Does PSS help to increase circularity? A framework for the circular design process and case study of five pilots in the Dutch infrastructure sector

Teigiserova, Dominika A.; Reit, Colin A.J.; Schraven, Daan F.J.

DOI
10.1016/j.resconrec.2023.107230

Publication date
2023

Document Version
Final published version

Published in
Resources, Conservation and Recycling

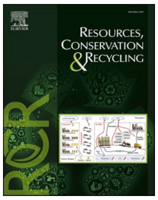
Citation (APA)
Teigiserova, D. A., Reit, C. A. J., & Schraven, D. F. J. (2023). Does PSS help to increase circularity? A framework for the circular design process and case study of five pilots in the Dutch infrastructure sector. *Resources, Conservation and Recycling*, *199*, Article 107230.
https://doi.org/10.1016/j.resconrec.2023.107230

Resources, Conservation & Recycling 199 (2023) 107230

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec



Does PSS help to increase circularity? A framework for the circular design process and case study of five pilots in the Dutch infrastructure sector

Dominika A. Teigiserova [a,b,*], Colin A.J. Reit [a], Daan F.J. Schraven [a,c]

[a] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Materials, Mechanics, Management & Design (3Md), Section of Integral Design and Management, Delft, the Netherlands*
[b] *Erasmus University Rotterdam, Rotterdam School of Management, Rotterdam, the Netherlands*
[c] *Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Management in the Built Environment (MBE), Delft, the Netherlands*

ARTICLE INFO

Keywords:
Circular economy
Product-Service Systems
Construction industry
Evidence-based
Framework
Data management

ABSTRACT

The circular economy (CE) has been established as one of the leading strategies to achieve a more sustainable system leading to national and global goals. One of the models coupled with CE is Product-Service Systems (PSS), with service integrated into products to various degree. PSS implementation in the infrastructure sector has been studied to a limited extent, with evidence of circularity lacking. This study analyzed five PSS infrastructure assets: bridge deck, guide rails, road lights, and municipal and provincial roads. Circularity improved in the design, input materials, and availability of secondary materials. A three-step framework is suggested to enable a circular process: incorporating R-strategies and circularity metrics during design, tracking material circularity, and evaluating implemented metrics and strategies. We suggest mandatory data collection by law to allow traceability, transparency, and the establishment of a secondary resource market.

1. Introduction

The construction sector is known as one of the most polluting, resource-intensive, and rigid sectors in the world. Attention to improving resource and environmental burden by implementing circular economy (CE) strategies has concentrated mostly on buildings (EC, 2020), with studies and guidelines for circular infrastructure lacking so far. In the Netherlands alone, the construction sector is responsible for 50% of raw material consumption, 40% of solid waste, and approximately 35% of GHG emissions (Government of the Netherlands, 2016). The Dutch government aims to transform the sector by reducing primary material use by 50% by 2030, eliminating GHG emissions, and achieving a high level of circularity by 2050 (Rijksoverheid, 2021; Verhagen et al., 2021).

Coenen et al. (2023) identified that circularity in Dutch infrastructure has socio-technical causal chains, with many lock-in mechanisms that are hard to overcome. Reaching circularity in this sector must go beyond material circularity and offer multidimensional and context-specific solutions.

Product-service systems (PSS) can offer a bridge between technical and social factors to reach a context-tailored model and help to overcome several barriers such as knowledge, co-creation, collaboration, stakeholder involvement, financing, reduction of waste, and more.

PSS is recognized as one of the circular strategies to decrease material and environmental footprint while engaging with the stakeholders (Kjaer et al., 2019; Tukker, 2015). PSS has various tangible and intangible elements for delivering optimal value to the client (Apostolov et al., 2018; Belkadi et al., 2020). They are seen as a business model strategies that can improve companies' circularity regarding resource use, namely by implementing R strategies (re-entering the materials back into the system R3-R9 ex., recycle, reuse, remanufacturing), narrowing and slowing materials loops, or rethinking the product use at the conceptual level (Guzzo et al., 2019; Kjaer et al., 2019; Kristensen and Remmen, 2019; Matschewsky, 2019; Ramsheva et al., 2020). However, circular PSS does not automatically lead to environmental benefits or circularity (Belkadi et al., 2020; Kjaer et al., 2019; Lingegård et al., 2021; Mont and Lindhqvist, 2003; Mont, 2002; Tukker, 2015). The same authors call for more proof of circularity.

There are various ways to include circularity in the PSS that can also be applied to the infrastructure. Design, manufacturing, servicing, and remanufacturing are seen as the role of producers, while the industrial customers are involved in usage and disposal (Aurich et al., 2007). Although the civil engineering and infrastructure sector (in the Dutch Grond/Weg/Waterbouw GWW sector) reports increased circularity with

---

[*] Corresponding author.
E-mail address: d.tgsrv@gmail.com (D.A. Teigiserova).

https://doi.org/10.1016/j.resconrec.2023.107230

almost equal use of primary and secondary resources (primary: secondary 46:54 in 2019), 88% of the secondary material input is recycled granulate used for roads foundation or site elevation (primary: secondary 89:11 excluding road infrastructure). Current projections for material demand indicate 27% and 13% theoretical deficiencies in 2030 and 2050, respectively (assuming 100% recycling or reuse of CDW) (Economisch Instituut voor de Bouw, 2022). These figures indicate the infeasibility of current circular practices and circular targets. Moreover, the systemic strategies concentrate on lower Rs in the R ladder, such as recycling instead of reducing and reusing materials (Zhang et al., 2020). One of the reasons could be that recycling is easier to track and measure, and it is already implemented in the industry (ex., road materials).

The PSS for infrastructure has been only studied by a few scholars previously, and the measurement of circularity is lacking (Eriksson et al., 2019; Lingegård et al., 2021, 2011; Lingegård and Svensson, 2014). Moreover, PSS integration must be matched with suitable measures for data linked to performance and functionality (Belkadi et al., 2020).

However, it is impossible to create the circular sector and apply new strategies, such as PSS, without appropriate data availability, which enables to uncover of points of improvement for circularity, current technology availability, enhancing discussion among stakeholders on the achievability of goals, and potentially decrease transaction costs by making the process of solution implementation faster (Schraven et al., 2023). There is insufficient knowledge of physical asset data traceability which impacts the uncertainty factor impeding the implementation of higher R strategies (Copper 8, 2022). There is limited experience in deconstruction and knowledge of reuse application of civil structures and elements (Huuhka and Hakanen, 2015), and in general, the CE has not yet embedded standards and (design) practices and generally entails higher upfront costs (Ghisellini et al., 2018; Grafström and Aasma, 2021). Lack of complete, systematic, and integrated data about CE projects prevents to build a source of quality knowledge and monitoring of CE (Morseletto and Haas, 2023).

Many efforts are currently in motion to improve the future potential for reuse realization using different tools such as Building Information Modeling (BIM), modular construction, and setting up reuse databases (Aguiar et al., 2019; Iacovidou and Purnell, 2016; Qu et al., 2020). However, these efforts come too late in the process to realize short-term change, leaving a large circularity potential untapped.

In this article, we provided insight of the analysis of five infrastructure pilots in the Netherlands from the Circular Road program (Schraven et al., 2023). The pilots included various infrastructure assets intending to increase circularity with PSS models: bridge deck, guide rails, road lights, municipal road, and provincial road. The PSS contracts for these were concluded in 2021 and 2022, which allows for an ex-post analysis.

Therefore, this article aims to bridge the gaps in the current scientific literature, namely a) lack of empirical proof on the circularity of PSS, b) further needed examples of infrastructure PSS c) lack of data availability and traceability. The objectives include 1) showcasing solutions for circularity and PSS intersection for the infrastructure sector, 2) providing evidence of the impact of PSS models on circularity metrics in the infrastructure sector, 3) elucidating the practical challenges in the data collection process for circularity data on existing and new projects to achieve circular economy and its monitoring.

2. Methods

2.1. Project specifics and infrastructure assets

Previous studies for the PSS of infrastructure elucidate the public-private relationship (Lingegård and Svensson, 2014), its connection to circular procurement (Lingegård et al., 2021), and case studies from Sweden and UK on railways, roads, and tunnels (Eriksson et al., 2019; Lingegård et al., 2011). However, concrete and measurable proofs of material circularity and circular strategies such as economic cost indicators (ECI), material circularity indexes (e.g., MFA), or life cycle assessments (LCA) are missing. These methods are not yet commonly and widely accepted and accessible in the construction sector. Thus, the present study included evidence-based measurement of circularity that complied with the Dutch infrastructure sector to enhance possible scale-up and integration into practice.

Table 1
Overview of pilot cases.

Infrastructure asset	Municipality/ Province	Details
Bridge deck	Amersfoort municipality	Wooden bridge with a bicycle path and pedestrian path.
Guide rails	Province of North Holland	Using refurbished guide rails with a new zinc layer whenever quality and safety allow it.
Road lights	Province of North Brabant	Digitally controlled dimmable road lights. Modular design for the new lamp posts.
Municipal road	Amersfoort municipality	Functional and sustainable reconstruction and maintenance of the road.
Provincial road	Province of Overijssel	Sustainable management of the provincial road.

The Circular Road Program (The Circulaire Weg) investigates the implementation of circular PSS in infrastructure under realistic conditions via the five pilots with different clients and various infrastructure assets, namely: bridge deck, road lights, municipal road, provincial road, and guide rails, see Table 1. More details can be found in the program report, such as capital costs, technical details, PSS framework for each case, and stakeholder analysis of barriers and enablers (Schraven et al., 2023). The pilots were relatively small to allow an experimental process associated with higher uncertainties, with capital costs around €700 thousand, except for the Provincial road, which was about €5.5 million, see section 2.3.2 in (Schraven et al., 2023). PSS was negotiated to increase circularity for the assets between the client's public authorities and the contractor. The aim of the stakeholders was to explore novel options to reach ambition circularity goals in the construction sector in the Netherlands (50% reduction of primary materials by 2030, waste-free economy by 2050 (Rijksoverheid, 2021; Verhagen et al., 2021)). The pilots each have the same single contractor but four various public clients/customers (one city and three provinces). These conditions allowed a level of consistency in terms of products and services offered in each pilot, with enough variety in the demand of public clients to introspect the conditions PSS infrastructure offers. As circular public procurement shifts towards a contract with price per delivered service (as opposed to traditional price per unit) (Lingegård et al., 2021), there is a need to provide clarity on how this can be achieved. Outsourcing each stage (design, construction, maintenance, end-of-life) separately leads to a lack of lifecycle perspective (Lingegård et al., 2021). If not included, both systemic circularity and systemic change of BAU are unlikely. PSS is among the solutions to achieve this as they shift the conversation between client and contractor. Within the project, it was found that lack of knowledge is among the strongest barriers (Schraven et al., 2023). Similar findings for PSS have been reported (Ceschin, 2012; Lambrecht Ipsen et al., 2021; Nag et al., 2021). This is even more prominent in the infrastructure sector as the government acts as the asset owner. In order to include circularity in the traditional contract, the client needs to include it in the criteria for the asset contract specifically. However, economic criteria are still dominant in winning the bid with the business-as-usual (BAU) approach that engages in little creativity (Limpers, 2020; Santen, 2020).

2.2. Measuring circularity

The data collection, processing, and analysis resulted from iteratively combining theoretical (from academic literature) and empirical insights (from the Dutch infrastructure practice) during the research

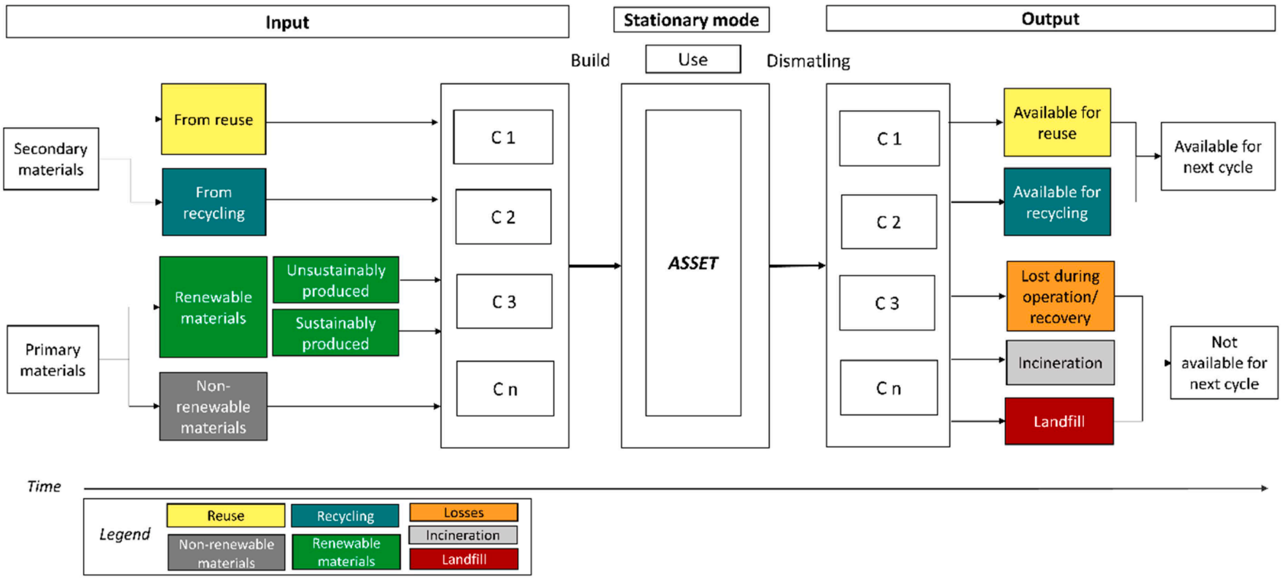


Fig. 1. Methodology overview for infrastructure assets based on platform CB'23 categories for input and output materials for the construction sector. C stands for a component of the asset. Same color coding is using the material analysis in the results.

process. The PSS model was modeled based on a functional hierarchy according to Van Ostaeyen et al. (2013). The model allowed us to distinguish clients' demand, function, and technicality of each project as well as generic infrastructure features, such as safety and availability of the asset, from circular and sustainable features, such as increased use of recycled input and improved ECI. Integrated solutions must be matched with adequate measures for data linked to performance and functionality (Belkadi et al., 2020).

To measure circularity, data on all material inputs and output were collected following Platform CB'23 version 2.0 of the Guide for measuring circularity (Platform CB'23, 2020), details on categories are included in Fig. 1. This considered materials needed for the asset construction and end-of-life according to the currently available technologies. Changes in the material flow during the maintenance were not considered except for the roads (due to BAU data available in the construction sector). Any new materials added or at the EoL during the maintenance will follow the same route are projected input and outputs. For example, the wood from the bridge deck will be recycled and not incinerated, and steel from the guide rails will be refurbished when quality allows it.

The CB'23 method is projected to be standardized in the Dutch construction industry, supported by Building & Utility (B&U) and civil engineering and infrastructure sectors. The CB23 method is similar to the traditionally-used Material Flow Analysis (MFA), which captures both inputs and outputs of materials, but it also distinguishes sustainability, primary, and secondary resources via several categories. Each category is subdivided into separate streams, as depicted in Fig. 1. It allows to capture of materials used throughout the whole lifecycle of construction projects and can be used for any scale (building elements to entire structure), considering an asset as a complex structure that can change its components over the lifetime. For example, the bridge can last several decades, but some of its components can be changed to prolong its lifetime and enhance its circularity.

The input materials have four distinct categories: primary materials, secondary materials, physical scarcity, and socioeconomic scarcity. The latter two are separate indicators that can be used in more detailed assessments for sustainability and can be determined using the predefined lists of physically/socioeconomically scarce materials in the guideline of CB'23. These are excluded from the present study (more can be found in Schraven et al. (2023)). It is important that in terms of building a sustainable circular sector, here not only primary non-renewable materials are distinguished, but also sustainable and unsustainable renewable materials. An example of sustainable renewable materials used in the project is timber with the Forest Stewardship Council certificate (Forest Stewardship Council, 2022), which was used as the main material for bridge deck pilot. Physical scarcity is defined by the "geological availability of stocks of raw materials and the risk of their becoming depleted." The degree of socioeconomic scarcity includes raw materials with regard to their economic relevance and risks of security of supply. The output materials or end-of-life use is based on what can realistically be expected for a certain material at the end of its lifetime.

In assessing the projects, a list of all material input was comprised. For each material individually, the categories of CB'23 were tracked by mass (kg, ton, etc.) and then transformed into percentages per category as specified in the generalized equation below to provide more tangible data for processing.

$$X_x = \frac{\sum i(m_i \times p_i)}{\sum im_i}$$

Where:

X_x represents the percentage of a given indicator (see Fig. 1) w.r.t. the total mass of the object. m_i is the mass of a single material for the given indicator. p_i is the proportion, by mass, of a single material w.r.t. the total mass of the object.

2.3. Data acquisition

Data collection methods for the material quantities per individual material used in each project for each CB'23 indicator varied across projects. The data were supplied directly from the contractor and their suppliers and verified with internal experts. The case of the Road Lights and 3–5% of other found cases (of the quantity of materials) was supplied via reference material from literature, LCA studies, EPD, or online databases such as DuboCalc (during year 2022). The reference material was obtained for the individual materials comprising the object (project). These reference materials were extrapolated to the approximated project case material quantities and their ECI values compared to the actual project to obtain insights on the circularity scores.

The 'physically scarce materials' indicator data was unavailable for all projects and therefore left out of the study. This has an insignificant impact on the circularity as it does not influence the input or output streams and can be seen as a separate metric for the sustainability of the

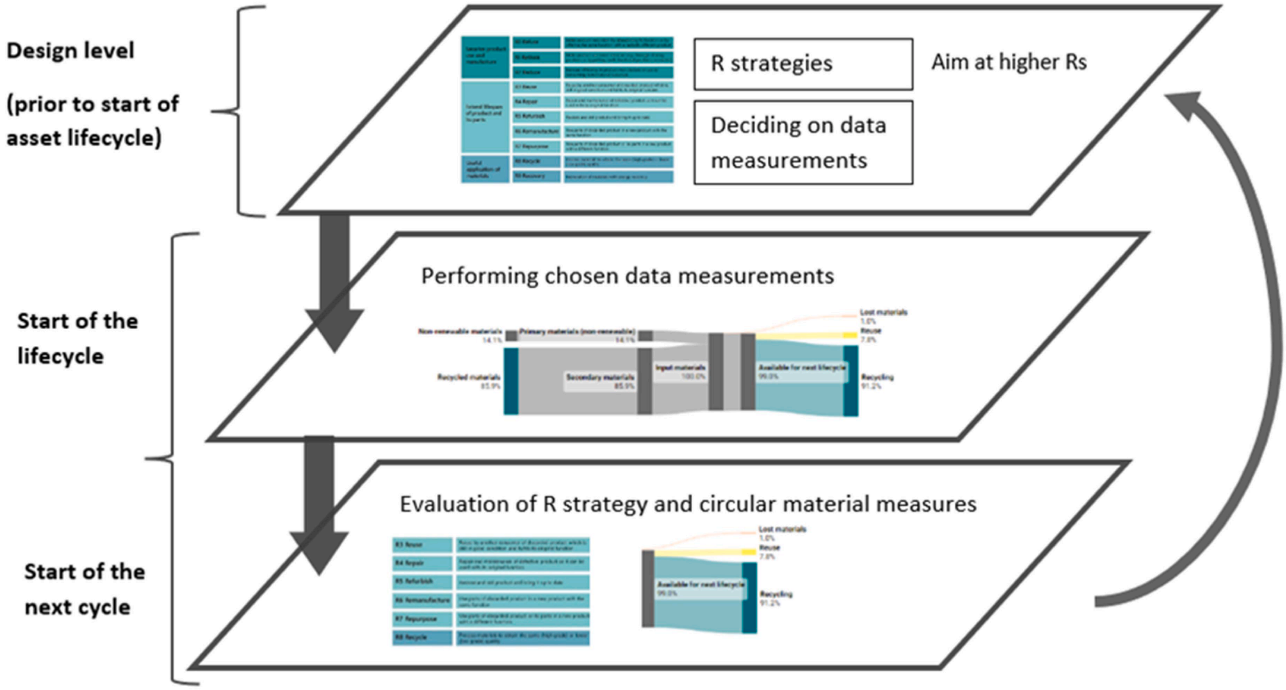


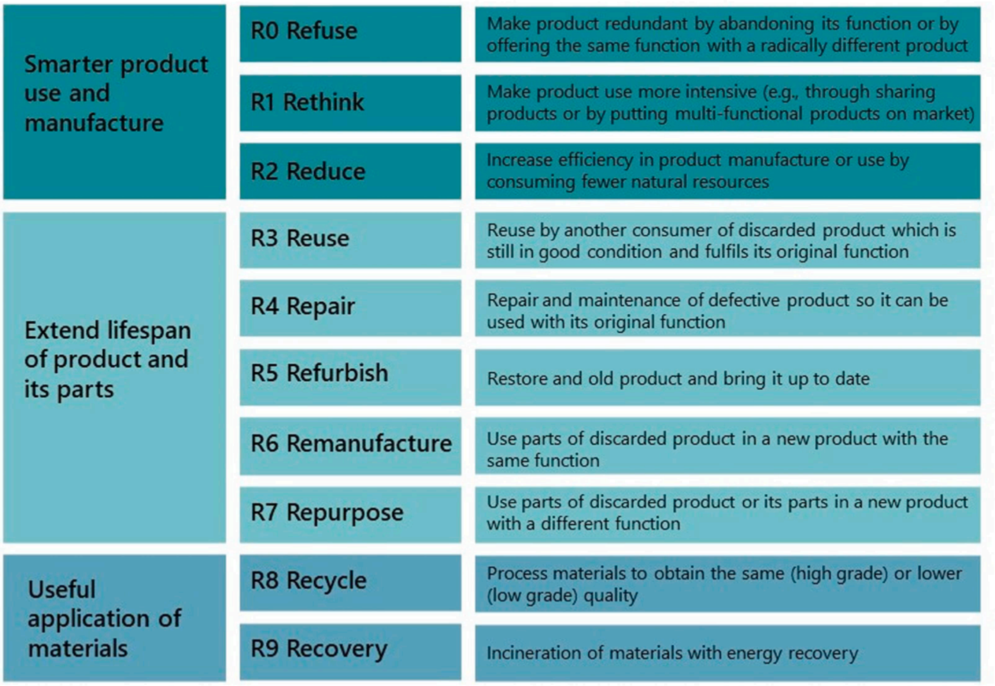
Fig. 2. Framework for circular PSS design process for infrastructure assets.

construction industry in relation to natural resource depletion.

3. Results

3.1. Framework for circular PSS design process for infrastructure assets

In the last decade, the relationship between PSS and the circular economy has been debated. A few key roles can be discerned. First, the PSS models promise that services can lead to more circularity for circular business model (Rosa et al., 2019). Some authors have even suggested that PSS is one of the paradigms of the CE transition (Delgadillo et al., 2019; Sopjani et al., 2020). The appeal of PSS to CE lies in the assumption that fulfilling customer needs (providing service) does not necessarily accompany the need to possess materials (providing product). Another circular aim of PSS models is unlocking opportunities to effectively manage the life cycle of products (Sousa-Zomer et al., 2017). However, scholars widely agree on the fact that more evidence is needed because PSS is not implemented at a large scale yet (Bressanelli et al., 2017; de Jesus Pacheco et al., 2019; Sousa-Zomer et al., 2017). There are several ways how to track circularity, with one of the most popular being

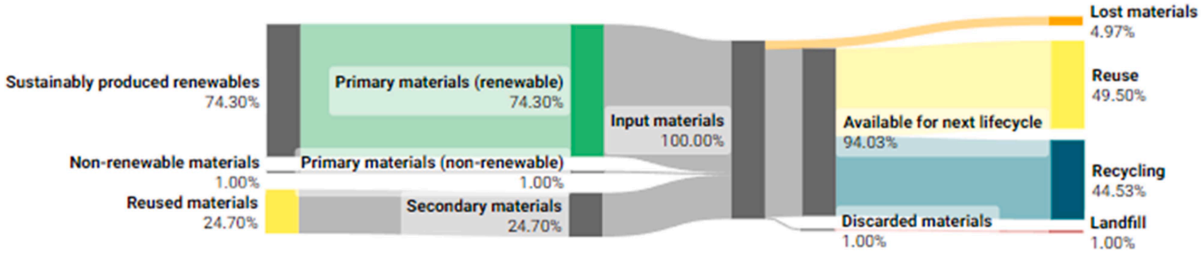


Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g., through sharing products or by putting multi-functional products on market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore and old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use parts of discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recovery	Incineration of materials with energy recovery

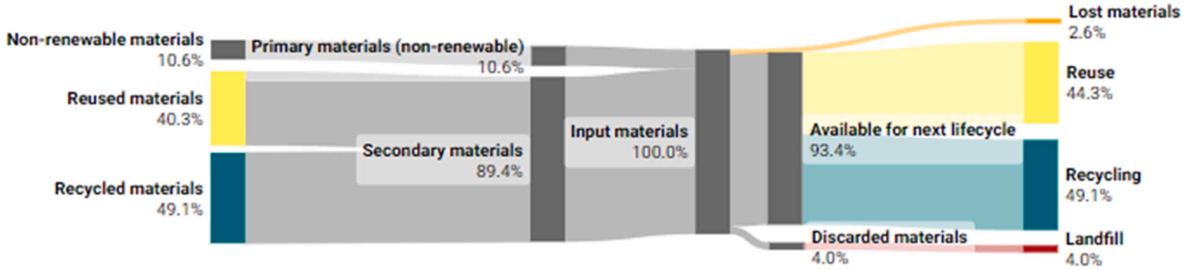
Fig. 3. The 10 R-strategies (Schraven et al., 2023) based on Morseletto (2020).

Table 2
The summary of R strategies implemented per pilot.

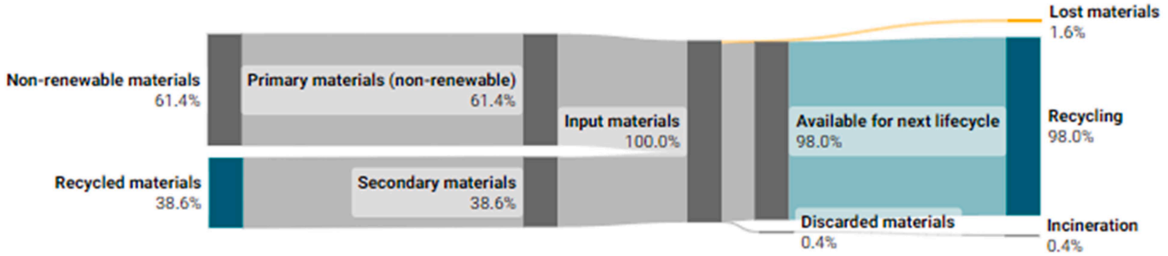
	Bridge deck	Guide rails	Road lights	Municipal road	Provincial road
R0 Refuse				Single road instead of double road, ultimately halving the amount of materials.	
R1 Rethink	Rethinking design, after alternatives for bridge materials, sustainably certified wood was chosen with additional coating prolonging the lifetime of the wood. Proper and timely maintenance to prolong lifetime.	Changing design from double to one-sided rail. Collaborating with local refurbishment company. Proper and timely maintenance to prolong lifetime.	Including digitalization with higher capital costs to prolong lifetime and increase efficiency. Gradual phasing of old lamp posts for modular design with prolonged lifetime.	Rethinking design including input from local residents with a discussion that led to a single instead of a double road. Proper and timely maintenance to prolong lifetime.	Implemented in the design and materials with a prolonged lifetime. Proper and timely maintenance to prolong lifetime with minimal disruption to the road users.
R2 Reduce	Reducing materials whenever possible, including reduction of primary materials	Reducing half of the materials with one-sided rail instead of double-sided rail	Included as 58% reduction of energy (not material reduction)	Reducing materials whenever possible, including reduction of primary materials	Reduction of primary materials
R3 Reuse	Ply wood planks are reused on the pedestrian side of the bridge deck	Reuse of steel whenever quality permits it.	A new modular design will allow reuse.		
R4 Repair	Bridge deck reparation and maintenance	Repair with refurbished parts when possible	Modular reparation and maintenance	Circular reparation	Maintenance
R5 Refurbish	Old wood planks are refurbished (antislip layer is added)	Refurbish the old guard rail with a new zinc layer	Modular reparation and maintenance		
R6 Remanufacture	*Not foreseen for any of the projects*				
R7 Repurpose	If possible, repurpose wood locally				
R8 Recycle	When wood quality is decreased beyond reuse, refurbish, and repurpose	When the quality of steel is decreased beyond refurbish	Recycling of materials whenever possible (metal, plastic, electronic parts, etc.)	Recycling at the end of life (ex., sand, asphalt)	Recycling at the end of life (ex., sand, asphalt)
R9 Recover	*Not foreseen for any of the projects*				



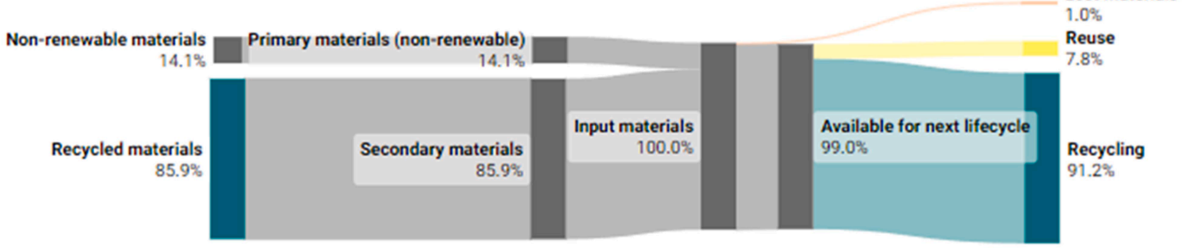
a) Bridge deck



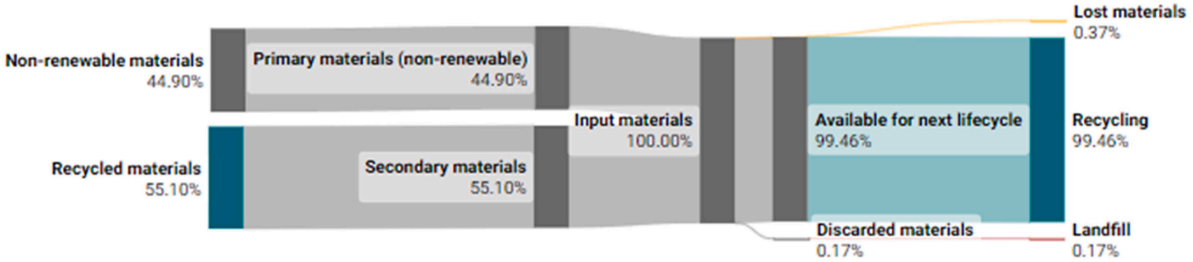
b) Guide rails



c) Dimmable road lights



d) Municipal road



e) Provincial road

Fig. 4. Material input and output per pilots a) Bridge deck b) Guide rails c) Dimmable road lights d) Municipal road e) Provincial road.

R-strategies (Morseletto, 2020) and tracking of input and output of the materials used via methods such as material flow analysis (MFA). However, to fully implement circularity, strategies need to be considered at the design level before the start of the lifecycle. Fig. 2 represents a framework for the circular design process in three levels. To align PSS integration with suitable measures for data, which are linked to performance and functionality (Belkadi et al., 2020). At the top level, the design elements are considered via R-strategies and possible circular measurements. At the middle level – the start of the lifecycle – strategies have been implemented, and the material circularity can be calculated.

At the bottom level, the circular evaluation of the asset/project takes place for a) implemented R strategies for re-entering the materials back into the system (R3-R9, details in the 3.2.1) b) material circularity data and methodology. The output of the evaluation is then input to the top level, where improvements in the circularity can be made again. The following sections go into detail using an evidence-based approach from the five pilots.

3.2. R-strategies

The R strategies considered in the pilots were based on the 10Rs (sometimes referred to as 9R), see Fig. 3. These strategies can be considered at the design level (prior to material use), for the input materials, and at the end-of-life (EoL) treatments. When it comes to the increasing circularity of materials, in general, not only in the construction sector, recycling is the most common strategy applied (Corona et al., 2019; Schöggl et al., 2020). Moreover, the strategies that can be measured are more common, i.e., reuse and recycling of materials. The top strategies, refuse and rethink, have a more descriptive than prescriptive (measurable) character when implemented and thus are less commonly used. In order to implement them, the overall project's design needs to be considered. Rethink is mostly included as a repair during the maintenance part of the contract, thus making it a service PSS feature. Usually, maintenance is a separate contract, subcontracted by the client (government), and provided by a different company than the original construction company. Rethink involves intensifying product use, including maintenance and repair to prolong the product's lifetime. Previous literature mentions repair and maintenance services as rethink strategy when buying products such as refrigerators or laptops for the duration of their lifetime (Kjaer et al., 2019).

Table 2 showcases the implementation of R strategies in the pilots. Rethink mostly refers to rethinking the design options either as choosing more intensive use of the asset, more circular aspects, and prolonging the lifetime, as well as a requirement to provide improved Environmental Costs Indicator (ECI, or in Dutch Milieu Kosten Indicator or MKI). All projects aimed to reduce primary materials at the design level, R0-R2, as well as prolonging the lifetime of the materials R3-R7, and R8 was considered when other options were not feasible based on state-of-art technologies (not novel technologies).

R3 to R7 are included in the various levels in the pilots due to the different asset management and limit of the material used (i.e., the difference between asphalt road and modular road light). Reuse was implemented as reused materials, when possible, but this is limited based on materials used and quality at the end of life. Remanufacture is not foreseen due to materials used in the project, as they are more likely to be directly reused (wood planks from bridge deck), refurbished (guide rails "upgraded" with new zinc layer), repurposed (wood planks used for different purpose on location, such as planters, or roads), or recycling. Recycle is the base strategy for all cases, either due to decreased quality of material not allowing higher R strategies, such as for wood or steel, or when the materials cannot be used for higher R strategies at the end life, such as asphalt. The pilots aim to have no energy recovery, mainly due to the material used, which do not commonly go to incineration, such as metal and asphalt. The wooden bridge deck will be reused and repurposed as much as possible instead of incineration with energy recovery with BAU.

3.3. Material circularity of case studies

Fig. 4 below represents the input and output material according to the categories of Platform CB'23. The five pilot cases all achieved higher circularity for inputs and outputs (Schraven et al., 2023), and Fig. 4 represents material flow details for individual pilots. The pilots decreased their input of primary materials for the Bridge deck from 100% (wood) to 75.3% (sustainable wood with plastic coating and 26.7% reused wood), Guide rails from 97,9% (mainly steel) to 10.6% (due to the use of refurbished steel); Municipal road from 19% to 14% due to an improved mixture of asphalt, which is the same case for Provincial road, but includes a higher scale leading to decrease from 93, 4% of primary materials to 44,9%, see Table A Appendix A (more on the comparison to the reference can be found in Table 6 in Schraven et al. (2023). Table A also includes details on output comparison to BAU with similar improvement per each case where R3-R9 has been increased. Road lights did not have a reference case due to digitalization and the gradual implementation of the modular design. It is likely that (not considering the lifetime) the input of primary materials increased, but will lead to future savings of materials, longer lifetime, and energy savings due to digitalization (dynamic dimming lights).

For the input materials for each case, primary non-renewable materials are still used; in the current cases, this is due to state-of-art technology (the pilots did not aim to explore novel technologies) and safety standards (for example, for guide rails and roads). There is minor landfilling for the outputs as not all construction materials can be processed for R strategies and CE, and the EoL only includes currently available technologies (not new/novel technologies) to represent realistically achievable scenarios. The only scenario not including landfilling is the road lights due to lack of data where theoretical reuse and recycling is very high due to the main material being metal. Overall, there are minor losses in the system. However, it can be assumed that these losses can be higher depending on the treatment and maintenance.

The bridge deck (4a) is the only case that uses renewable materials. The cases of roads, guide rails, and road lights currently do not embed renewable materials as state-of-art or common practice. The bridge deck was made from reused wood planks resulting in 24.8% primary material savings. The planks used are FSC-certified wood, considered a sustainably produced material. The municipality and contractor aim to reuse the wood locally at EoL, either on the walking path or for other uses. If the degradation of wood prevents reuse, the wood will be recycled instead of traditional EoL, which is incineration.

The guide rails (4b) integrate a novel approach of reusing the old beams and adding a new zinc layer decreasing primary material input by 87.3%. However, for safety reasons, this is only possible for the upper part of the guide rail beams, not for the poles (connected to the ground). Thus, this case can be considered as the peak of circularity that can be achieved under the current state-of-art technology. If the quality of the beam is decreased, that part of the cut, together with beam parts that cannot be processed otherwise, is sent for recycling (metal scrap dealers.). Such design for guard rails is not yet common practice, and if standardized, it can lead to significant material saving for steel, which is both environmentally and economically burdensome material (Carter et al., 2000; Wang et al., 2018).

The road lights (4c) include higher primary resource consumption as input due to a combination of old lamposts still being in use and the installation of a new modular design (which includes primary materials). There was no reference case that the savings on primary material inputs were not available. However, this case represents a high potential for reuse and recycling of the output due to the modular design, which allows to efficient replace only the faulty or damaged part instead of the entirety of the lamp post. What is not visible in Fig. 4c is the energy saving achieved by installing the digital system for dimming the lights. The Sankey diagram is limited to the material used for the pilot. However, this pilot has energy efficiency in mind from the start and achieved a 58% energy reduction in the first year of employment (Schraven et al., 2023). This case also has the potential for scale-up and becoming more common practice and can benefit from the current advances in the digital PSS.

The cases of municipal (4d) and provincial (4e) roads both use similar state-of-art materials. It is now common practice for asphalt to have a high recycled material input and output. Asphalt is the main component of the road (weight and volume). The difference between the road is the type of asphalts used in the mixture, which has more recycled content for the municipal road mainly due to safety and durability as the

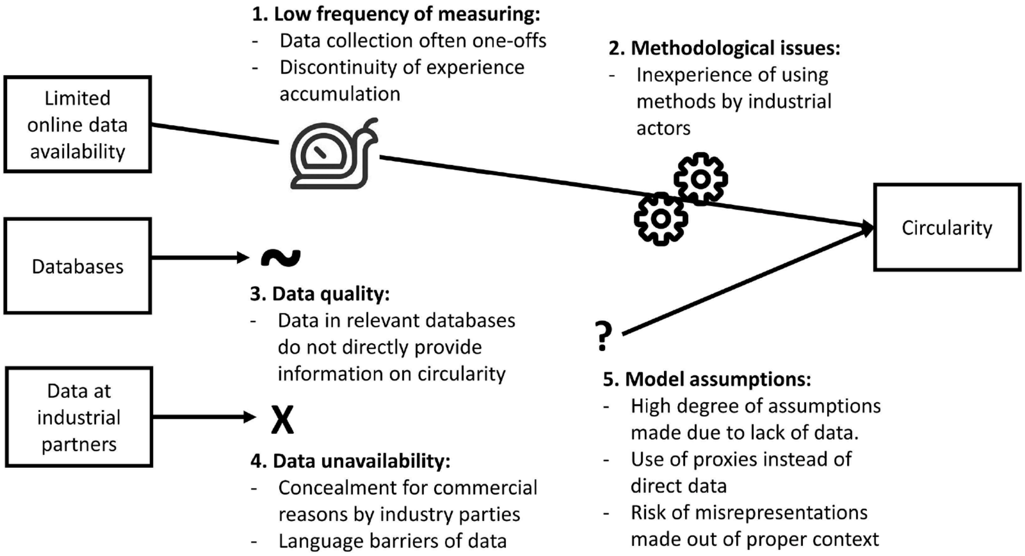


Fig. 5. Challenges of circular data collection.

provincial road is under more duress. Due to materials used for the roads, recycling is the main strategy available, and little reuse can be expected. The provincial road resulted in 48.5% primary material saving when compared to the BAU reference, while the municipal road saved 4.9%. Additionally, Fig. 4d for the municipal road only reflects the material used, not the design. This design included a 50% material reduction prior to the pilot implementation due to a decrease in the size of the road after agreement with the residents.

4. Discussion

4.1. Pilot PSS models and circularity

PSS models differentiate between client and contractor responsibilities, where at some point during the contract formulation, the client stops defining the service and leaves the responsibility to the contractor. For example, the client of the road asks for a decrease of primary materials but does not specify how the contractor needs to achieve it. It also means that some client demands can be very specific and more important than others, especially for the infrastructure sector. Similarities are found in all models: safety and following the guidelines (national and EU level) is the top priority in the PSS infrastructure contracts. These differ per type of asset. For example, the bridge has to follow different safety and technical requirement than the road or guide rails. Other guidelines include internal municipal or provincial guidelines (e.g., esthetic rules). This is applied for input materials, maintenance of the asset, and end-of-life of materials. Circularity is a secondary demand. Thus, the current guideline and policies have a great influence. For example, the steel can only be refurbished for certain parts of the guide rails due to safety standards.

All pilots integrated circularity in different ways. More circularity was found in the PSS when the client was more involved in the contract formulation and “pushed” for more circular features (Bridge deck and municipal road), while less circularity was found (in the contract) when the client was less involved (guide rails, road lights, and provincial road). The most innovative pilot technology-wise are road lights, which required close demonstration and collaboration between contractor and client to decrease uncertainties for the safety when using dimming lights.

In all cases, knowledge exchange was found as critical and most influential for both PSS contract formulation, the increase of circularity, and the decrease of uncertainties (identified via analysis in Schraven et al. (2023).

4.2. The challenges of data transparency and data acquisition

In order to create a transparent circular economy that is ready to share best practices and create a sector for a fully circular exchange of construction materials, data availability is of utmost relevance. However, the data acquisition process, transparency of data, and communication by industry players (i.e., contractors and suppliers) in the construction sector are very challenging. Reference for products and individual materials are accessible to a limited extent. Additionally, the data collection and circular strategies, such as R strategies, need to be considered at the design level, as illustrated in the result section. Strategies such as refuse include material reduction that happens before the lifecycle starts, and thus, while being the preferred strategy to enhance material decoupling, it is not visible when performing an analysis of material circularity for the lifecycle of the asset.

The following observations were made by the authors regarding this issue, represented in Fig. 5:

- Despite the general awareness of the CE transition and its urgency, measuring circularity in projects is difficult to implement and, therefore, not done frequently. Hence the low quantity of data to be found online.
- When the (required data for) circularity indicators are available, industry players tend to conceal this information to maintain their competitive advantage for future tenders (e.g., asphalt mixes).
- Industry players are still getting accustomed to measuring LCA/ECI data for their projects. These measures are mostly calculated if the client has specifically asked for them or the contractor has a high interest in environmental and sustainable advancement.
- Reports are often only shared in the country’s language, limiting data availability significantly.
- Sharing LCA/EPD data is more common for other industries (e.g., manufacturing) as they produce large quantities of shelf products where measuring requires relatively low costs as opposed to one-off infrastructure projects in the construction industry.
- The available documentation mainly concerns LCA/ECI studies, where the limited information on circularity is disclosed outside of high-level assumptions on the entire product.
- Assigning certain recycling/reuse/loss/landfill/incineration percentages for a given material based on material averages found in literature can grossly misrepresent the project case as it could be that the contractor is highly aware of circular concepts or very negligent during deconstruction or demolition. For example, it does not make

sense that it is decided that only 80% of the screws are recycled, 10% reused, 5% landfilled, and 5% lost while there is the possibility to recycle 100%. Generally, decisions are made to do one (though there can be losses in realizing this).

In addition to these points, it was observed that the 'go-to' databases for sustainability and circularity, such as DuboCalc (Netherlands) (DuboCalc, 2023) or EcoInvent (Europe) (Ecoinvent, 2023), are aimed at LCA/ECI data for individual products. Although there are efforts to increase this data transparency, such as the National Environmental Database (in Dutch: Nationale Milieu Database (NMD)), it is observed that circularity data is still lacking as efforts are focused on LCA/ECI data that do not directly provide information on circularity (e.g., reuse possibilities). Even though LCA studies include the aspect of circularity in their D-indicator (taking into account emission savings through reusing/recycling), it is very challenging to derive the level of circularity as the metrics are expressed in 'negative emissions' based on the weight and characteristics of the given material. Moreover, these databases are not freely accessible to the general public, decreasing the accessibility of reference data even more significantly.

It is very difficult for industry players to determine the rate of R strategies (R3-R7) for the materials due to the long lifecycle of infrastructure assets (sometimes 80–100 years), as those rates cannot be guaranteed in the present, leading to uncertainties. These projections can only be reliable once technologies have become part of the BAU. For example, current-day recycling technology is still considered 'downcycling', which is not a sustainable method for a circular economy (Di Maria et al., 2018; Zuidema et al., 2016).

Some of the key drivers for short-term change in the industry concern detailed study and understanding of previously reported data for construction assets via third-party databases (e.g., MADASTER, Bruggenbank), improving circularity data transparency (Dräger et al., 2022), standardizing methods for measuring and monitoring circularity (Abadi et al., 2021; Dräger et al., 2022; Platform CB'23, 2020), and employing new business models to incentivize circular decision-making (Voorzitter Transitieteam Circulaire Bouweconomie, 2022).

By increasing circularity data transparency for new construction projects, data gaps for existing structures can be better approximated, and new projects can be compared and validated to create more accountability along the supply chain, including engineers/designers (by integrating measurements into the design). Without measuring and monitoring circularity and sustainability during the design phase, the goals are difficult to integrate into the decision-making process (Sassanelli et al., 2019; Tokazhanov et al., 2022). Moreover, the projects that do measure circularity and/or sustainability mostly tend to do so once the design is finalized. By then, reworks for circularity are expensive and generally not pursued (Chakra, 2019). This calls for standardized circularity measuring metrics from design to improve the applicability and effectiveness in practice.

4.3. Recommendation for policymakers

Considering the findings, the author recommends that transparency and availability of data need to become mandatory. Although disclosing a high level of detail is not possible under current conditions to not hamper the free market and competitive advantage, some level of detail needs to be available in order to create a market for secondary resources. Such strategies are supported by the Dutch construction industry, Platform CB'23 (Platform CB'23, 2020), the Building & Utility (B&U) sector, and the civil engineering and infrastructure sector.

Moreover, the EU should provide a platform where a similar level of details on secondary input and outputs is available in the English language to enhance the potential use of the materials domestically and internationally (ex., neighboring countries such as in the case of BENELUX region).

The tender law needs to be closely inspected to investigate as an enabler and barrier of the circular economy progress, especially when it comes to a mandatory short-term contract that supports short-term goals for the construction sector instead of optimizing circularity, a lifetime of assets and sustainability (note: short-term in the infrastructure sector can vary from 2 to 5 years depending on the lifetime of the structure which can be up to 50–80 years).

From the pilots analyzed in the present study, the case of guard rails is of particular interest for future standardization leading to higher circularity and material savings of steel.

5. Conclusion

This article has provided a circular analysis of five different infrastructure PSS previously lacking in the scientific literature. It has shown that the PSS can significantly increase the project's material circularity due to interaction between the client and PSS provider, i.e., the construction company. We suggested a three-step framework that includes circularity consideration at the design level via R strategies and circularity metrics consideration, actual material measurement during the lifecycle, and the evaluation stage of implemented metrics and strategies as input for further improvement. By doing so, the barrier of lack of knowledge between the client and contractor is overcomed, and collaboration is enhanced, which enables the integration of higher R-strategies, such as Reduce and Rethink, at the design level before the asset's lifecycle. As a result, circularity was improved in the design, input materials, and availability of secondary materials for all studied infrastructure assets: bridge deck, guide rails, road lights, municipal road, and provincial road. While the material circularity of the roads is currently well-establish due to recycled content and EoL treatment of asphalt, the case of municipal road shows that substantial savings can be made at the design level (50%material reduction before the lifecycle of the asset began). The guide rails represent a significant opportunity to make systemic changes that resulted in substantial material savings via refurbishing steel components. Similarly, using digital technology for dimmable road lights leads to substantial energy savings, increases future circularity due to modular design, and can be upscaled to more locations. The bridge deck showed that when using biodegradable materials, the effort can be made to reuse and recycle the materials locally instead of the typical treatment of incineration (commonly used for EoL wood). The measurements have been limited to these five objects, and thus more infrastructure objects and different scales should be studied to provide more proof.

This article established a sense of urgency within the industry by recommending centralized data transparency for circularity data using a standardized measuring methodology. The authors suggest improving data quality systematically and making data reporting mandatory by law in a harmonized way that allows setting up the market for secondary resources. Soon-approaching global and national goals for 2030 and beyond need traceable and transparent measures. Moreover, the data availability is then improved, leading to higher certainty levels on both environmental and economic impacts, which now often stem from proxy measures and have limited transparency when obtained under non-disclosure agreements.

CRediT authorship contribution statement

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

Declaration of Competing Interest

The authors declare that they have no known competing financial

Table A
The summary of Platform CB'23 indicator per pilot, with the addition of material losses. Reference is a business-as-usual scenario (BAU) There is no reference for the North Brabant road lights. A – Amersfoort; PNB – Province North Brabant; PNH – Province North Holland; O – Overijssel; U- Utrecht. Adapted from (Schraven et al., 2023).

Pilot Indicator	A Residential Road (%)	A Residential Road - Reference[1] (%)	A Bridge deck (%)	A Bridge deck Reference (%)	PNB Road lights (%)	PNH Guide rails (%)	PNH Guide rails – Reference (%)	O Provincial road (%)	O Provincial road – Reference (%)
1.1 The quantity of primary materials	14,1	19,0	75,3	100	61,4	10,6	97,9	44,9	93,4
1.1.1 The quantity of non-renewable primary materials	14,1	19,0	1,0	0,0	61,4	10,6	97,9	44,9	93,4
1.1.2a The quantity of sustainably produced, renewable primary materials	0,0	0,0	74,3	100	0,0	0,0	0,0	0,0	0,0
1.1.2b The quantity of unsustainably produced, renewable primary materials	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
1.2 The quantity of secondary materials	85,9	81,0	24,7	0,0	38,6	89,4	2,1	55,1	6,6
1.2.1 The quantity of secondary materials from reuse	0,0	0,0	24,7	0,0	0,0	40,3	0,0	0,0	0,0
1.2.2 The quantity of secondary materials from recycling	85,9	81,0	0,0	0,0	38,6	49,1	2,1	55,1	6,6
1.3 The quantity of physically scarce materials	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.4.1 The quantity of socio-economically scarce raw materials used	0,0	0,0	0,0	0,0	0,3	0,8	1,5	0,0	0,0
1.4.2 The quantity of socio-economically abundant raw materials used	100	100	100	100	99,6	99,2	98,5	100	100
2 Amount of output material	99,0	99,9	95,0	95,0	98,4	97,3	97,4	99,6	99,6
2.1 The quantity of end-of-life materials available for reuse	7,8	0,2	49,5	0,0	0,0	44,3	30,6	0,0	0,0
2.2 The quantity of end-of-life materials available for recycling	91,2	99,7	44,6	0,0	98,0	49,1	62,8	99,5	99,4
3.1 The quantity of end-of-life materials used for energy production	0,0	0,0	0,0	95,0	0,4	0,0	0,0	0,0	0,0
3.2 The quantity of end-of-life materials sent to landfill	0,0	0,0	1,0	0,0	0,0	4,0	4,0	0,2	0,2
Material losses (use, re-processing etc)	1,0	0,1	5,0	5,0	1,6	2,6	2,6	0,4	0,4

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This research has been funded by De Circulaire Weg partner program, Rijkswaterstaat and the Province of North Holland.

Appendix A

References

Abadi, M., Moore, D.R., Sammuneh, M.A., 2021. A framework of indicators to measure project circularity in construction circular economy. 175, 54–66. https://doi.org/10.1680/JMAPL.21.00020.

Aguiar, A., Vonk, R., Kamp, F., 2019. BIM and circular design. IOP Conf. Ser. Earth Environ. Sci. 225 https://doi.org/10.1088/1755-1315/225/1/012068.

Apostolov, H., Fischer, M., Olivotti, D., Dreyer, S., Breitner, M.H., Eigner, M., 2018. Modeling framework for integrated, model-based development of product-service systems. Procedia CIRP 73, 9–14. https://doi.org/10.1016/J.PROCIR.2018.03.307.

Aurich, J.C., Schweitzer, E., Fuchs, C., 2007. Life cycle management of industrial product-service systems. Adv. Life Cycle Eng. Sustain. Manuf. Businesses - Proc. 14th CIRP Conf. Life Cycle Eng. 171–176. https://doi.org/10.1007/978-1-84628-935-4_30.

Belkadi, F., Boli, N., Usatorre, L., Maleki, E., Alexopoulos, K., Bernard, A., Mourtzis, D., 2020. A knowledge-based collaborative platform for PSS design and production. CIRP J. Manuf. Sci. Technol. 29, 220–231. https://doi.org/10.1016/J.CIRPJ.2018.08.004.

Bressanelli, G., Perona, M., Saccani, N., 2017. Reshaping the washing machine industry through circular economy and product-service system business models. Procedia CIRP 64, 43–48. https://doi.org/10.1016/J.PROCIR.2017.03.065.

Carter, C.J., Murray, T.M., Thornton, W.A., 2000. Cost-effective steel building design. Prog. Struct. Engng Mater 2, 16–25. https://doi.org/10.1002/(SICI)1528-2716(200001/03)2:1.

Ceschin, F., 2012. Critical factors for implementing and diffusing sustainable product-Service systems: insights from innovation studies and companies' experiences. 10.1016/j.jclepro.2012.05.034.

Chakra, H.A., 2019. The impact of design changes in construction projects on the cost charged by consultant offices. BAU J. -Sci. Technol. 1.

Coenen, T.B.J., Visscher, K., Volker, L., 2023. A systemic perspective on transition barriers to a circular infrastructure sector. Constr. Manag. Econ. 41, 22–43. https://doi.org/10.1080/01446193.2022.2151024.

Copper 8, 2022. Materialen Expeditie EDITIE 2022 Geleerde lessen Rondom Hergebruik Tussen Projecten en Organisaties.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498 https://doi.org/10.1016/J.RESCONREC.2019.104498.

de Jesus Pacheco, D.A., ten Caten, C.S., Jung, C.F., Sassanelli, C., Terzi, S., 2019. Overcoming barriers towards sustainable product-service systems in small and medium-sized enterprises: state of the art and a novel decision matrix. J. Clean. Prod. 222, 903–921. https://doi.org/10.1016/J.JCLEPRO.2019.01.152.

Delgadillo, J., Estephania, E., Reyes Carrillo, T., Baumgartner, R., 2019. Circular PSS strategies: an exploration of the integration of territorial resources. In: Proceeding of the International Conference on Engineering Des. ICED 2019-August, pp. 3191–3200. https://doi.org/10.1017/DSI.2019.326.

Di Maria, A., Eyckmans, J., Van Acker, K., 2018. Downcycling versus recycling of construction and demolition waste: combining LCA and LCC to support sustainable policy making. Waste Manag. 75, 3–21. https://doi.org/10.1016/J.WASMAN.2018.01.028.

Dräger, P., Letmathe, P., Reinhart, L., Robineck, F., 2022. Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database. Environ. Sci. Eur. 34, 1–16. https://doi.org/10.1186/S12302-022-00589-0/TABLES/11.

DuboCalc, 2023. Dubo Calc Portal [WWW Document]. URL. https://www.dubocalc.nl/. accessed 3.21.23.

EC, 2020. Circular Economy Principles For Buildings Design.

Ecoinvent, 2023. Home - ecoinvent [WWW Document]. URL. https://ecoinvent.org/. accessed 3.21.23.

Economisch Instituut voor de Bouw, 2022. Materiaalstromen in de Bouw en Infra Materiaalstromen, Milieu-Impact en CO2 - Emissies in 2019, 2030 en 2050.

Eriksson, E., Volker, L., Kadefors, A., Lingegård, S., Larsson, J., Rosander, L., 2019. Collaborative procurement strategies for infrastructure projects: a multiple-case study. Manag. Procure. Law 172. https://doi.org/10.1680/jmapl.19.00016.

Forest Stewardship Council, 2022. Home Page | Forest Stewardship Council [WWW Document]. URL. https://fsc.org/en. accessed 3.30.22.

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod. 178, 618–643. https://doi.org/10.1016/J.JCLEPRO.2017.11.207.

Government of the Netherlands, 2016. Circular Dutch economy by 2050 | Circular Economy | Government.nl [WWW Document]. URL. https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050. accessed 3.9.23.

Grafström, J., Aasma, S., 2021. Breaking circular economy barriers. J. Clean. Prod. 292, 126002 https://doi.org/10.1016/J.JCLEPRO.2021.126002.

Guzzo, D., Trevisan, A.H., Echeveste, M., Costa, J.M.H., 2019. Circular innovation framework: verifying conceptual to practical decisions in sustainability-oriented product-service system cases. Sustain 11. https://doi.org/10.3390/su11123248.

Huuhka, S., Hakanen, J., 2015. Potential and barriers for reusing load-bearing building components in Finland. Int. J. Hous. Sci. Appl. 39, 215–244.

Iacovidou, E., Purnell, P., 2016. Mining the physical infrastructure: opportunities, barriers and interventions in promoting structural components reuse. Sci. Total Environ. 557–558, 791–807. https://doi.org/10.1016/J.SCITOTENV.2016.03.098.

Kjaer, L.L., Pigosso, D.C.A., Niero, M., Bech, N.M., McAloone, T.C., 2019. Product/Service-systems for a circular economy: the route to decoupling economic growth from resource consumption? J. Ind. Ecol. 23, 22–35. https://doi.org/10.1111/JIEC.12747.

Kristensen, H.S., Remmen, A., 2019. A framework for sustainable value propositions in product-service systems. J. Clean. Prod. 223, 25–35. https://doi.org/10.1016/J.JCLEPRO.2019.03.074.

Lambrecht Ipsen, K., Pizzol, M., Birkved, M., Amor, B., 2021. How lack of knowledge and tools hinders the eco-design of buildings-a systematic review. Urban Sci. 5, 20. https://doi.org/10.3390/urbansci5010020, 2021Page 20 5.

Limpers, J.W.M., 2020. Green Public Procurement in the Dutch Construction Sector: A qualitative Research on the Inclusion of Environmental Requirements in Procurement of Construction Projects. Delft University of Technology.

Lingegård, S., Havenvid, M.I., Eriksson, E., Rada, E.C., 2021. Circular public procurement through integrated contracts in the infrastructure sector. 10.3390/su132111983.

Lingegård, S., Lindahl, M., Svensson, N., 2011. PSS contracts for rail and road infrastructure. Funct. Think. Value Creat 291–296. https://doi.org/10.1007/978-3-642-19689-8_51.

Lingegård, S., Svensson, N., 2014. Scenarios for resource efficient rail infrastructure-applying integrated product service offerings. Procedia CIRP 16, 134–139. https://doi.org/10.1016/j.procir.2014.06.001.

Matschewsky, J., 2019. Unintended circularity?-Assessing a product-service system for its potential contribution to a circular economy. Sustain 11. https://doi.org/10.3390/su11102725.

Mont, O., Lindhqvist, T., 2003. The role of public policy in advancement of product service systems. J. Clean. Prod. 11, 905–914. https://doi.org/10.1016/S0959-6526(02)00152-X.

Mont, O.K., 2002. Clarifying the concept of product–service system. J. Clean. Prod. 10, 237–245. https://doi.org/10.1109/ACIIDS.2009.18.

Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553 https://doi.org/10.1016/J.RESCONREC.2019.104553.

Morseletto, P., Haas, W., 2023. Perspective A call for high-quality data to foster a decisive transformation towards a circular economy. 10.1016/j.resconrec.2023.107092.

Nag, U., Sharma, S.K., Govindan, K., 2021. Investigating drivers of circular supply chain with product-service system in automotive firms of an emerging economy. J. Clean. Prod. 319 https://doi.org/10.1016/j.jclepro.2021.128629.

Platform CB'23, 2020. Measuring circularity. Working Agreements for Circular Construction. Version 2.0.

Qu, C., Guan, J., Wang, T., Jiang, S., Sun, C., Mackenbach, S., Zeller, J.C., Osebold, R., 2020. A roadmap towards circularity-modular construction as a tool for circular economy in the built environment. IOP Conf. Ser. Earth Environ. Sci. A Roadmap Towar. Circ. Constr. as a Tool Circ. Econ. Built Environ. You may also like Dev. Dir. Focus new energy Ind. Jilin Prov. O… 588. 10.1088/1755-1315/588/5/052027.

Ramsheva, Y.K., Moalem, R.M., Milios, L., 2020. Realizing a circular concrete industry in denmark through an integrated product, service and system perspective. Sustain 12, 1–20. https://doi.org/10.3390/su12229423.

Rijksoverheid, 2021. Uitvoeringsprogramma circulaire economie 2021-2023 een Nieuw circul.

Rosa, P., Sassanelli, C., Terzi, S., 2019. Towards circular business models: a systematic literature review on classification frameworks and archetypes. J. Clean. Prod. 236, 117696 https://doi.org/10.1016/J.JCLEPRO.2019.117696.

Santen, L., 2020. The Role of Relational Governance in Achieving Sustainability in Infrastructure by Using MEAT Criteria. Delft University of Technology.

Sassanelli, C., Rosa, P., Rocca, R., Terzi, S., 2019. Circular economy performance assessment methods: a systematic literature review. J. Clean. Prod. 229, 440–453. https://doi.org/10.1016/J.JCLEPRO.2019.05.019.

Schöggl, J.P., Stumpf, L., Baumgartner, R.J., 2020. The narrative of sustainability and circular economy - A longitudinal review of two decades of research. Resour. Conserv. Recycl. 163, 105073 https://doi.org/10.1016/J.RESCONREC.2020.105073.

Schraven, D.F.J., Teigiserová, D.A., Noppers, F., 2023. Infrastructure as a Service: An analysis of the Circular Effectiveness, 2 ed. Technische Universiteit Delft, Delft.

Sopjani, L., Arekrans, J., Laurenti, R., Ritzén, S., 2020. Unlocking the linear lock-in: mapping research on barriers to transition. Sustain 12. https://doi.org/10.3390/SU12031034.

Sousa-Zomer, T.T., Magalhães, L., Zancul, E., Cauchick-Miguel, P.A., 2017. Lifecycle management of product-service systems: a preliminary investigation of a white goods manufacturer. Procedia CIRP 64, 31–36. https://doi.org/10.1016/J.PROCIR.2017.03.041.

Tokazhanov, G., Galiyev, O., Lukyanenko, A., Nauyryzbay, A., Ismagulov, R., Durdyev, S., Turkyilmaz, A., Karaca, F., 2022. Circularity assessment tool development for construction projects in emerging economies. J. Clean. Prod. 362, 132293 https://doi.org/10.1016/J.JCLEPRO.2022.132293.

Tukker, A., 2015. Product services for a resource-efficient and circular economy - a review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2013.11.049.

Van Ostaeyen, J., Van Horenbeek, A., Pintelon, L., Duflou, J.R., 2013. A refined typology of product-service systems based on functional hierarchy modeling. J. Clean. Prod. 51, 261–276. https://doi.org/10.1016/j.jclepro.2013.01.036.

Verhagen, T.J., Sauer, M.L., Voet, E.van der, Sprecher, B., 2021. Matching demolition and construction material flows, an urban mining case study. Sustain 13, 653. https://doi.org/10.3390/SU13020653, 2021Page 653 13.

Voorzitter Transitieteam Circulaire Bouweconomie, 2022. Adviesroute Naar een Circulaire Economie Voor de Bouw. https://doi.org/10.47711/0868-6351-190.

Wang, P., Kara, S., Hauschild, M.Z., 2018. Role of manufacturing towards achieving circular economy: the steel case. CIRP Ann 67, 21–24. https://doi.org/10.1016/J.CIRP.2018.04.049.

Zhang, C., Hu, M., Yang, X., Miranda-Xicotencatl, B., Sprecher, B., Di Maio, F., Zhong, X., Tukker, A., 2020. Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. J. Clean. Prod. 266, 121718 https://doi.org/10.1016/J.JCLEPRO.2020.121718.

Zuidema, M., Saitua, R., Smit, N., 2016. Macro-economische verkenning betonakkoord.