfaction* on user *revenues* (B3c) and *availability of resources* (B3e, B3f).
	B3b	U	
	B3c	U	
	B3d	SM	
	B3e	SM	
	B3f	SM	
Asset sale losses loops	B4	SM	They refer to the decrease in asset manufacturing activity postponed by the services on the servitised manufacturer's *revenues* and the consequent loss from new *asset sales* (B4).

TABLE 7 | Area of decision-making enabled by the developed CLD.

Area	Benefit	Description
Systemic vision	Understanding interconnections among variables	Help visualise how services simultaneously impact costs, revenues, environmental and social dimensions.
Trade-off management	Anticipating tensions between objectives	Supports the definition of balancing strategies between economic, environmental, and social benefits.
Scenario-based decision support	Qualitative simulation of strategic alternatives	Facilitates more robust decision-making by exploring the effects of different service scenarios.
Communication and internal alignment	Effective internal communication tool	Makes complexity visible to various stakeholders, fostering alignment on sustainable strategies.

Finally, while this work focuses on product-oriented services, we argue that the proposed CLD model can be easily adapted to use- and result-oriented configurations where the SM retains the asset ownership. Some of the links should be revised to align the model with use- and result-oriented configurations. These links are particularly associated with cost sources for the user, such as asset purchase, which would no longer exist (only service charges would remain), and asset disposal expense, which should fall under the provider's responsibility. This adaptation is key to address the need to understand the impact of the lack of ownership change on the value creation mechanism (Gnoni et al. 2017) and sustainable PSS paradoxes.

5.3 | Decision-Support Towards Higher Sustainable Value in PSS

The developed CLD and findings regarding synergies and tensions generated by product-oriented services helped reinforce the potential of this qualitative tool to comprehensively and simultaneously provide a systemic vision of the impacts of different service categories on the TBL dimensions, highlighting interconnections among variables, while anticipating tensions between economic, environmental, and social dimensions. This can enable a more conscious management of trade-offs and win-win situations in designing and delivering service offerings, such as a more effective preventive maintenance planning to reduce the number of travels impacting negatively on sustainability dimensions. The tool allows for qualitatively visualising the effects of different service scenarios on sustainability dimensions while facilitating communication of TBL impacts of services that can be used as leverage points internally for business development and externally for customer acceptance.

Overall, the CLD model serves as a valuable tool for decision-makers to navigate PSS complexity, anticipate sustainability tensions and trade-offs, and align service offerings with long-term corporate and regulatory objectives towards sustainability. Table 7 summarises the key benefits of using the CLD model in a managerial context, highlighting its potential to guide effective planning and alignment of business strategies with sustainability goals. These benefits were discussed and consulted with experts from the case study.

6 | Conclusions

PSS business models are seen as strong contributors to economic, environmental and social sustainability. However, their TBL benefits and impacts are often questioned in the literature, which suggests the presence of tensions and paradoxes when dealing with PSS sustainability. Addressing this challenge requires moving beyond isolated sustainability assessments and adopting a systemic perspective capable of capturing the complex interdependencies among sustainability dimensions and stakeholders within PSS ecosystems. To address this need, this study developed a CLD model for product-oriented PSS configurations in a B2B context, incorporating systems thinking, life cycle thinking and paradox theory.

6.1 | Theoretical Contributions

From a theoretical perspective, this work results in three key contributions. First, the proposed CLDs model reveals the key interdependencies linking economic, environmental, and social outcomes, addressing RQ1. Previous works focused more on the environmental impacts generated by PSS and neglected the interplay with the other dimensions. Most studies link the TBL dimensions through the use of PSS sales as a key variable, but this approach fails to capture the true nature of sustainability. In our model, we identify eight key connecting variables related to the asset, the service and the context that are at the core of the interdependencies between impact categories in all TBL dimensions: asset reliability, asset degradation, asset obsolescence, number of travels, energy and material consumption, waste, pollution prevention cost and social cost. In particular, asset reliability, degradation, and obsolescence emerged as critical mechanisms connecting profitability, resource efficiency, emissions, and health and safety outcomes across the ecosystem. These variables act as main drivers of sustainable creation in PSS context and are also involved in generating tensions. This leads to the second contribution of the study. Addressing RQ2, the findings further demonstrate that product-oriented PSS offerings generate sustainable value through reinforcing feedback mechanisms associated with asset availability, operational efficiency, and longevity (i.e., reinforcing loops show synergies between variables and TBL dimensions), while simultaneously creating balancing dynamics that reflect service paradoxes, rebound effects, and sustainability trade-offs. This causal understanding contributes to reaching the full potential of sustainability-oriented actions (Guzzo et al. 2024). Considering that there are other less well-known paradoxes emerging from the discussion around PSS sustainability (Hahn and Pinkse 2022), this work may represent the basis for displaying and understanding these other tensions.

By making these dynamics explicit, the current study reinforces the ability of system thinking (and CLD as a qualitative tool) to assess the sustainability of PSSs and capture the TBL dimensions comprehensively. Other CLDs can be found in the literature but the developed CLD is able to capture simultaneously the TBL dimensions through a comprehensive list of sustainability impact categories brought together from the direct involvement of case study experts and the PSS literature, and unified into a final impact category for each TBL dimension. The model also captures the unintended consequences (via reinforcing and balancing loops), considering different stakeholders of a PSS ecosystem, and with a level of detail that models the life cycle services for product-oriented PSS, and not generic PSS or use-oriented ones as mainly done by existing studies. Thanks to the combination of the direct observations from the single case study and the literature review to enlarge the generalisation of the behaviours using other case studies from the literature, this study presents a novel CLD that can be applied across different manufacturing B2B contexts.

6.2 | Managerial Contributions

The harsh reality that PSS is not sustainable by default but could be designed to be sustainable (Roman et al. 2023) is demonstrated by the CLD model, as it identifies balancing loops affecting the performance of the TBL dimensions. As defined by paradox theory, the first step in resolving tensions is accepting them, as this enables more complex and challenging resolution strategies (Smith and Lewis 2011). Addressing RQ3, feedback from industry practitioners involved in the case study suggests that the proposed CLD provides the necessary systemic vision to make explicit the feedback structure underlying PSS dynamics and the existence of tensions. Therefore, CLD is appropriate for assisting in decisions aiming to align after-sales services, as part of a PSS configuration, with sustainability objectives. The proposed CLD represents a supporting tool for managers to identify synergies, trade-offs and leverage points, helping to scale up the PSS offerings without having detrimental effects on any of the TBL dimensions. Nevertheless, the CLD is valuable for internal communication, helping to connect the service business portfolio to the sustainability strategy. It also serves marketing purposes, engaging both prospective and existing customers.

6.3 | Limitations and Future Studies

The model's adaptability in different PSS scenarios and the resolution of limitations due to the system boundaries used in this study should be tested through additional case study applications, which will strengthen the generalisation of the identified relationships in the CLD and also will help find some more variables. Despite the fact that theoretical generalisation does not always require a multiple-case design, the "evidence from multiple case studies is often considered more compelling" than a single one (Tsang 2014). Therefore, future developments should address the involvement of varied industrial contexts to consolidate a generic but also service-specific and detailed enough CLD. For instance, it could be helpful to broaden the service offerings included in the model, i.e., investigate use-oriented and result-oriented configurations targeting, for example, asset availability or asset operational efficiency, and expand the model to include other possible stakeholders with an interest in and influence over the service provision, such as partners acting on behalf of the asset manufacturer to provide the services, but also governments, communities, and society at large scale which are relevant stakeholders in PSS (Delgadillo et al. 2021). This would lead to incorporating and simulating the role of policy in the model, which constitutes another limitation of the actual model. Future developments building on this work may precisely address this limitation.

The next phase, in accordance with Sterman's instructions, would be to create a stock and flow diagram that would statistically recreate the dynamics and feedback found in the CLD. This final stage will be undertaken in future phases of the study, once all necessary data have been gathered to minimise uncertainty in the results.

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Appendix A

TABLE A1 | Impacts of product-oriented services on the economic dimension of the TBL.

Product-oriented service	Description	Impact category	POV	Polarity
Care services (PS1)	Preventive and condition-based maintenance can increase asset *reliability* during its use phase, which increases the *availability* of the asset itself (Holgado et al. 2020; Mourtzis et al. 2018; Xing et al. 2013). According to the concept of reliability, the availability of an asset is related to its *failure rate*, and if preventive maintenance services are performed on the asset, its availability will increase (Mokhtari et al. 2012). Preventive and condition-based maintenance also influences asset *degradation* and increases *material efficiency* of the asset that forms the basis for good final products (Holgado et al. 2020). Increased asset availability and quality increase the *valuable operating time*, which positively affects asset productivity potential (Jasiulewicz-Kaczmarek et al. 2021) that can be transformed into revenues. In the B2B setting specifically, these after-sale services are essential to preventing *downtime* and lost revenues (Szwejczewski et al. 2015).	Revenues	U	(+)
	Preventive and condition-based maintenance, as well as user training, can increase asset *reliability* during its use phase, leading to reduced hidden costs or unexpected costs, such as *costs of downtime* and *corrective maintenance costs*, for the customer due to the failure (Franciosi et al. 2017; Holgado et al. 2020; Mokhtari et al. 2012; Xing et al. 2013). Maintenance and higher uptime contribute most to the cost savings economic indicator (Till Blüher et al. 2020; Mourtzis et al. 2018).	Costs		(−)
	Maintenance can lead to assets staying in use for a longer time, thereby prolonging their lifetime (Bressanelli et al. 2018; Kjaer et al. 2019). This means postponing the fast replacement of assets (mass consumption) due to *obsolescence* (Kjaer et al. 2019), thus postponing the *disposal cost*.	Costs		(−)
Advisory services (PS2)	Advisory services can increase both *asset reliability* and *asset degradation*, which increases the *asset availability* and the overall *valuable operating time* of the asset. After-sales services deliver top productivity (Szwejczewski et al. 2015), leading to an increase in the user's *revenues*.	Revenues		(+)
	Advisory services can support more economical product usage, e.g., in terms of reduced *operating & maintenance costs* (Aurich et al. 2006). Such knowledge shared with the user allows the firm to improve product quality and thus reduce production costs (Zhang et al. 2016).	Costs		(−)
Modernization services (PS3)	Upgrades and retrofitting extend the lifespan of the asset by delaying its obsolescence and thus allows old assets to remain competitive (Pueo et al. 2019). As a result, asset disposal and replacement is postponed over time (Bressanelli et al. 2018; Kjaer et al. 2019). Choosing to retrofit an *obsolescent* asset means less investment compared to a new asset purchase (Pueo et al. 2019). Therefore, the customer can save money by avoiding costs related to complete product substitution/replacement.	Costs		(−)
	Upgrades and retrofitting can increase *resource efficiency* (e.g., energy) during the middle of life (Bressanelli et al. 2018), thus decreasing *operating & maintenance costs*.	Costs		(−)
All	All services are not for free; therefore, the customer has to pay for the purchased product-oriented service. This has a direct impact on the total *costs*.	Costs		(+)
Modernization services (PS3)	Modernization services reduce new *asset manufacturing* activity and thus lowers the total *costs* of the servitised manufacturer.	Costs	SM	(−)
	Modernization services reduce new *asset manufacturing* activity because the asset owner is less willing to buy new products if more newly invented products can be added to the used products to improve their quality (Ho and Chang 2022). Thus, the *revenue* generated by the sale of a new asset is lower.	Revenues		(−)
All	After-sale services can generate high *revenues* because of repeated sales (Szwejczewski et al. 2015).	Revenues		(+)
	All services are not free for the manufacturer, who has to display resources (materials, equipment, employees, etc.) for the provision of the service, increasing the total *costs* of the servitised manufacturer	Costs		(+)

TABLE A2 | Impacts of product-oriented services on the environmental dimension of the TBL.

Product-oriented service	Description	Impact category	POV	Polarity
Care services (PS1)	Preventive and condition-based maintenance can increase *asset reliability* during its use phase (Xing et al. 2013) and reduces the need for *corrective maintenance* or repair. Thus, it has environmental impacts through the reduction of corrective maintenance actions that generally require the replacement of the component or product (depending on the gravity of the failure), and preventive maintenance contributes to lower *consumption* and *waste*.	Energy consumption, material consumption, waste	U	(−)
	Preventive and condition-based maintenance can improve asset performance, such as by reducing leakages or unwanted dispersion of air/gases (Holgado et al. 2020), which is translated into lower *energy consumption*.	Energy consumption		(−)
	Preventive and condition-based maintenance can improve the ability to process the input materials of the asset by reducing their *degradation* (Holgado et al. 2020). This increases the *material efficiency* and reduces both material consumption and scrap generation (i.e., *waste*) from the production operations (Holgado et al. 2020).	Material consumption, waste		(−)
	Maintenance can lead to the products staying in use for a longer time, thereby prolonging their lifetime (Bressanelli et al. 2018; Kjaer et al. 2019). This means postponing the fast replacement of assets due to *obsolescence* (Kjaer et al. 2019) and reducing the *wastes* generated at asset *disposal*.	Waste		(−)
	Maintenance is not carried out without the following: consuming *energy* for the use of maintenance equipment, consuming *materials* and generating *wastes* derived from the eventual replacement of a malfunctioning component (Franciosi et al. 2020).	Energy consumption, material consumption, waste		(+)
Advisory services (PS2)	Advisory services positively affect *efficient operations*, which leads to a significant reduction of the overall amount of *consumed resources* (Aurich et al. 2006; Kjaer et al. 2019).	Energy consumption, material consumption		(−)
	Advisory services implies the use of a supporting tool, such as computers and video projectors at the customer site (Moritz F. Glatt et al. 2019), or a specific training centre, which increases *energy consumption*.	Energy consumption, material consumption		(+)
Modernization services (PS3)	Retrofit is seen as strong contributors to a more sustainable performance (Aurich et al. 2006; Mourtzis et al. 2018). Retrofit solutions can be used to increase *energy efficiency* and thus lowering *energy consumption* (Azcarate-Aguerre et al. 2022; Bressanelli et al. 2018; Pueo et al. 2019).	Energy consumption		(−)
	By replacing an obsolescent component with a new and updated one, PS3 reduces the need for complete asset replacement and disposal (Kjaer et al. 2019), thus reducing waste.	Waste		(−)
Care services (PS1)	Maintenance is not carried out without consuming fuel for the travel of maintenance technicians and, consequently, generating *emissions* (Franciosi et al. 2020).	Energy consumption, CO_2 emissions	SM	(+)
	Maintenance reduces the need for producing new assets by ensuring asset longevity (Kjaer et al. 2019). This means reducing *resource consumption* and *waste* generation for new asset manufacturing.	Energy consumption, material consumption, waste		(−)
Advisory services (PS2)	Depending on the site at which it is performed, PS2 is not carried out without consuming *energy*, e.g., electrical energy for PC utilisation or fuel for the travel of technicians.	Energy consumption		(+)
Modernization services (PS3)	Modernization service solutions should be installed at the customer site, which implies shipping the solution to the customer site, thus generating *emissions*.	Energy consumption, CO_2 emissions		(+)
	To produce the necessary software, hardware and other components for retrofit solutions, the manufacturer consumes *energy and materials* and generates *waste*.	Energy consumption, Material consumption, waste		(+)
	By replacing an *obsolescent* component with a new and updated one, PS3 reduces the need for complete asset manufacturing (Kjaer et al. 2019). This implies a reduction of *resource consumption* and *waste* generation.	Energy consumption, material consumption, waste		(−)

TABLE A3 | Impacts of product-oriented services on the social dimension of the TBL.

Product-oriented service	Description	Impact category	POV	Polarity
Care services (PS1)	Maintenance can increase the *H&S* of workers and equipment by reducing the eventual *number of injuries* arising from the *failure* of one or more components of the asset (Franciosi et al. 2017, 2020; Holgado et al. 2020; Jasiulewicz-Kaczmarek et al. 2021). Particularly, preventive maintenance is essential in areas with hazardous materials to avoid health-related risks (Holgado et al. 2020).	Health and safety	U	(+)
Advisory services (PS2)	Advisory services can increase workers' skills and knowledge and therefore improve the *H&S* of workers.	Health and safety		(+)
	Staff training can increase U's empowerment and career development opportunities (Holgado et al. 2020).	Staff development		(+)
Modernization services (PS3)	Retrofit solutions can increase the *H&S* of the workers by adapting the equipment to current safety legislation (Pueo et al. 2019).	Health and safety		(+)
All	In general, PSS offerings harm the number of jobs on the customer side but increase the *job opportunities* of the PSS provider (Schröter et al. 2012). Therefore, *job creation* of the user is directly linked to *job creation* of the servitised manufacturer.	Job creation		(−)
All	PSS adoption increases *job creation* since the servitised manufacturer should hire workers, train them and provide them to customers (Abramovici et al. 2014; Schröter et al. 2012).	Job creation	SM	(+)
	Moving from a product-centric to service-oriented business indirectly results in restricted *job creation* in the manufacturing phase.	Job creation		(−)
	An increase in the amount of travel due to service interventions can increase travelling-related risks and therefore lower the *H&S* of service technicians.	Health and safety		(−)
	Moving from a product-centric to a service-oriented business can decrease the *number of injuries* that occur in manufacturing activities and can therefore increase the *H&S* of workers.	Health and safety		(+)

Appendix B

Appendix B contains two tables detailing all the individual loops (reinforcing and balancing) that can be found in Figures 6 and 7 of the paper, grouped into the thematic loops typology defined and explained in the paper, and according to the point of view (POV). The tables aim to guide the reader in the identification of the loops inside the CLD.

TABLE B1 | Involved model variables of the reinforcing loops.

Reinforcing loop	ID	Involved model variables	POV
Asset availability	R1a	*Preventive and condition-based maintenance—LV and MV equipment reliability & LV and MV equipment degradation—revenues U—profit U—service demand—preventive and condition-based maintenance*	U
	R1b	*Preventive and condition-based maintenance—LV and MV equipment reliability—downtime cost—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R1c	*Preventive and condition-based maintenance—LV and MV equipment reliability—spare parts cost—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R1d	*Preventive and condition-based maintenance—LV and MV equipment reliability—technical support and repair—energy/material consumption U/waste U—maintaining and operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
Asset operational efficiency	R2a	*Preventive and condition-based maintenance—LV and MV equipment degradation—LV and MV equipment obsolescence—energy consumption U—maintaining and operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R2b	*Preventive and condition-based maintenance—LV and MV equipment energy consumption U—maintaining and operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R2c	*Preventive and condition-based maintenance—LV and MV equipment degradation—waste U—maintaining and operating costs—total costs U—profits U—service demand—preventive and condition-based maintenance*	U
Asset longevity	R3a	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—waste U—disposal costs—total costs U—profits U—service demand—preventive and condition-based maintenance*	U
	R3b	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—wastes SM/energy consumption SM—LV and MV equipment manufacturing cost—LV and MV equipment purchase cost—total costs U—profits U—service demand—preventive and condition-based maintenance*	SM, U
	R3c	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—wastes SM—LV and MV equipment manufacturing cost—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
	R3d	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—energy consumption SM—LV and MV equipment manufacturing cost—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
	R3e	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—material consumption SM—raw materials or components cost—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
Soft sustainable benefits	R4a	*Preventive and condition-based maintenance—LV and MV equipment degradation or LV and MV equipment obsolescence—material consumption U/energy consumption U/waste U—CO2eq emissions U—prevention pollution costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R4b	*Preventive and condition-based maintenance—LV and MV equipment degradation or LV and MV equipment obsolescence—material consumption U/energy consumption U/waste U—CO2eq emissions U—health and safety U—social costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R4c	*Preventive and condition-based maintenance—LV and MV equipment reliability/LV and MV equipment degradation/LV and MV equipment obsolescence—n. of injuries—health and safety U—social costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	R4d	*Preventive and condition-based maintenance—LV and MV equipment reliability/LV and MV equipment degradation/LV and MV equipment obsolescence—n. of injuries—health and safety U—satisfaction U—revenues U—profit U—service demand—preventive and condition-based maintenance*	U
	R4e	*Preventive and condition-based maintenance—LV and MV equipment reliability—stress level U—satisfaction U—revenues U—profit U—service demand—preventive and condition-based maintenance*	U
	R4f	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—wastes SM/energy consumption SM/material consumption SM—CO2eq emissions SM—pollution prevention costs SM total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
	R4g	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—wastes SM/energy consumption SM/material consumption SM—CO2eq emissions SM—health and safety SM—satisfaction SM—availability of resources—preventive and condition-based maintenance*	SM
	R4h	*Preventive and condition-based maintenance (—LV and MV equipment degradation)—LV and MV equipment obsolescence—n. of injuries SM—health and safety SM—satisfaction SM—availability of resources—preventive and condition-based maintenance*	SM
Word of mouth	R5	*Preventive and condition-based maintenance—R4d—satisfaction U—new customers—service demand—preventive and condition-based maintenance*	U
Service profitability	R6	*Preventive and condition-based maintenance—revenues SM—profits SM—availability of resources—preventive and condition-based maintenance*	SM

TABLE B2 | Involved model variables of the balancing loops.

Balancing loop	ID	Involved model variables	POV
Service efforts	B1a	*Preventive and condition-based maintenance—service working hours/n. of travels—service cost—service purchase cost—total costs U—profit U—service demand—preventive and condition-based maintenance*	SM, U
	B1b	*Preventive and condition-based maintenance—service working hours/n. of travels—service cost—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
Service footprint	B2a	*Preventive and condition-based maintenance—material consumption U—operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	B2b	*Preventive and condition-based maintenance—energy consumption U—operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	B2c	*Preventive and condition-based maintenance—waste U—operating costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	B2d	*Preventive and condition-based maintenance—n. of travels—energy consumption SM—service cost—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
Soft sustainable costs	B3a	*Preventive and condition-based maintenance—energy consumption U/material consumption U/waste U—CO2eq emissions U—prevention pollution costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	B3b	*Preventive and condition-based maintenance—energy consumption U/material consumption U/waste U—CO2eq emissions U—health and safety U—social costs—total costs U—profit U—service demand—preventive and condition-based maintenance*	U
	B3c	*Preventive and condition-based maintenance—energy consumption U/material consumption U/waste U—CO2eq emissions U—health and safety U—satisfaction U—revenues U—profit U—service demand—preventive and condition-based maintenance*	U
	B3d	*Preventive and condition-based maintenance—n. of travels—energy consumption SM—CO2 emissions SM—prevention pollution costs—total costs SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM
	B3e	*Preventive and condition-based maintenance—n. of travels—energy consumption SM—CO2 emissions SM—health and safety SM—satisfaction SM—availability of resources—preventive and condition-based maintenance*	SM
	B3f	*Preventive and condition-based maintenance—n. of travels—health and safety SM—satisfaction SM—availability of resources—preventive and condition-based maintenance*	SM
Asset sale losses	B4	*Preventive and condition-based maintenance—asset obsolescence—asset sales—revenues SM—profit SM—availability of resources—preventive and condition-based maintenance*	SM

Appendix C

To reduce the complexity of the visualisation and interpretation of the results obtained from the development of the CLD, the paper displays and discusses the reinforcing and balancing loops of just one of the three main service solutions considered in the study (i.e., preventive and condition-based maintenance). However, this choice was driven by analysing all the services, as reported in the following tables. It can be observed that preventive and condition-based maintenance is the service solution involved in the highest number of loops, followed by advice, training, and consultancy services solutions; while looking at the retrofit solution, the loops decrease.

TABLE C1 | Analysis of the reinforcing loops across all service solutions.

Reinforcing loop	ID	POV	Proactive care services	Reactive care services	Advisory services	Modernization services
Asset availability	R1a	U	√	—	√	—
	R1b	U	√	—	√	—
	R1c	U	√	—	√	—
	R1d	U	√	—	√	—
Asset operational efficiency	R2a	U	√	—	√	—
	R2b	U	√	—	√	√
	R2c	U	√	—	√	—
Asset longevity	R3a	U	√	—	√	√
	R3b	SM, U	√	—	√	√
	R3c	SM	√	—	√	√
	R3d	SM	√	—	√	√
	R3e	SM	√	—	√	√
Soft sustainable benefits	R4a	U	√	—	√	√
	R4b	U	√	—	√	√
	R4c	U	√	—	√	√
	R4d	U	√	—	√	√
	R4e	U	√	—	√	—
	R4f	SM	√	—	√	√
	R4g	SM	√	—	√	√
	R4h	SM	√	—	√	√
Word of mouth	R5	U	√	—	√	√
Service profitability	R6	SM	√	√	√	√

TABLE C2 | Analysis of the balancing loops across all service solutions.

Balancing loop	ID	POV	Proactive care services	Reactive care services	Advisory services	Modernization services
Service efforts	B1a	SM, U	√	√	√	√
	B1b	SM	√	√	√	√
Service footprint	B2a	U	√	√	√	—
	B2b	U	√	√	√	—
	B2c	U	√	√	—	—
	B2d	SM	√	√	√	√
	B2e	SM	—	—	—	√
	B2f	SM	—	—	—	√
	B2g	SM	—	—	—	√
Soft sustainable costs	B3a	U	√	√	√	—
	B3b	U	√	√	√	—
	B3c	U	√	√	√	—
	B3d	SM	√	√	√	√
	B3e	SM	√	√	√	√
	B3f	SM	√	√	√	√
Asset sale losses	B4	SM	√	—	√	√