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A comprehensive framework for circular product-service systems in infrastructure: Enhancing customer-contractor collaboration

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ABSTRACT

Product-service systems (PSS) represent a business model that increases material decoupling and decreases environmental risks while providing customer value. PSS can help realize a more sustainable construction industry, which remains among the largest polluting and waste-generating sectors. Systemic change in the infrastructure sector requires client involvement, which is represented by the government. However, establishing circular PSS is challenging due to the complexities, which need to combine the lifecycle approach, customer-client aspects, new contracting, knowledge transfer, technology, and PSS-specific aspects. It requires ex-ante evaluation of real case studies to increase knowledge and understanding. This article presents a first-of-its-kind framework for infrastructure based on the current literature and analysis of five infrastructure pilots in the Netherlands (bridge deck, digital road lights, guide rails, roads). The final multistakeholder integrated circular PSS framework includes i) lifecycle perspective and circularity, a) materials and b) management, ii) customer-contractor relationship including a) customer-perspective b) co-creation aspects, c) client-customer hierarchy, iii) technology perspective (functions and resources) iv) business aspects such as a) network and b) value creation and retention. The framework allows customer-contractor communication and can serve as decision support. It is applicable to circular PSS where the customer has more involvement in the formulation of PSS.

1. Introduction

With the rise of a plethora of environmental and social issues, the economic system has been put under the microscope. Various new models and solutions have been proposed to solve resource efficiency and waste production. One of the solutions is moving to the service economy, i.e., dematerializing the economy, where material products are considered capital assets, not just consumables, offering products and services with an equivalent level of performance but with a lower environmental footprint (Mont, 2002; Tukker, 2015). Product-service systems (PSS) are one of the proposed models to lower environmental risks while providing value to customers (Apostolov et al., 2018). PSS integrate tangible and intangible elements with various degrees (Belkadi et al., 2020). In 2004, Tukker famously distinguished three types of PSS depending on the level of product dependency: a) product-oriented, such as consultancy; b) use-oriented, such as product renting or leasing; and c) result-oriented, such as the pay-per-service unit. For both consumers and producers, PSS might involve a change in property rights (Mont, 2002). However, Tukker himself pointed out a wide range of PSS sub-classifications and dimensions that characterize PSS in his review ten years later (Tukker, 2015). This also included controversies that PSS does not automatically lead to environmental benefits or circularity (Kjaer et al., 2019; Tukker, 2015). And while customers are at the heart of PSS, PSS oriented at the customers' perspective is lacking (Schmidt et al., 2015; Zarrin et al., 2024). Consumers shift from a product to buying services and/or system solutions. This involves a higher level of customer involvement and education by producers. Producers and service providers have a high degree of responsibility for the product's full life cycle design of the closed-loop system (Mont, 2002). In this way, PSS is linked to the circular economy. Belkadi et al. (2020) proposed

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specificity in the PSS definition by including its impacts, producer's responsibility, and solution-centric customer approach more explicitly as a "knowledge-intensive socio-technical system that aims to fulfill the customer demand by providing an agreed-upon level of availability where the economic and competitive interest of the providers continuously seeks environmentally and socio-ethically beneficial new solutions" (p.221).

Despite circular strategies, the built environment remains one of the most polluting sectors and highest waste generators, accounting for 35% of all waste and 50% of material extraction in the EU (EC, 2020), and 30% of emissions and over 40% of the waste produced in the Netherlands (PBL, 2023). More strategies and solutions are needed to alleviate these issues. Using public procurement to integrate sustainability and circularity is considered essential for achieving sustainability in the construction industry (Lingegård et al., 2021). PSS is considered one of the ways to increase sustainability in public procurement of the infrastructure sector. It is defined by the public-private partnership and contracts, which changes the way PSS can be applied. The sector has a very high customer dominance (represented mostly by the government), only a few players, one-off products, long lead-up time, rigid rules, and an uncreative environment. The push for change has come from circular public procurement, which includes price per delivered service contract instead of the traditional price per unit (Lingegård et al., 2021). However, the solutions for larger-scale infrastructures are limited, with only a few studies published in Scandinavia and the UK (Lingegård et al., 2011, 2021; Lingegård and Svensson, 2014). There is a lack of lifecycle perspective and a disconnect between circular management due to separate outsourcing of design, construction, and maintenance (Lingegård et al., 2021). The word "infrastructure" in PSS is usually used in a generic form as any type of infrastructure (technological, digital), often used as a natural part of PSS but rarely in the context of the construction industry. PSS requires a long-term relationship with various stakeholders (clients, suppliers, information technologies, and others) (Belkadi et al., 2020), which requires a multistakeholder approach. This can make PSS challenging to formulate as it requires a combination of stakeholder involvement and communication (or lack thereof), lifecycle perspective, and interconnection between the demands of the client and the functions and technology of PSS provided.

The objective of this article is to address the aforementioned challenges of circular PSS in infrastructure and propose a framework that allows a) a multistakeholder co-creation process (communication and iterations are crucial in public-private contracts), b) incorporate organizational issues such as hierarchy in client-contractor relationships, c) to include life cycle perspective and circularity for both top-down (design and high R strategies: Rethink, Refuse, Reduce) and bottom-up strategies (lower R strategies such as reuse, recycling). We have provided evidence of increased circularity on both strategic and material levels, detailing R strategies implemented and the input and output of materials per each case in our previous publication (Teigiserova et al., 2023). PSS integration can thus have a significant impact, more specifically to:

- Stimulate systemic change due to multistakeholder involvement. Four groups of actors are more powerful and, consequently, have better chances of initiating and facilitating the change: producers, consumers, financial organizations (Mont and Lindhqvist, 2003), and government in the infrastructure sector (Lingegård and Svensson, 2014).
- Stimulate the co-creation process to include a lifecycle perspective, as design, construction, and maintenance are still outsourced separately and not integrated and procured together (Lingegård et al., 2021).
- Integrate circular strategies into the decision process for top-down strategies, not only at the end of the pipe, which is often the case in the construction industry.
- Increase circularity, dematerialization, and technology innovation (incl. digitalization) for the infrastructure sector (Teigiserova et al., 2023).
- Reduce environmental burden, which is not traditionally accounted for in the market prices; thus, company leaders do not usually consider them when they make decisions about product and system design (Mont and Lindhqvist, 2003).
- The shift from traditional eco-design approaches to system design requires the involvement of many actors within and outside the supply chain (Mont and Lindhqvist, 2003).
- Increased circularity can lead to an approximately 11% increase in the European Gross Domestic Product (GDP), representing about €1.8 trillion by 2030 (Bressanelli et al., 2018).

These elements are present in the PSS framework, often separately or in combinations of a few, but rarely are they addressed complexly in one framework. For example, Kjaer et al. (2019) address circularity and lifecycle but not other elements, such as the relationship with the customer, which in turn is addressed by other authors such as Delgadillo et al. (2021) and Bertoni (2019), while frameworks by Liu et al. (2022) and Halstenberg et al. (2019) address both but to a limited extent. There is a need to bring these elements together to unlock holistic understanding, collaboration, and multidisciplinary. To achieve our objective, we first analyze the current circular PSS frameworks and assess their potential for application in the infrastructure sector. Secondly, the findings are combined with an analysis of five empirical case studies with several types of infrastructure: bridge decks, digital road light systems, residential roads, provincial roads, and guide rails. Lastly, we present the final framework for multistakeholder circular PSS models.

2. Methods

The methods consisted of a literature review of current PSS frameworks. Its outcome was combined with the analysis of case studies, including PSS models conducted with a variety of stakeholders as we as their input on organizational aspects and enablers and barriers. The key aspects of the framework are mentioned in this article, with the full extent of case studies included in the Technical Report (Schraven et al., 2023).

2.1. Literature review

We conducted a literature review focusing on PSS frameworks. The product-service system research field delivers a substantial amount of research and frameworks. However, the intersection of circular economy and PSS still represent a niche with just over 55 results when searching Scopus for "PSS" AND "framework" AND "circular" OR "product-service system" AND "framework" AND "circular" using a new search field (May 2024). The sources were limited to the English language, all open access and excluded books. Adapted PRISMA protocol for systematic review (Moher et al., 2009) resulted in 14 frameworks for analysis, see Fig. 1. The main criteria were that the visual framework for PSS representation must be included with further eligibility criteria for applicability in the infrastructure sector: a) their ability to capture customer-contractor relationships for public-private contracting to allow multistakeholder approach and co-creation, b) their potential to capture circularity and lifecycle of the infrastructure (both top-down and bottom-up approach b)ability to capture hierarchy in PSS formulation (while contractor provides PSS it is heavily influenced by the needs of the tender – government contract) d) their ability to capture the dichotomy between technology and customer value (i.e., customer value is more important than a technology-centric focus for public-private contracts), e) business perspective, including different ways of contracting (revenues). Although no time constraint was assigned, the majority of articles have been published since 2017 due to the rising interest and impacts of PSS models in the circular economy.

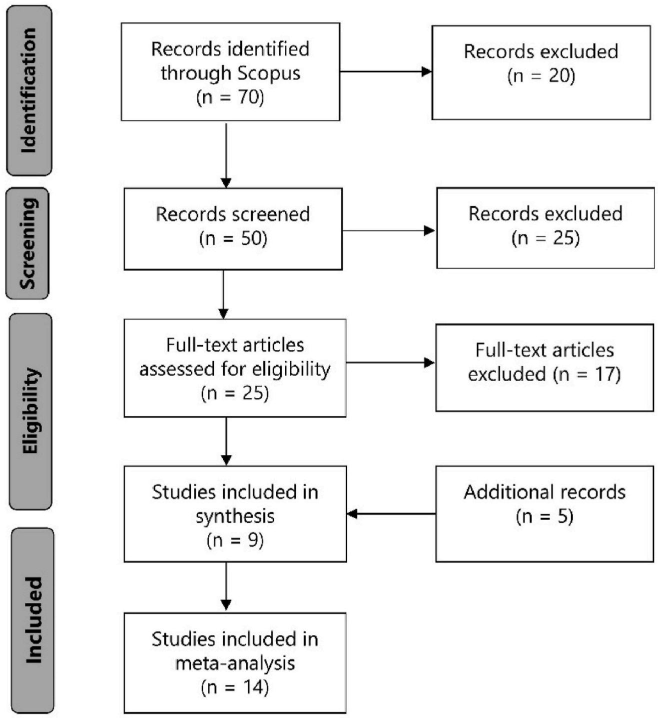

Fig. 1. Adapted Prisma protocol for systematic literature review following four stages of selection.

2.2. Case studies

The Circular Road Program (De Circulaire Weg) in the Netherlands investigated the Infrastructure as a Service model for five pilots: bridge deck, digital road lights, municipal road, provincial road, and guide rails in different municipalities and provinces. These included 4 different government clients and 1 construction company. PSS formulation and negotiations started between 2018 and 2020, with different stages for each project, with the first version of the program (presented results) finishing in June 2022. Details on each pilot can be found in the technical report (Schraven et al., 2023). The different clients and the same contract allowed for homogeneity in data handling when it comes to circularity and materials, but enough variety to notice patterns even when different cases are applied. Most cases were similar in scope, except the provincial road. Additionally, the program stakeholders hold regular meetings to update each other.

To construct the PSS contract model, the adapted Van Ostaeyen et al. (2013) framework was used with the additional elements to distinguish types of strategic goals and functions (PSS-oriented and generic) from a customer-centric Schmidt et al. (2015), life cycle perspective, and circularity aspects, represented in Fig. 2. A functional Hierarchy framework was chosen to allow evaluation from both contractor and client (government), solution offering, PSS functionalities, and differentiating between various tasks within the contract. The demand level is the main requirement of the client at the highest level of abstraction (ex., providing a sustainable road), which is then distinguished between PSS-specific demand (ex., increase in sustainability) and generic demand (ex., availability and safety of the road). At the next level, specific demands are matched with suitable functions and solutions defined by the contractor and client (e.g., maintenance and increased material circularity). The contractor usually chooses respective technologies and structures unless they consider regulation-prescribed requirements (e.g., safety guidelines, circularity, circular material input, and reuse and recycling at the end of the lifetime).

The framework was used with stakeholders during the final stages of the PSS contract formulation. At this stage, both the client and contractor could give the most input due to their increased knowledge and experience with the case. The first version of the PSS models was based on pilot documentation and communication between the client and contractor, including early contract communication and

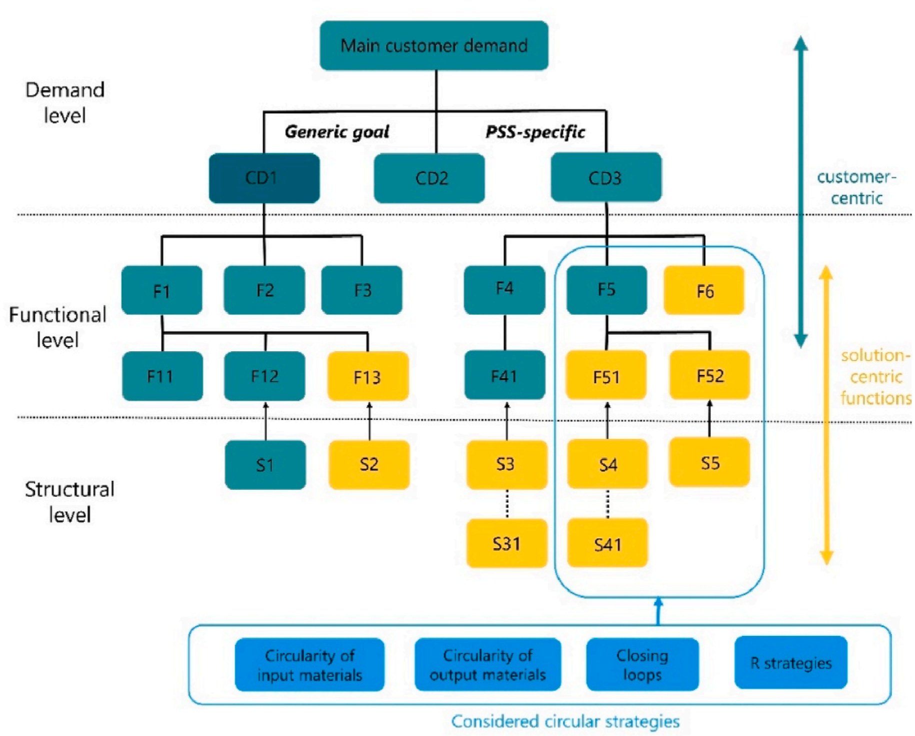

Fig. 2. Adapted Functional Hierarchy Product-service-systems (PSS) model based on Van Ostaeyen et al. (2013) with distinguishing types of strategic goals and function (PSS-oriented and generic), customer-centric Schmidt et al. (2015) and addition of circular strategies. CD customer demand, F function, S structure.

negotiations, client demand, technical aspects, etc. Afterwards, we conducted 3–5 sessions with stakeholders for each pilot (separately and with client and contractor). These sessions did not influence the final contract formulation, and the researcher's role in PSS formulation was to observe and analyze. The framework served merely as a visual representation of the contract. However, it brought some clarity, as the overall contract was visually represented instead of with long documentation. Here, the customer-centric approach combined with the PSS solution (functional level) was useful, as in traditional contracts, the government selects the indicators to assess the functionality (ex., availability of the road for the users, increase in circularity of materials, Environmental Costs Indicator ECI). It is crucial to select these adequately to allow information matching with the appropriate measure of performance and functionality, as also highlighted by (Belkadi et al., 2020). These indicators are often represented at the structural and functional levels of the PSS model, as visualized in Fig. 2. Each case has its own model, which is included in the technical report (Schraven et al., 2023).

Circularity included R strategies for material input (avoiding materials, using recycled materials) and identifying the closing of a loop at the end of the life cycle. Often, R strategies are implemented at the end of life for reuse, recycling, and recovery. Maintenance is added as an essential part of the PSS model to allow optimization to prolong the lifetime, which is traditionally subcontracted by a different company. When considering R strategies during the design (also PSS contract formulation), construction waste can be reduced using input materials from reuse (ex., direct reuse of bricks) and materials with recycled content, providing life cycle optimizations and integrated designs (Lingegård et al., 2021). PSS generally do not automatically lead to lower environmental impacts or increased circularity (Belkadi et al., 2020; Lingegård et al., 2021; Mont and Lindhqvist, 2003; Mont, 2002). Thus, specific attention to solutions for circularity is needed. In this case, all pilot studies achieved increased circularity in strategic approach (higher R strategies) and material circularity, which we reported on in Teigiserova et al. (2023). All stakeholders focused on increased circularity. While recycling is a common strategy for materials, when possible, Refurbish, Repair and Reuse were employed. For example, reusing wooden planks from the bridge locally for pathways, refurbishing old guardrails when quality allows it, and ongoing maintenance strategies that keep circularity in mind. Rethink and Reduce were achieved in all cases, and in the case of the municipal road, Refuse was achieved by holding a discussion with residents, who agreed on decreasing the width of the road, ultimately halving the input of the materials. More details on R strategies per each case can be found in Table 2 in Teigiserova et al. (2023) and the technical report of the program (Schraven et al., 2023).

Platform CB'23 version 2.0 (Platform CB'23, 2020) was used to measure sustainable circularity. This method is planned to be standardized in the Dutch construction industry. It is similar to Material Flow Analysis (MFA), tracking inputs and output, but includes specific indicators on circularity, distinguishes sustainability, primary, and secondary resources via several categories (for example, a quantity of sustainably (and unsustainably) produced renewable materials, a quantity of secondary materials from reuse, the quantity of materials available for reuse, etc.), for more see Table A in Appendix A in Teigiserova et al. (2023).

Secondly, we include insights from the enabler and barriers analysis from the program. The full extent is included in Chapter 4, the technical report of the program (Schraven et al., 2023). In this article, we integrated those factors influencing the framework's applicability and usability. The analysis included two surveys with 30 people who contributed to the project and nine semi-structured interviews with the main stakeholders from each pilot. The surveys included statements with a Likert scale of 7 (1- Very strongly disagree, 7- Very strongly agree). Each statement represents an element chosen based on previously identified categories and factors (e.g., political, organizational, financial, etc.). Semi-structured interviews were conducted with the project leaders for both client and contractor: three project owners, four project managers, one sustainability expert in policy, and one policy advisor. All interviews, except one, were performed online in English and recorded (audio). The duration was from 40 to 90 min. Microsoft Excel was used to analyze the results from the surveys and interviews, identifying patterns in the most common barriers and enablers. In interviews, the frequency and co-occurrence of notions were tracked and categorized (refer to Chapter 4 in Schraven et al. (2023)). The analysis, which combined various government representatives with industry, confirmed which aspects are crucial among all the parties.

3. Results and discussion

3.1. Theoretical frameworks: aligning for circularity and client-customer relationships

The resulting 14 frameworks and their eligibility elements are represented in Table 1. Eligibility criteria, i.e., elements needed for circular infrastructure PSS framework, have been included in the literature to various extents. One of the criteria (capturing the hierarchical relationship between client and contractor) was found only in the functional hierarchy model by Van Ostaeyen et al. (2013) and was thus not included in Table 1. The table represents the frameworks analyzed and their inclusion of four eligibility. Some include the life cycle perspective but lack the customer-contractor relationship representation and value capture, while others are very strong in the latter but lack the life cycle perspective. Each of these can be applied in the infrastructure sector to a limited extent. The life cycle perspective and circular elements are essential for more sustainable PSS in the infrastructure sector. It is especially important when the government as a client has limited knowledge of circularity, and consequently, circularity is limited in the tender criteria (to win the contract) (Lingegård et al., 2021).

The life cycle perspective has been explicitly included Kjaer et al.

Table 1
Frameworks evaluated according to eligibility criteria for possible use on infrastructure Product-Service-Systems in the construction industry across four categories for holistic multidisciplinary approach.

Reference	Circularity and lifecycle	Customer-contractor relationship	Customer value and technology functionalities	Revenue mechanisms
(Kjaer et al., 2019; Matschewsky, 2019)	Yes	–	–	–
Kristensen and Remmen (2019)	Yes (if extended)	Yes	–	Yes
Bertoni (2019)	Yes (if extended)	Yes	Yes	Limited
Guzzo et al. (2019)	Yes	–	Limited	–
Halstenberg et al. (2019)	Limited	–	Limited	Limited
Ramsheva et al. (2020)	Yes	–	Yes	–
Delgadillo et al. (2021)	–	Yes (if extended)	Yes	Yes
Liu et al. (2022)	Yes	Limited	Limited	–
Van Ostaeyen et al. (2013)	–	Yes	Yes	Yes
Schenkl et al. (2014)	–	Yes	Limited	–
Schmidt et al. (2015)	–	Yes	Limited	–
Apostolov et al. (2018)	–	Limited	Yes	–
Kusumaningdyah and Tetsuo (2017)	–	Yes	Yes	Yes

(2019) and Matschewsky (2019). Matschewsky (2019) adopted Kjaer et al. (2019) framework with the same elements; thus, it is addressed as one framework. The important element is the critical view of PSS for resource decoupling in the circular economy. In their view, PSS should support resource reduction while supporting economic growth to achieve sustainability targets. It is connected to the eco-efficiency and eco-effectiveness of retaining material value over time and keeping the relationship between ecology and economy, as initially represented via regenerative design for a circular economy by the Ellen MacArthur Foundation (2013). This is an important factor in the construction sector since infrastructure has life time over several decades and immense resources are being used to build them (both materials and financial). Thus, product efficiency, product longevity, operational efficiency, and usage intensity, are important factors to consider. However, the framework concentrates on materials decoupling and thus does not represent customer relationship and supporting companies in implementing circular business models. Yet, it offers a holistic point of view on resource use in PSS for infrastructure.

The lifecycle aspects in the framework by Guzzo et al. (2019) concentrate on the resource-effectiveness to facilitate innovation and decision-making when implementing circular PSS. The authors selected the strategies based on the literature review of 45 PSS cases (including six business-to-government relationship types, mainly waste-to-energy systems). The framework links conceptual, strategic, and practical strategies for operationalization, which can help to enable stakeholder communication. It includes potential customer value capture, but it serves more as an example of strategies than the conceptual framework, which limits its usability for infrastructure projects. However, construction companies can use it internally when identifying strategies to meet client demands.

The framework by Halstenberg et al. (2019) features three out of four criteria to a limited extent. The authors created an adaptable framework combining Smart PSS and Model-based Systems Engineering to form a Methodology for Smart Service Architecture Definition (MESSIAH). The methodology was validated on the example of a Smart Sustainable Street Light System for Cycling Security (SHEILA), similar to one of the pilots (road lights) included in this study. This framework is useful for infrastructure assets that have digitalization (smart PSS). It can be advantageous in communication since different flows are visualized, such as materials, information, product function, service function, costs, societal value, and other elements that can be assigned to the PSS. It also makes hotspots for circularity visible, such as maintenance, which is traditionally subcontracted by a different company than the contractor/builder of the infrastructure asset.

Liu et al. (2022) constructed a blockchain (emerging digital technologies) enhanced PSS framework for sustainable furniture, including the whole lifecycle stage. It consists of a high-level framework including three levels of user, system, and knowledge from a strategic perspective. While it is applied to furniture, it includes elements important for client-contractor communication and clarification, the linkages to lifecycle and sustainability strategies, and its challenges across the supply chain (manufacturing, distribution, consumer). It allows for the viewpoint of different stakeholders to be involved.

Ramsheva et al. (2020) and Kristensen and Remmen (2019) developed similar circular PSS frameworks based on each PPS dimension separately, i.e., ‘product,’ ‘service,’ and ‘system.’ The final frameworks clearly visualize each PSS dimension and its boundaries. Both frameworks offer an understanding of value for multiple stakeholders at the aggregate level and enable clients to see connections to the value proposition and circularity. Kristensen and Remmen (2019) further include considerations of the economic, environmental, and social value proposition for sustainability. The ‘system’ dimension includes the socio-technical context –spatial and temporal – of the organizations, collaboration, and networks across different stakeholder groups; for example, environmental, social, and economic needs, design and production that needs current and future needs, knowledge sharing, collaborative platforms, tracking and improving performance. Although both frameworks allow for a good visual representation for stakeholder communication to distinguish between product, service, and system-level connections to circular elements, they include general categories at a high level of abstraction. This means that the model is limited by the input provided and can be hard to connect to individual components without deep knowledge of each PSS category. The authors showcase possible framework applications in examples. Ramsheva et al. (2020) included a study of the concrete industry, where service level includes design and performance, represented by plan and design building for flexibility and operations, respectively, in the case application. The supply chain category is represented by burden reduction for technical staff and local employment service, for example, PSS in the school furniture case in Kristensen and Remmen (2019).

Bertoni (2019) presented a decision support tool capable of visualizing value for the customer, where the customer and PSS provider can decide on priorities and strategies. However, this decision support tool (Fig. 3 in Bertoni (2019)) may be used in the infrastructure sector if technical aspects, asset performance, and functionalities are extended in more detail. Because the tool uses weighting factors, it can also identify hotspots for circularity and sustainability from the clients’ and contractors’ perspectives. Potentially, such a tool has value in very early project formulations to discover ambitions and strategies for both parties and align the goals of the project (i.e., in the case of the co-creation PSS process).

Delgadillo et al. (2021) created a territorial PSS framework linking resources, networks, and value creation concerning their geographic proximity. The authors highlight the social embeddedness of relations as an important factor and the diversity of territorial actors as a pre-condition for PSS for sustainability transitions and resilience. The notions of co-design, co-production, and co-evaluation are considered for a more adaptive PSS. The client/customer is then part of the process when the producer/contractor is formulating PSS, and some of the decisions and burdens are shared. Since infrastructure depends on regional and/or national relationships, this framework adds key aspects that should be embedded into the infrastructure PSS models. Identifying and visualizing sustainability elements can prove especially useful, as more tenders ask for some level of sustainability in the project. Nevertheless, this framework concentrates on value creation and lacks details necessary for client communication in infrastructure, such as functional performance and life cycle perspective.

Similar co-creation elements can be found in the framework of Kusumaningdyah and Tetsuo (2017), with a focus on networks and technology. For infrastructure, this is more useful for the contractor to identify the connection between technology and value creation for the client and identify co-creation management.

The frameworks of Schenkl et al. (2014) and Schmidt et al. (2015) include a layered structure of relationships between the client, customer, and technology. Schenkl et al. (2014) include a technology-centred view distinguishing technology and solutions connected to the (PSS-specific, quality, and strategic) goals and strategies. Schmidt et al. (2015) further expanded on this with a customer-centric approach, adding a customer barrier, which allows to address concerns such as costs and usability. PSS can then be customized based on the area targeted (such as low costs, which are then a priority). While the framework allows choosing the right customer, the government (customer) chooses a contractor in the infrastructure sector. Both frameworks are useful as they allow for identifying the connection between the strategies-to-solution (e.g. quality goal for maintenance linked to safety requirements, PSS-specific goal linked to circular strategies in decreasing material inputs), which is crucial for both contractor and government for the tendering and PSS process. It enables to distinguish several goal levels as there can be both national and municipal goals at different levels of priority that contractor has to fullfill. It also ensures that relevant barriers are addressed, which is a crucial aspect due to the novelty of PSS contracts in public-private

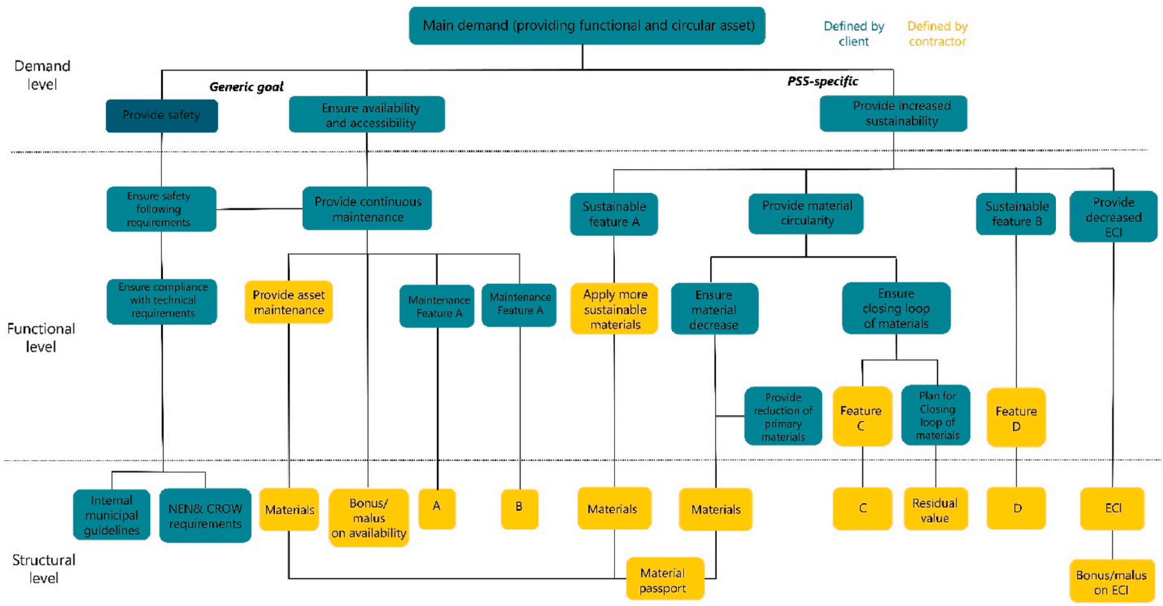

Fig. 3. Adapted Functional Hierarchy Product-service-systems (PSS) model based on Van Ostaeyen et al. (2013). Environmental Cost Indicator (ECI) as evaluation criteria. A,B,C,D represent elements chosen to measure or tract selected element. Material passport are details on material inputs and potential output use.

partnerships.

Finally, Apostolov et al. (2018) and Van Ostaeyen et al. (2013) include a hierarchy level in the client-customer relationship, PSS functional level, and physical aspects. Both frameworks include main stakeholders as the top layer, i.e., the most influential level, where demands of PSS are set. Next, the functionalities of PSS are determined, and an appropriate service model is chosen, which is then connected to actual physical resources and structures. For the infrastructure sector, this represents a visualization of the most important levels where both client and contractor see the key concept and can connect them between levels. The Functional Hierarchy framework of Van Ostaeyen et al. (2013) is a good fit strategy for solution offering, PSS functionalities, and differentiating between various tasks within the contract. Additionally, it includes the possibility of addressing revenue mechanisms. In the Functional Hierarchy framework, the demand level is the main requirement of the client at the highest level of abstraction (ex., providing a sustainable road). Subsequently, appropriate functionalities and solutions are defined (functional level) to reach the demand (ex., safety, circularity). Respective technologies and structures are then chosen to provide the best functionality (e.g., safety guidelines, circular material input, and reuse and recycling at the end of the lifetime).

3.2. *Case studies: infrastructure as a service in the Dutch construction industry*

3.2.1. *PSS models and factors*

Among the five different infrastructure pilots studied (bridge deck, digital road lights, municipal road, provincial road, and guide rails), there were common features, namely a) safety, b) availability (achieved via proper maintenance), and c) sustainable and/or circular goals. PSS thus represents an integrated public circular contract, differentiating itself from traditional contracts, where maintenance is subcontracted. While safety is an intuitively comprehensible criterion, appropriate maintenance needs to be undertaken following safety standards and ensuring the asset is available as much as possible. This is guaranteed by a financial bonus or deduction (malus) in the contract to ensure the asset is available to the residents/users. It also needs to be performed according to sustainable/circular demands.

The second level includes functional requirements and further specifications for achieving the clients' demands. For example, if the client demands increased sustainability at the top level, it can be achieved via increased circularity or sustainable materials at the functional level. It is up to the client to define this in a more abstract (e.g., circular materials) or concrete way (e.g., use material A; lower environmental impacts by X%). The functional level can then have several layers that link more abstract demands to more concrete ones. At some point, the client gives the contractor the authority to achieve the demand. For instance, when the client demands increased circularity for input materials but leaves it to the contractor to formulate a solution on how to reach it. While circularity features are specific to the project, there has been a common feature among all projects studied: decreasing primary materials, increasing input of reused or recycled materials, making sure that materials are recycled at the end of their lifetime, and improving environmental performance via Environmental Cost Indicator (ECI).

Keeping one element as direct as possible is advised to allow for the potential use of metrics to track the goals (i.e., the proof of the performance and fulfilment of the contract conditions). Tracking system performance and evaluating improvements are key aspects of PSS, also included in the 'systems' level of Ramsheva et al. (2020). Some examples can include the input of materials with recycled content or decreased use of primary materials, which should be distinguished from just "circular materials." These distinctions are crucial for the PSS of infrastructure as they give the scope for the contracting.

The third level, the structural level, contains the technical details, such as concrete materials, resources, equipment, or guidelines (i.e., technical and safety requirements prescribed by regulations and internal municipal documents).

In the studied pilots, safety and maintenance have the same components, with differences seen due to type of the assets, such as different technical and safety requirements. While ownership is in part transferred to the contractors (infrastructure as a service), it is still part for the city or a province, who remain the main responsible stakeholders for the safety of residents.

As visible from Fig. 3, the client retains a dominant position in PSS formulation of sustainability and circularity functions (color blue on the right side), and similarly to maintenance, the differences are observed in small details between different infrastructure assets. For example, ensuring disassembly at the design level for the bridge, asphalt mixture with high recycled content for all the roads, providing annual monitoring and ensuring reusability of guard rails, gradual change of old lamp posts for a modular design that allows the exchange of faulty parts in the digital road light system. All pilots implemented various R strategies matched with materials used in the asset and management (i.e., 'refurbish' is applied for bridge deck, guard rails, and lights, but cannot be applied for road materials), however, only residential road implemented 'Refuse' at the design level (by decreasing the size of the road). The digital light system achieved the lowest rate of material circularity (since lamp posts are not yet exchanged fully for modular designs), but it is considered the most successful, and it is the longest-running pilot. Their main aim was reducing energy, which was decreased by 50%, thus achieving high environmental and economic benefits for both client and contractor. All five pilots have their own PSS model in the technical report (Schraven et al., 2023). Highlights from the pilots in Appendix B, comprise pilot cards with R strategies, main circular elements of the PSS contract, circular indicators, and main enablers and barriers per pilot.

3.2.2. Organizational aspects: stakeholder view on PSS models for infrastructure

To achieve the full potential of circularity and decreased environmental impacts, these factors need to be addressed at the design stage (Mont and Lindhqvist, 2003), which, in the case of infrastructure, means the project formulation stage. Yet, despite PSS being a customer-driven concept, it lacks customer involvement at the design level (Schmidt et al., 2015). At the same time, co-creation management, co-design, and even burden sharing are highlighted as crucial for creating more impactful and lasting PSS (Delgadillo et al., 2021; Kusumaningdyah and Tetsuo, 2017). However, these elements are rarely present in the construction industry, especially in the public procurement area. The surveys and interviews with the stakeholders offered a close look at the contextual factors influencing PSS implementation in the infrastructure sector, with findings supporting previous research (Delgadillo et al., 2021; Kusumaningdyah and Tetsuo, 2017). The analysis of enablers and barriers of the five pilots revealed key aspects that need to be more explicit in the final framework to realize PSS:

- PSS offers a change of status quo by establishing a space for co-creation.
- Co-creation is a crucial element, and circularity needs to be a focus for all parties involved from the start.
- Inter (collaborative) and intra-organizational iterative processes are necessary to realize the change. For example, to re-evaluate the scope of the PSS contract, consult with experts, and increase knowledge transfer.
- Lack of knowledge and knowledge transfer are the most significant barriers to implementation and are needed to increase and maintain trust, motivation, and commitment.
- There is a lack of helpful tools to address the complexities of PSS (both from the management and process view and knowledge and information view).
- Keeping track of internal and external networks a) to monitor potential resistance to change, b) to track possible future collaborators and market opportunities, and c) to increase the economic potential and value creation.

Additionally, old structures, bureaucratic processes, and a lack of procedural changes lead to the need for internal persuasion and hesitation in implementing new ways of working. These factors negatively influenced the provincial road pilot, where after a great start due to co-creation initiatives, various organizational challenges prevailed, as well as further concerns such as safety and transfer of ownership. However, this asset was much larger than all other pilots.

Yet, these challenges can be mitigated by knowledge sharing and co-creation management. The exploratory co-creation style at the beginning of the PSS formulation was highlighted as a big strength, a surprising factor from the government partners as they often stay less involved in the process. Including collaborative aspects and burden sharing were significant factors in one of the most successful cases - digital road lights. Sharing the responsibilities was met with high uncertainty factors, but it was overcome with trust among the stakeholders due to the continuation of the initial co-creation process and transparent and frequent knowledge sharing.

Similarly, the communication and trust between the client and the contractor can be assigned to success in the guardrails pilot. This pilot had a truly explorative style and was the only case that took longer to explore several assets before selecting guard rails, which would not be achieved without co-creation.

The client of the bridge deck and residential road experienced different co-creation, as in this case, they were driving the change for more environmental and social value. The city has organized a special session with local citizens regarding the residential road design, which resulted in 50% input material reduction. The bridge deck contract enhanced sustainability value to create less noise nuisance for residents, use more sustainable materials (i.e., certified wood) and plan local reuse at the end of life.

Across all pilots, a motivation to incorporate PSS contracts was gaining the experience and knowledge to enhance economic potential and partnerships in the future market. Improving collaboration between government and industry was seen as essential to achieving systemic change, and PSS creates a space for a more creative approach and more entrepreneurial space for solution providers (contractors). While interest in other pilots was also a strong motivator, due to challenges in project formulation, it was not realized during the program duration. These barriers and enablers showcase the need for comprehensive frameworks to be shared, helping to solve the multitude of barriers faced in PSS implementation in the infrastructure sector.

3.3. Multistakeholder integrated circular PSS framework for the infrastructure sector

As Belkadi et al. (2020) state, "nor product nor service is alone the point of focus, but the final solution, which is a simultaneous combination of the products and services, is the target of the system. Thus, to move towards the adoption of the PSS business model, industries need to create a new integrated system of solution providing". Our findings from the current scientific circular PSS framework, empirical studies, and stakeholder evaluation allowed us to develop a final framework for the multistakeholder integrated circular PSS model represented in Fig. 4. The key factors that circular PSS must possess are i) lifecycle perspective and circularity, a) materials and b) management, ii) capture customer-contractor relationship and thus include a) customer-perspective b) co-creation aspects, c) client-customer hierarchy (one has more authority, over demand, one over technology delivery) iii) technology perspective (functions and resources) iv) business aspects to address a) network and b) value creation and retention. On top of that, the framework should be intuitively comprehensible and direct enough to allow for customer-contractor communication. Some levels of the framework can be extended internally. For example, the contractor can extend details on technology and resources for their own purposes, and clients can use it to make their overall strategies and values visible.

The framework is structured in five layers where all need to address co-creation elements, as highlighted by Delgadillo et al. (2021), Kusumaningdyah and Tetsuo (2017), and Bertoni (2019), and include iteration to arrive at the final PSS model.

- Top layer concentrates on the client's strategic level distinguishing a) generic b) sustainable c) circular, and d) PSS-specific goals based on Schmidt et al. (2015). A difference between sustainable and circular goals can be the use of sustainable biobased materials (which do not have to be circular), and using materials following R strategies. These can be later interlinked, for example, by 'prolonging the lifetime' strategy (circular strategy). Here, goal visualization can

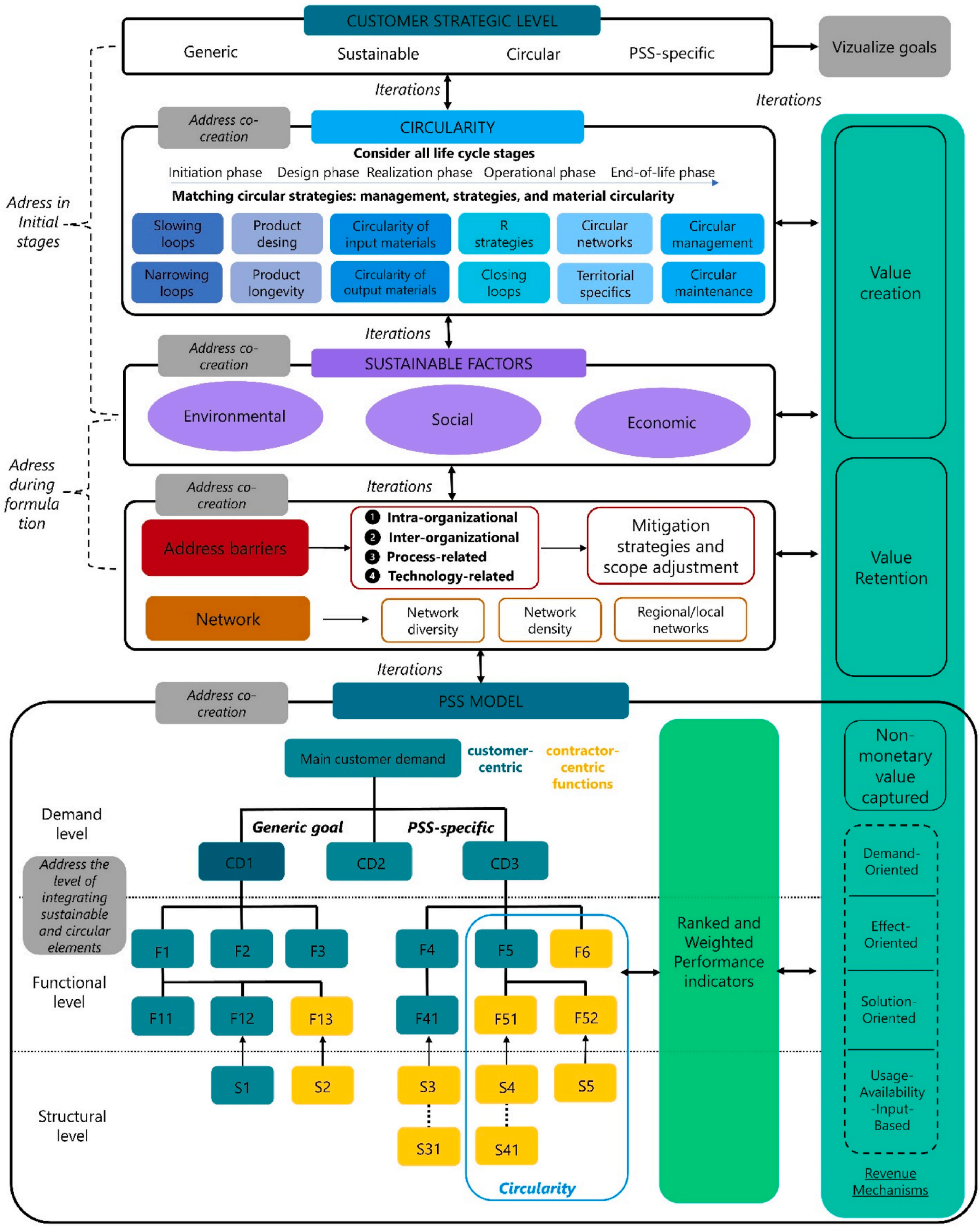

Fig. 4. Integrated multi-stakeholder circular PSS model. The arrows represent iterative process. PSS hierarchical model is taken and revenue mechanism are based on Van Ostaeyen et al. (2013). PSS model can have several iteration and be formed during the PSS project formulation to help vizualize connections between strategies and potential functional and technological and other solutions. Twelve circular strategies and four barriers represent examples and can be further expanded upon. The grey boxes represent special points of attention.

support maintaining the strategy and priorities and can be combined with the Motivation-Opportunity-Ability (MOA) framework by Verleye et al. (2024) or the visualization framework by Bertoni (2019).

- The second to fifth layer involves a co-creation process and thus should be formulated and addressed together between the client and contractor/PSS provides
- The second layer includes twelve examples of circular strategies connected to life cycle stages to reach resource efficiency, as emphasized by Guzzo et al. (2019), Kjaer et al. (2019), and (Matschewsky, 2019). These are important for physical asset and their maintenance to increase product efficiency, product longevity, and operational efficiency. These examples can be further expanded upon.

- The third layer is represented by sustainability spheres, also included in Delgadillo et al. (2021) and (Liu et al., 2022). As the latter suggested, this can be used to identify barriers and challenges and, consequently, to develop mitigation strategies to improve sustainability (across various stakeholders involved). Sustainability is also linked to the decision and implementation of circularity in the previous layer and the next layer, which discusses barriers and networks (supply chain and local sustainability partnerships). Other examples include a discussion of social and environmental impact locally and in the supply chain (i.e., subcontracting and materials used) and tracking these with indicators (in our case, Platform CB23, certified suppliers, and use of local networks.) However, this layer is highly dependent on a case-by-case basis, as different PSS contracts, clients, and objectives can lead to different sustainability strategies and discussions.
- After discussing the first three layers, the client and contractor can address layer four: Network and barriers.
  - o Enabling addressing barriers via a customer-centric view, as emphasized by Schmidt et al. (2015), and including barrier categories can help to enhance problem-solving actualization since some barriers can have a high level of abstraction- and can be harder to formulate. The four examples included should be specified and expanded when needed. For example, the Circular Road program addressed intra and inter-organizational, technical, economic, contextual (ex., knowledge transfer, motivation), political, and legal aspects (chapter 4 in Schraven et al. (2023). These are important to formulate drivers and mitigation strategies and adjust the contract scope. For example, continuous knowledge dissemination was essential to overcome several barriers and build trust and motivation, which are crucial for the co-creation process. Another example to overcome barriers and help co-creation is to communicate continuously regarding goal and scope reminders (to not fall into business-as-usual and conflict among stakeholders) and to talk to experts when needed. More examples, taken from the program report, are included in Appendix A.
  - o The distinction between inter- and intra-organization aspects is also included in the example included in the 'system' level of Kristensen and Remmen (2019).
  - o Network diversity and local partnerships based on Delgadillo et al. (2021) and (Kusumaningdyah and Tetsuo, 2017). Infrastructure and many other types of partnerships depend on regional and/or national relationships. Further, it can help establish a collaborative platform for knowledge sharing along the value chain, as mentioned in "systems" elements in Ramsheva et al. (2020).
- The bottom layer includes two parts: the PSS model based on Van Ostaeyen et al. (2013) and Schenkl et al. (2014) and performance indicators:
  - o Left-side
- Enable distinguishing demand to solution to technology in the three-layered functional hierarchy (described in section 3 and further developed in section 4)
- Allow customers to link different strategies and demands (generic and PSS-specific) to functions and solutions. This framework was highlighted by all stakeholders as a helpful tool to visualize complexities (*"it is helpful to see it represented in one picture instead of reading twenty pages and needing to discuss same things again and again"*)
- A special point of attention is addressing the level of integrating sustainable and circular elements. It considers if sustainability and circularity are additions or a must for PSS (described as three types of circular PSS, Fig. 3, in section 4.1).
  - o The right side is connected to value retention via performance indicators. These indicators can be assigned in a weighted and ranked fashion, as Bertoni (2019) suggested.
- All levels except the strategic level are linked to the value creation and retention (right-side of Fig. 3)
  - o Value creation and retention are spread across social, environmental, and economic dimensions.
  - o It is linked to network and barriers to enable co-design, co-production, co-evaluation, and adaptive PSS, as suggested by Delgadillo et al. (2021), and co-creation management (Kusumaningdyah and Tetsuo, 2017). For example, a key component in establishing the PSS of guide rails was a partnership with a local company refurbishing old guide rails to technical quality (also acting as an intermediary to scrap dealers).
  - o Revenue mechanisms are based on Van Ostaeyen et al. (2013) to establish the form of payment.

The five layers are meant for parallel iterative processes (represented by arrows) to enhance communication and transparency and overcome and reduce barriers faced when implementing PSS while creating value. The first three layers should be discussed and expanded upon from the start. For example, the second layer of circular strategies should be used in the project formulation/initial processes, and discussion on sustainability should take place. We have previously identified that the inclusion of higher R strategies (refuse, rethink, reduce) is enabled during project formulation. (Teigiserova et al., 2023), which makes it crucial to discuss at the beginning from both client and customer perspectives. We suggest a combination with Guzzo et al. (2019) to explore and include some of their twenty-one circular strategies and seventy-seven practices to operationalize strategies. It consists of a mixture of lifecycle strategies applicable for infrastructure assets, namely at the beginning of the life cycle with the "pure inputs" category and during the asset lifetime by incorporating prolonged life cycle strategies (maintenance) and end of lifecycle strategies in the same category of "circling longer" (ex. reprocessing, spare parts, take-back), "cascade use" is also possible to achieve when local subcontractors and local circulation of materials is implemented (for ex. instead of discarding old bricks, using them for a parking lot in the close-by area, which is made by a local subcontractor). This is important for increasing the knowledge of both parties, as usually one is an expert and one is not, which leads to misunderstanding, complications, and misalignment of goals. By sharing more information, stakeholders get insights into each other's decision-making and restrictions (such as what is realistically achievable regarding material circularity). This also helps to increase transparency and trust. The level of information should be shared with care, usually at the non-expert level, with enough details to provide context and explanations of possibilities and their limits. This helps in parallel with working on the fourth level, identifying barriers, and finding mitigation strategies. For example, in the case of the guard rails, open conversation and transparency led to a speedy contract agreement and finding local supplies to refurbish old guard rails. The material and safety limitations were freely shared, as guard rails can only be used again if safety allows it, which may decrease the circularity achieved. All information was available to the client by the contractor, and in turn, the contractor also understood the limitations of the internal structure and understood better which information needed to be shared and why. Similarly, in the case of road lights, the client was given tours of the system and continuous updates with more information that is usually shared, so when the complication arose, they were immediately brought to the table and discussed, strengthening the trust and finding solutions (or understanding delays). This led to PSS, which was more of a partnership, where some burdens were shared, and common goals and revenue mechanisms were more easily established.

Using iterative processes and project re-evaluation allows the implementation of cross-connections and trade-offs to create efficient PSS models and circular strategies to support resource reduction while supporting economic growth to achieve sustainability targets. We also recommend a combination with the framework by Delgadillo et al. (2021) to address territorial considerations, such as networks and stakeholders within geographical boundaries. A combination with the decision-support tool developed by Bertoni (2019) can also help visualize, harmonize, and capture value co-creation and enhance knowledge transfer.

Lastly, when forming the final PSS representation in the fifth layer, some sustainable and circular goals can be revisited as the final contract visual will help to clarify them. The strategies and form of PSS need to be matched with indicators and measures defined by both parties (ex., how much circularity was achieved) at structural and functional levels. Here, we recommend using a weighting factor to establish priorities and importance. This is highly dependent on the case-specific but allows for transparent decisions, as maybe the client perceives something at a higher level of importance. For example, in some cases, social sustainability can be weighted more by the client, giving the contractor more incentive to allocate more effort to finding solutions. Social sustainability is often “an afterthought” in the construction industry. As stated, examples of PSS contract visuals in the fifth layer are included in the program report for each pilot case (Schraven et al., 2023).

3.4. Use beyond infrastructure

While we focused on the infrastructure sector in public-private partnerships, this framework can be adapted and used for any type of complex co-creative PSS when circularity and life cycle need to be addressed more explicitly while maintaining a customer-centric approach and technology/solution provision. The process described above is feasible for any PSS contract with more client involvement or client-contractor interaction. In a sense, it offers guiding categories that can function as decision support when discussing PSS, which is not formed yet (either not knowing the exact scope, or sustainability and circularity or not knowing the objective of PSS) or revisiting existing PSS that want to increase sustainability and circularity and level of interaction between the client and contractor. In the latter, the PSS layer five can be formed to visualize the current contract and revisit its circular and sustainable elements, indicators, and improvements and possible barriers to achieving them to form an improved version of the PSS. With the new PSS visual, stakeholders also have a comparative representation that brings clarity into the main ongoing process on each side of the contract and opens space for continuous improvement.

4. Recommendations for policymakers

In public-private partnerships and public procurement, support from government is essential. Circular public procurement slowly shifts towards a contract with price per delivered service (as opposed to traditional price per unit) (Lingegård et al., 2021), but lack of knowledge, knowledge transfer, and other barriers persist. Mont and Lindhqvist (2003) reported failure in promising eco-design initiatives in the Netherlands due to the termination of governmental financial and technical support, which was caused by a lack of a constant driver and policy framework that would ensure continuation. If the construction industry is to be systematically changed, the government (a client for most infrastructure assets) needs to increase its knowledge and implement more innovative management strategies. Circular Public Procurement (CPP) aims to have products and services with an extended life span and value retention (Lingegård et al., 2021). It is the government that formulates tender conditions and selects contractors, thus, increasing knowledge of circularity and sustainability is an essential aspect. For instance, all life cycle stages need to be considered together for the asset, as they are usually outsourced at each stage separately (design, construction, maintenance, end-of-life) (Lingegård et al., 2021).

PSS offers a change in the status quo, a more collaborative approach with higher knowledge transfer. Understanding PSS can help formulate policies that promote sustainable patterns. PSS offer a new way of understanding and influencing stakeholder relationships and viewing product networks, facilitating the development of more efficient policies, as also highlighted by Mont (2002). In the infrastructure sector, the client can then formulate more circular tenders. If not included, both systemic circularity and systemic change of BAU are unlikely to happen. The EU and the United Nations Environment Programme (UNEP) programs that fund various PSS projects in design and manufacturing (Belkadi et al., 2020) should thus be continued and extended to other relevant sectors. An example is the ICP4Life framework, which proposes a collaborative tool for supporting the creation and the lifecycle management of industrial PSS and uses a shared knowledge repository and collaborative platform for customers, manufacturers, and suppliers (Belkadi et al., 2020). More programs like the Circular Road are needed to decrease uncertainty by gaining more knowledge and experience with new management and contract types.

Additionally, PSS can be used as a funding scheme where smaller financial contributions are needed initially. For example, when updating an old light system for modular lighting, a smaller investment is needed in PSS models than in traditional schemes, which requires higher one-time capital costs (as also reported by Circular Road Pilot on digital road lights). Further, in case of digitalization, Internet of Things (IoT) or blockchain integration to PSS can help to improve traceability and circularity (Alcayaga et al., 2019).

5. Conclusion

Product-service systems (PSS) represent a business model that increases material decoupling and decreases environmental risks while providing value to customers. PSS can help realize a more sustainable construction industry, which remains among the largest polluting and waste-generating sectors. Influencing the infrastructure sector can lead to systemic change, as the client is represented by the government. There have been a limited number of studies of PSS in infrastructure as it requires ex-ante evaluation of real case studies to increase knowledge and understanding. This article included input from five different infrastructure pilots in the Netherlands (bridge deck, digital road lights, municipal road, provincial road, and guide rails). Organizational aspects and input from stakeholders were included as essential factors contributing to the effectiveness of the framework.

On top of that, there are only a number of holistic circular PSS frameworks, which include process, customer, and technology in the same model to a limited degree. We have extended this approach and developed a framework for infrastructure based on the current literature and analysis of infrastructure pilots. The final multistakeholder integrated circular PSS framework consists of a five-layer model, which allows for co-creation and knowledge sharing. The first layer established generic, circular, sustainable, and PSS-specific goals, and these can be matched with circular strategies at the second layer, considering all life cycle stages and the right management and materials. The third layer comprises sustainable dimensions (environment, society, economy). The fourth layer includes addressing barriers to define mitigation strategies and identifying network specifications. Findings from these layers contribute to value creation, while the value capture (non-monetary and monetary) is selected in the final fifth layer, where the PSS model is developed and matched with weighted performance indicators. The PSS model includes the hierarchy of demand (defined by the client), which is matched with functions, solutions, materials, and other structures (determined by the client and contractor). The framework allows technology-enabled circular economy and customer-contractor communication. It can serve as decision-support and support formulation of circular and performance indicators. It can help formulate PSS beyond infrastructure, where the customer has more involvement. Moreover, it helps with the most significant barriers to experiences in infrastructure and PSS formulation in general: knowledge transfer and communication to facilitate collaboration. It can be combined with other frameworks developed by the author to enhance customer-client relationships.

CRediT authorship contribution statement

Dominika A. Teigiserova: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daan F.J. Schraven:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Conceptualization.

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.jclepro.2024.144010.

Appendix A. Barrier to solution example

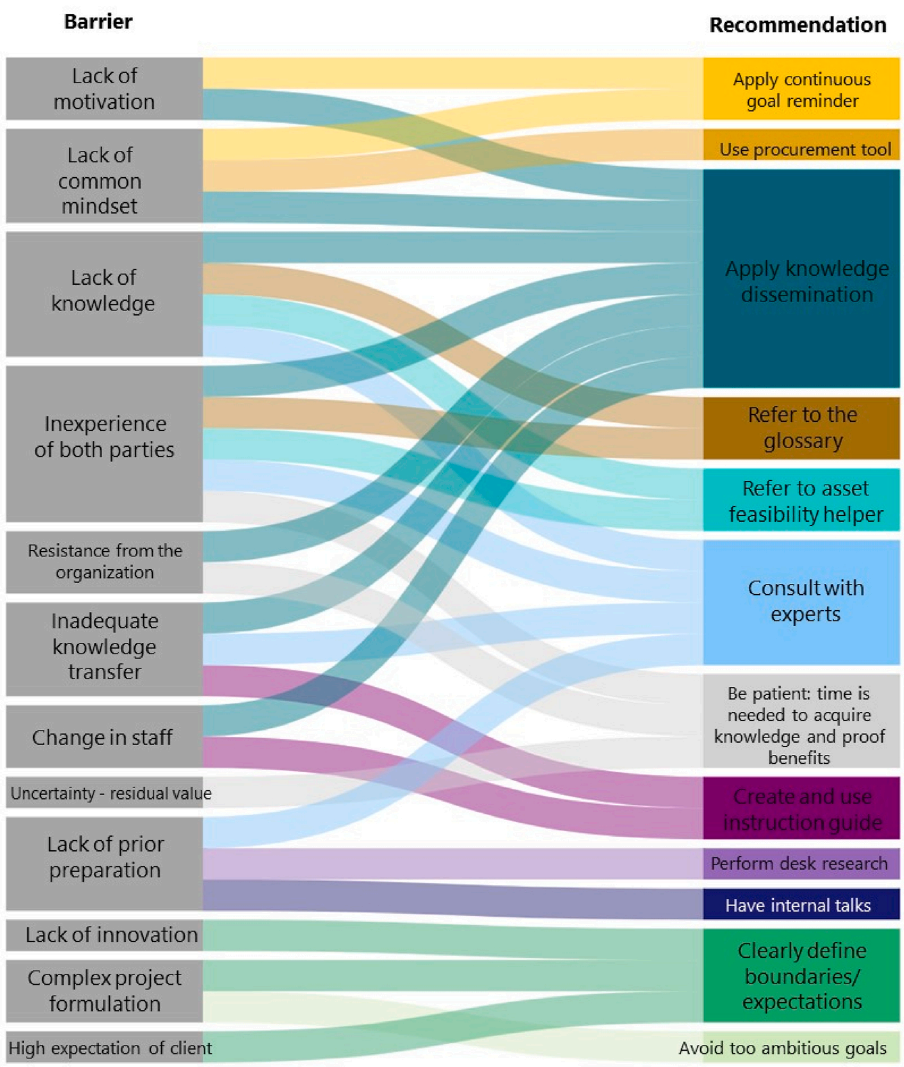

Fig. A. Barriers and solution/mitigation strategies were identified by stakeholders via two surveys and interviews, taken from Schraven et al. (2023), with more details included. Some of the barriers identified had several possible strategies to mitigate the challenges faced.

Data availability

The data that has been used is confidential.

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