A guide for evaluating the environmental performance of Product/Service-Systems

DTU Technical University of Denmark

Louise Laumann Kjaer
Daniela C. A. Pigosso
Tim C. McAloone

This guide is one of the results of a PhD project at the Section for Engineering Design & Product Development, Department of Mechanical Engineering, Technical University of Denmark (DTU).

The project was co-funded by the TORM Foundation.

The guide is intended to assist designers and professionals working with sustainability and environmental assessments of Product/Service-Systems.

The authors would like to thank the following experts within the field, who were consulted and contributed to developing the guide:

Torben Chrintz, *Chief Knowledge Officer, CONCITO*
Mark Goedkoop, *CEO, PRé Consultants*
Michael Hauschild, *Professor, Technical University of Denmark*
Jannick Schmidt, *Associate Professor, Aalborg University*
Anne-Marie Tillman, *Professor, Chalmers University of Technology*

Authors:
Louise Laumann Kjaer, *Technical University of Denmark*
Daniela C. A. Pigosso, *Technical University of Denmark*
Tim C. McAloone, *Technical University of Denmark*

Layout and design: Claudia Roca Hornero and Cecilie Marie Hansen
Bottom left cover photo: With permission from Dansk Retursystem
Printed: MercoPrint A/S
Publication year: 2017
Edition: 1st
ISBN 978-87-7475-493-0
ISBE 978-87-7475-494-7

Contents

Introduction 5

Step 1: Goal definition 15

Step 2: PSS and reference system exploration 19

Step 3: Comparability assessment 31

Step 4: Process mapping 41

Step 5: Quantification 47

Step 6: Interpretation and recommendations 53

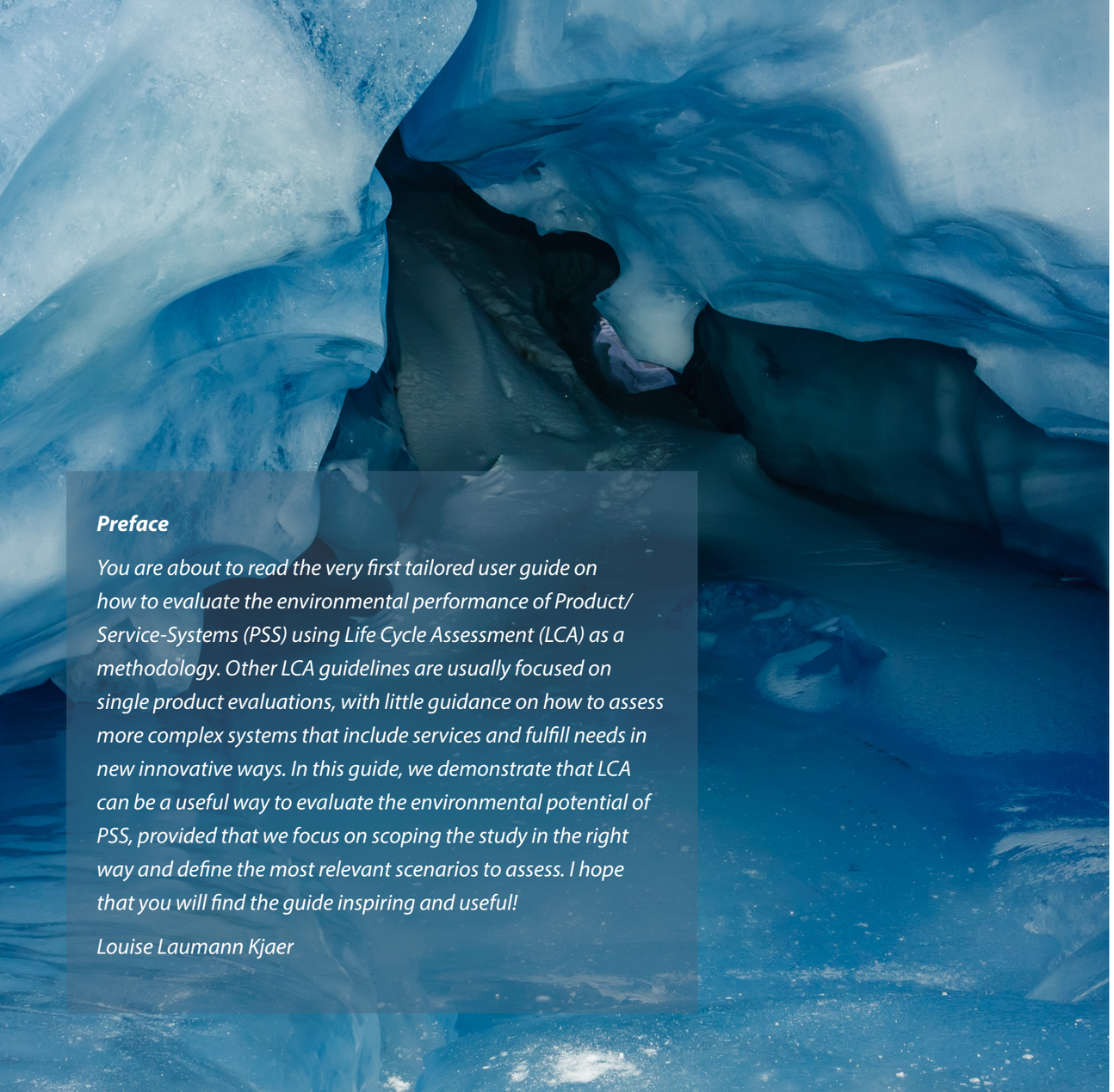
Glossary 58

Appendix 1: Impact categories 60

Appendix 2: Modelling different end-of-use options 62

Appendix 3: Process, Input-Output and Hybrid LCA 64

Appendix 4: Case examples 66



Preface

You are about to read the very first tailored user guide on how to evaluate the environmental performance of Product/Service-Systems (PSS) using Life Cycle Assessment (LCA) as a methodology. Other LCA guidelines are usually focused on single product evaluations, with little guidance on how to assess more complex systems that include services and fulfill needs in new innovative ways. In this guide, we demonstrate that LCA can be a useful way to evaluate the environmental potential of PSS, provided that we focus on scoping the study in the right way and define the most relevant scenarios to assess. I hope that you will find the guide inspiring and useful!

Louise Laumann Kjaer

Introduction

Environmental issues, such as climate change, resource depletion and pollution are societal concerns, which are also increasingly affecting the way we do business.

Concepts such as *circular economy*, *sharing economy*, and *service economy*, often highlight that more sustainable businesses can be created when focusing on product performance (e.g. by offering lighting as a service) rather than the physical products (e.g. by selling light bulbs).

Such strategies of integrating products and services to deliver required user functionality are often termed Product/Service-Systems (PSS).

This guide is intended to support studies that aim to explore if or when a PSS is leading to environmental improvements.

The guide consists of six steps, which will assist the user to evaluate the environmental performance of PSS using Life Cycle Assessment (LCA) methodology. Special attention is given to the scoping phase of the study.

This section of the guide introduces PSS as a concept, explains the aim of the guide, and provides an overview of stakeholders with potential interest in the guide plus the set of competences needed to perform the study.

What is a PSS?

A PSS can be defined as: *Product(s) and service(s) combined in a system to deliver required user functionality*[1]. Developing and offering PSS is an opportunity for companies to add value by switching focus from "selling products" to "providing functions" to customers. Focus is placed on providing a solution that fulfils the actual need of the customer, while the role of the physical products needed to provide the result may be more or less visible to the customer.

A PSS often entails a transfer of ownership from customer to provider. Customers pay, to a larger extent, for the outcome (e.g. number of copies) instead of the products (the copying machine). A PSS can also be more traditional, where after-sales services support the product throughout its life cycle. Examples include: extended warranties, maintenance agreements, operational support and take-back services.

Definitions

Product/Service-System (PSS): both product(s) and service(s) combined in a system to deliver required user functionality.

Product: a physical good (e.g. a computer) or a non-physical good (e.g. a piece of software), provided to the customer for him/her to make use of.

Service: an activity performed on behalf of the customer.

[1] *Baines, T.S. et al. 2007. State-of-the-art in product-service systems. Journal of Engineering Manufacture.*

Why PSS?

A company will often develop PSS solutions as a response to increased competition. Offering a PSS can create a closer bond to the customer and can be a way for companies to compete on other value parameters, rather than manufacturing cost alone.

PSS are also known to have the potential to lead to environmental improvements. The sustainability philosophy is that when companies move profit centres away from the physical products towards the result delivered, they are motivated to save resources and thereby lower the environmental impact of the needs fulfilment.

However, offering or buying a PSS does not necessarily lead to environmental improvements, as illustrated in Box 1.

These examples show that having a PSS business model does not guarantee environmental improvements and can even have the opposite effect.

Nevertheless, when designed properly, a PSS can have the potential for environmental improvements. Investigating this potential can be interesting for decision-makers, both from supplier, customer, and societal perspectives.

The aim of this guide

This guide is intended to support the evaluation of the environmental performance of Product/Service-Systems through a six-step approach.

The guide can be applied at different stages (pre- or post-implementation of the PSS) and by different stakeholders, e.g. as assistance during the design stage of a PSS or assisting decision-makers considering buying or promoting a PSS solution for environmental reasons.

The purpose of the study should be to investigate improvement options from a PSS provider perspective and/or evaluate from a customer and/or societal perspective whether or not changing to a PSS will lead -or has led- to environmental improvements.

The aim is to guide the user to perform a study, where the environmental performance of a PSS is objectively evaluated and quantified, taking a holistic perspective when comparing different options for needs fulfilment.

As such, the guide is intended to support change-oriented studies and not stand-alone assessments, where no comparison between systems is made.

The guide builds on Life Cycle Assessment (LCA) as a methodology. Special attention is given to defining the relevant scenarios within which LCA can be applied. It can be used for a screening LCA (sometimes also called streamlined LCA) as well as extensive, detailed LCA studies, depending on the goal and scope of the study.

A screening LCA requires less data and less precision in the collected data and is meant to give a first indication of whether the PSS can be assumed to be environmentally beneficial or not. Such studies often focus on a few environmental indicators, such as energy consumption, material consumption, or greenhouse gas emissions. It can be useful to apply screening LCA for PSS, in order to be able to focus on multiple scenarios, in contrast to assessing a single scenario in detail, taking constraints on time and resources into account.

Often the process will be iterative. The study starts from a screening LCA, after which the systems under analysis are reassessed with more detailed and precise data, in order to further support decision-making.

This guide can be used as a stand-alone document. However, it may be defined in your study goal that the study should be carried out as a full LCA, living up to ISO requirements. In these cases, the ISO standard (ISO 14044) needs to be followed simultaneously with this guide, since more requirements than those explained here will be needed.

Box 1 *Examples* - Why a PSS is not necessarily environmentally superior

Mobile phone subscription

Through a mobile phone subscription, the customer pays a monthly fee for a total package, which includes the provision of the newest smartphone every year. This is unlikely to be environmentally better than buying the phone and the mobile subscription separately, since mobile phones are normally replaced by the user every 2-3 years[2], on average. The mobile phone subscription is therefore likely to increase the replacement rate.

Car-sharing system

At first hand, sharing a car would seem beneficial, since fewer cars would need to be produced, compared to if each user had their own car. However, firstly, seen from a life cycle perspective, the use of the car is a dominating life cycle stage in terms of environmental impacts. Secondly, studies have shown that the majority of customers of a car-sharing system are usually people who previously used public transport, such as buses or trains.

Only if the car-sharing system would lead to less car driving and/or the implementation of less polluting cars, such as electrical cars, would the PSS potentially lead to environmental improvements. Therefore, in order to evaluate the environmental performance, it is crucial to assess what the PSS is actually substituting.

[2] *Suckling & Lee : Redefining scope: the true environmental impact of smartphones? International Journal of Life Cycle Assessment. 2015*

Who should use this guide and why?

The guide is intended to support organisations, consultants and company employees, who are to perform an environmental evaluation of a PSS. The reasons for initiating such a study will be different.

The study might be done as a pre-assessment during the design-stage, in order to guide the design process towards creating the most sustainable solution. Such an evaluation is especially relevant for companies developing PSS solutions.

The guide might also be used for post-assessments, where the PSS is already implemented and the purpose of the study is to evaluate the environmental impact of the PSS against relevant alternatives. This evaluation is relevant for PSS providers, who want to document the environmental performance of their solution or use the evaluation for inputs to improve their PSS design.

A study could also be initiated by policy-makers, independent organisations or PSS procurers who want to assess – from a customer perspective – the consequences of transitioning to a PSS in terms of environmental impacts.

In all cases, the evaluation will be done to support decision-making and enhance knowledge regarding under which circumstances a PSS leads to environmental improvements. The guide might be relevant for the following four groups of stakeholders, see also Figure 1. Note that the guide may also be used in projects where the stakeholder groups collaborate.

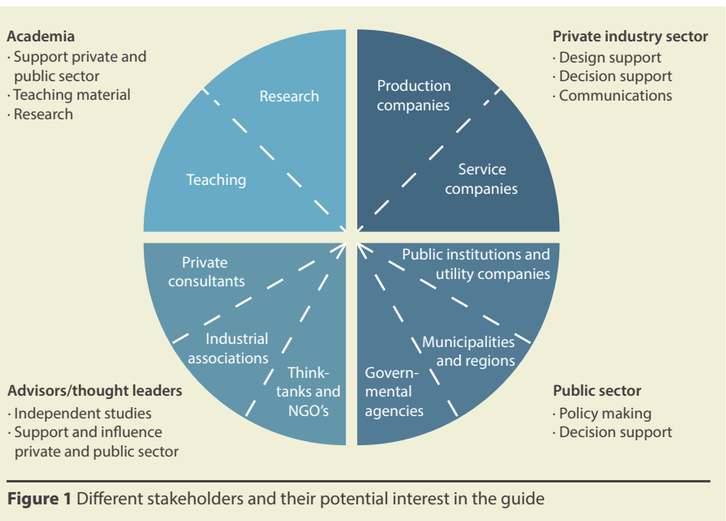


Figure 1 Different stakeholders and their potential interest in the guide

Private industry sector
The private industry sector covers both production and service companies.

- **Production companies** might have a strategy to "servitise" their business by increasingly developing and offering PSS solutions to their customers. The reason might be to enhance market shares, but can also be to enhance their profile as a sustainable company that aims to decouple their business from increased environmental impacts and resource consumption. An objective evaluation of the environmental performance of their offerings can be initiated for different reasons. The company might have an internal environmental strategy, which they have obligations to live up to. The company might need to satisfy sustainability requirements from customers or investment and collaboration partners. Or it might be important for the company's reputation to avoid claims of "greenwashing".

- **Service companies** can similarly profit from integrating specific products with their services and thereby enhance the value of their offerings. Service companies are in many cases already considered as PSS providers, since they almost always utilise products and materials when providing their services (e.g. a cleaning company use detergents and equipment). However, when service companies want to enhance their market share and/or take over activities traditionally done by the customer (can be seen as outsourcing from a customer perspective) while arguing that this transition will reduce the environmental impacts, this guide can be used to support the evaluation needed to verify that claim.

Depending on the position of the company in a value chain, private companies can both be interested in PSS from a provider or a customer perspective. Companies that are potential PSS customers can be interested in knowing if implementing PSS in their procurement strategy is likely to result in environmental improvements. Potential customers can also play a role as collaborative partners, when a PSS provider is designing/improving a PSS. A potential customer can support the study with relevant data and knowledge on the traditional system, to which the PSS should be compared. They can also provide valuable information on which parameters are important for a PSS to be successful, both in terms of acceptance and implementation and to ensure environmental improvements. Private companies can perform the study themselves, or hire consultants to support them during the process.

Public sector
The public sector might be interested in this guide for various reasons:

- **Public institutions and utility companies** might be interested in applying the guide, especially from a procurement perspective.

- **Municipalities and regions** might also be interested in evaluating PSS solutions aimed at citizens and companies within their geographical area. Examples are PSS aimed at supporting the transport system such as a car or bike sharing systems.

- **Governmental agencies** can be interested in knowing under which circumstances PSS lead to environmental improvements, especially since PSS are often promoted as means to create a sharing or circular economy, where businesses can thrive in an economy based on fewer non-renewable resources.

Advisors/thought leaders
This group of stakeholders represents institutions that might use the guide when advising and directing the private and public sector, as well as citizens towards more sustainable production and consumption patterns.

- **Think-tanks and NGO's** can initiate studies themselves and use the guide to evaluate the environmental performance of different PSS, e.g. to show good and bad examples to support the debate on what are sustainable business models. These stakeholders can also play a role in promoting the guide.

- **Industry associations** can play a similar role in promoting the guide or commence studies themselves.

- **Private consultants** are very relevant as a target group for using the guide. It is common practice for conducting LCA studies that the study commissioner and the LCA practitioner come from different institutions. Companies often hire consultants to perform all or part of the study on their behalf, to ensure the required objectivity as well as expertise.

Academia
For academia, such as universities or other teaching and research institutions, the guide might be used as **teaching** material or to support **research** within PSS design and sustainability science, which include the LCA community. Research institutions might also collaborate with companies in projects where the guide is used.

Setting the right team

Before initiating a study using this guide as support, it is important to ensure that the right competences are present within the team or individual carrying out the study.

The guide assumes that three stakeholder competence profiles are represented: "LCA practitioner", "PSS designer" and "strategic decision-maker" (Figure 2).

Note, that depending on the study context, the three profiles may not necessarily be represented by three different people. The three profiles might be represented by one person or a much larger team.

Figure 2 Competence profiles for guideline users

LCA practitioner
The "LCA practitioner" has an important role in the quantitative part of the study and needs to be involved in all phases of the study. In an organisation, the "LCA practitioner" belongs to the operational level and knows the basic tools and methods related to environmental assessment, including LCA.

This guide therefore assumes that the study is carried out by individuals who have basic knowledge on LCA and environmental impacts. This will be needed in order to interpret the guide, since it is partly built on LCA methodology and terminology.

For studies where the quantitative part plays an important role, it is recommended that a sufficient level of LCA expertise is involved in the process, e.g. if it is decided that the study needs to live up to the requirements of the ISO standard on LCA (ISO 14044).

In cases where the quantitative assessment is done on a screening level, it is also recommended that one or more people with LCA experience are involved, since they will have the knowledge needed to judge the validity of the results. If the competence is not present or available in-house, companies might choose to subcontract the LCA expertise by hiring external consultants.

See Box 2 for supplementary reading on LCA.

PSS designer
The "PSS designer" plays an important role in the framing of the study, including analysing and defining the PSS solution(s) under evaluation in order for the LCA practitioner to understand the study context.

The "PSS designer" also plays an important role in interpreting the results, especially when the study is carried out as a pre-assessment, during the design stage of developing a PSS.

In an organisation, the "PSS designer" represents the tactical level and must have the competencies to build a bridge between the "LCA practitioner" and "Strategic decision-maker", both in terms of translating goals and visions into a frame for the LCA practitioner to work within, and subsequently interpreting and implementing results in collaboration with the "strategic decision-maker".

As with the "LCA practitioner", the role of the "PSS designer" may also be subcontracted by hiring external consultants or collaborating with research institutions.

See Box 2 for supplementary reading on PSS.

Strategic decision-maker
The "strategic decision-maker" is the profile who initiates or approves the study and acts upon the results and recommendations that the study reveals. In an organisation, the "strategic decision-maker" will have influence on a strategic level.

Competences to understand the decision-making context are especially relevant in the beginning of the study, in order to define the right study goal and towards the end, to help interpret the results and ensure that recommendations can be implemented.

Box 2 ***Supplementary information*** **- Examples of reading material**

Supplementary reading on LCA

ISO standards:

ISO 14040:2006: Environmental management - Life cycle assessment - Principles and framework

ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines

Text books on LCA:

Jolliet et al.: Environmental Life Cycle Assessment. CRC Press. 2015

Hauschild et al. (eds.): Life Cycle Assessment - Theory and Practice. Springer. 2018

Klöpffer & Curran (eds.): LCA Compendium - The Complete World of Life Cycle Assessment (book series). Springer. 2015-2017

Supplementary reading on PSS

Workbooks:

PROTEUS workbook series, Technical University of Denmark. 2013

Journal articles on PSS:

Beuren et al.: Product-service systems: a literature review on integrated products and services. Journal of Cleaner Production. 2013

Mont: Clarifying the concept of product–service system. Journal of Cleaner Production. 2002

Tukker: Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Business Strategy and the Environment. 2004

Kjaer et al.: Challenges when evaluating Product/Service-Systems through Life Cycle Assessment. Journal of Cleaner Production. 2016

Overview of steps

1. Goal definition
"What is the purpose?"
In this step, the purpose and desired learnings of the study are decided, taking into account the intended audience. The study complexity is considered, together with the time and resources available. The purpose of this step is to guide the assessment in terms of how scenario-based the approach should be and the level of detail to be involved.

2. PSS and reference system exploration
"What to compare?"
In this step, the scope of the study is decided, along with a definition of the reference system. The PSS and its reference system are explored, in order to define the systems to be analysed in the subsequent steps.

3. Comparability assessment
"How to compare?"
In order to compare the systems to be analysed, they need to provide the same functionality. This is defined along with the *functional unit* upon which the comparison(s) will be based. The system is subdivided into a specification, describing "how" the functionality is provided. This is followed by an assessment of "how well" the customer perceives the utility and value of the compared systems, in order to identify differences in performance, which might trigger rebound effects.

4. Process mapping
"What to measure?"
The purpose of this step is to create an overview of the quantitative data that need to be gathered. A flowchart is used to create a visual overview of all processes, followed by specifying the system boundary, which delimits which processes are included in the assessment. Lastly, the impact categories that are going to be measured are defined.

5. Quantification
"How to measure?"
In this step, inventory data are gathered for all relevant processes for the systems to be analysed. The types of data are defined and if the inventory data are assessed using an impact assessment method, this is also defined. The purpose of this step is to build the LCA model within which results can be interpreted.

6. Interpretation and recommendations
"What to conclude?"
Lastly, the results are evaluated and presented, both quantitatively and qualitatively, highlighting the most important influencing parameters.

If included in the study purpose, a set of recommendations might be formulated, such as how to optimise the PSS design or guide the PSS strategy, in order to ensure proper adoption.

Figure 3 shows the six steps, the sub-steps within each and their connections, plus an overview of how the steps correspond to the LCA phases described in the ISO standards on LCA.

Even though the steps are presented in sequence, the study process will be iterative in nature, similar to what is recommended in relation to the phases of an LCA.

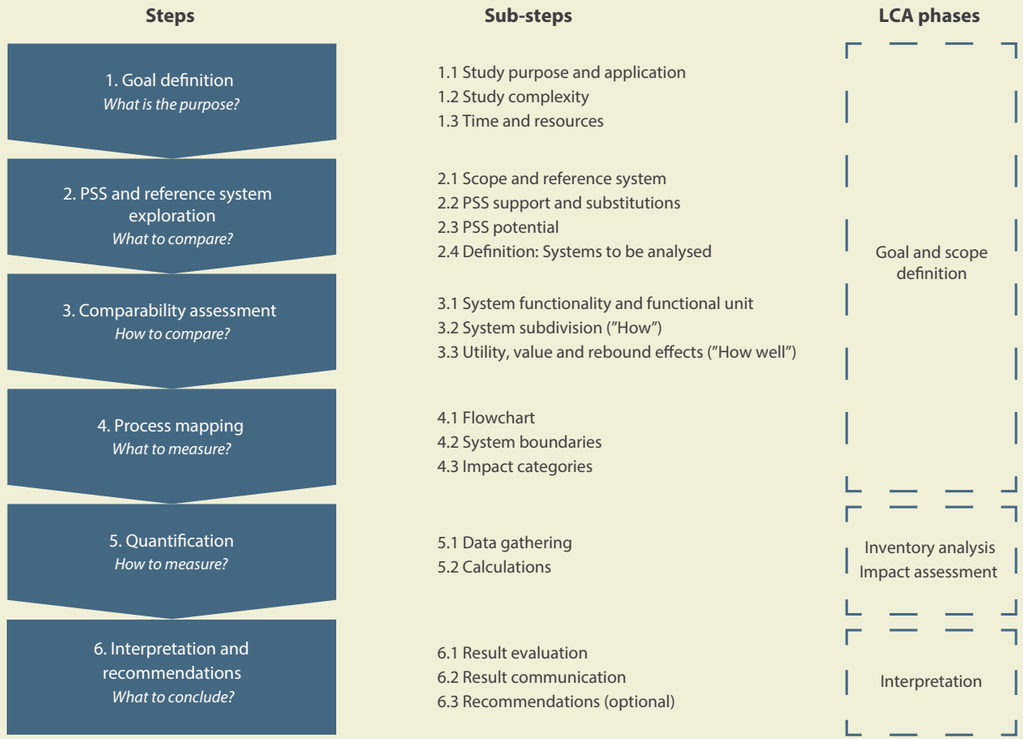


Figure 3 Overview of steps and sub-steps and how they link to the phases of an LCA process

1 Goal definition

"What is the purpose?"

The aim of this step is to define the purpose and application of the study (sub-step 1.1), the study complexity (sub-step 1.2), as well as the time and resources available (sub-step 1.3), in order to guide the following steps.

Start the goal definition by identifying the relevant stakeholders who will be using as well as conducting the study. The overview of stakeholders from the introduction of this guide can be used as inspiration.

Note that the study goal might be redefined during the process as more knowledge about the studied systems, including data availability, becomes clearer.

In defining the study goal, all three competence profiles should be represented.

Strategic decision-maker

PSS designer

LCA practitioner

1.1 Study purpose

The first task is to describe the study purpose and the desired learnings.

Identify the **intended audience** who is going to use the result of the study and describe the **desired learnings** from the study.

If the study commissioner (who initiates and/or finances the study) is different from the intended audience, they will also have expectations of the study outcome and should be considered as a relevant stakeholder as well. Three groups of stakeholders are always important to consider:

- The PSS provider(s)
- The PSS customer(s)
- Governmental authorities or other external institutions with an interest in the PSS and/or the study results.

Consider if the study is done as an evaluation (post-implementation) or to support designing the PSS (pre-implementation):

- If the study is done **post-implementation**, it will be retrospective and actual data can be gathered. Results will be less uncertain, compared to studies done pre-implementation. For a PSS provider, the purpose can e.g. be to use the results internally for re-design of the PSS, or externally for communication.
- If the study is done **pre-implementation**, it is prospective and more assumptions need to be made, especially regarding the use of the PSS, since actual data are not yet available. Consider if a screening LCA will be appropriate. This will make the results more uncertain, but provide useful knowledge at a time where it is easier to influence the PSS design and strategies. As a result, the study will be more scenario-oriented and focus should be on the learnings during the LCA process, rather than the quantified results themselves.

If the **impact categories** to be measured are predetermined, this should be stated in the goal definition. For example, if the intended audience is only interested in a carbon footprint calculation, the only the impact category *climate change* needs to be measured. In all other cases, this will be refined during the next steps and finally defined in step 4.

Definitions

Intended audience: Stakeholders who will make use of the study result, including decision-makers who will be able to influence the result.

Study commissioner: Stakeholder who initiates and finances the study. Can be different from the intended audience.

Impact category: Classification of environmental issues of concern, to which life cycle inventory analysis results may be assigned (ISO 14044). E.g. "CO_2 emissions" are assigned to the impact category "climate change".

1.2 Study complexity

Based on the study purpose, consider how complex the study will be.

The study complexity is influenced by the **number of application scenarios** relevant to include and the **number of assumptions** that need to be made, see also Figure 4:

- The number of relevant **application scenarios** is determined by the reference system, which the PSS is to be analysed against. Often, the reference system will be external – the study aims to compare the PSS to one or more alternative ways of needs fulfilment. Step 2 will help explore the reference system, in order to define the systems to be analysed. Still, in this step, try to consider which alternative application scenarios it is relevant to include. See also tip in Box 3.
- The number of **assumptions** is influenced by data availability and uncertainty. It is higher for pre-assessments than for post-assessments, as actual data is less available. If data on customer behaviour, resource consumption etc. is not available, simulation techniques can be used to generate proxies. The more assumptions, the more "what-if scenarios" must be generated, increasing the study complexity.

More knowledge on the study complexity will be revealed, once the systems to be analysed have been defined (Step 2) and data collection has been initiated (Step 5). Remember to revisit the goal definition after these steps.

Box 3 *Tip* - Consider if single or multiple customers are relevant

Is the PSS only to be operated by a single customer? Then the reference system equals that customer's behaviour, without the PSS, and this is the only application scenario to consider. A single customer perspective can be useful as a pilot study, or as "proof-of-concept". However, if the purpose of the study is to provide knowledge on the more general adoption of the PSS (e.g. all household or whole industry), more application scenarios need to be considered, taking into account the different customers' behaviours. This will increase the study complexity, since more data need to be gathered.

Figure 4 The study complexity depends on the number of assumptions required and number of application scenarios relevant to include.

1.3 Time and resources

Consider the amount of time and resources available.

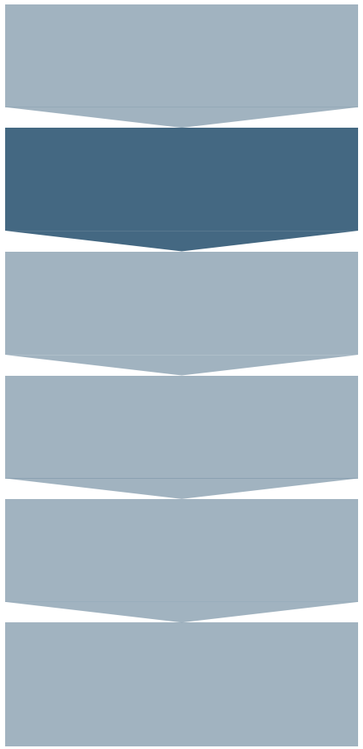
Practical constraints on time and resources will set a natural limit to the amount of scenarios feasible to include in the study and/or the detail level of the analysis.

In this regard, it should be considered if a "full" LCA is applicable or if a screening LCA, based on more aggregated data, is more suitable, considering the purpose and desired learnings from the study, as well as the assumed study complexity.

Note that if it is part of the goal of the study to be compliant with the ISO standards on LCA, special requirements are needed if the study is to be used for external communication (see ISO 14044).

SUMMARISING QUESTIONS

- Who are the relevant stakeholders commissioning, using and conducting the study?
- What is the purpose and desired learning of the study?
- Is the study done pre- or post-implementation?
- Are impact categories to be identified during the study or are they predetermined?
- Is the anticipated number of application scenarios small or large?
- Based on the stakeholders' cur-rent knowlege, to what degree will the study rely on assumptions?
- How much time and resources do we have for the study?
- Which type of LCA is adequate (screening LCA or full LCA)?
- Should the study live up to LCA ISO requirements?



2 PSS and reference system exploration

"What to compare?"

The purpose of Step 2 is to explore the PSS and its reference system, in order to guide the study scope and support the interpretation of the results.

If not predefined in the goal definition, it is useful already in this step to consider which impact categories (e.g. climate change, resource consumption, eco-toxicity, etc.) could be of concern for the study.

As knowledge about the PSS and its reference system is gained, relevant environmental hotspots will be revealed, indicating which impact categories to focus on. Start by considering if all three "areas of protection" (Human health, Eco-systems and Resources) should be covered. Appendix 1 provides an introduction to choosing impact categories and explains some of the most common impact categories used in LCA. The final decision on impact categories is done in Step 4.

It is important that expertise within both the fields of PSS design and LCA are represented during this step, with the "PSS designer" having the most significant role.

PSS designer

LCA practitioner

2.1 Scope and reference system

Start by defining the study scope and the type of reference system relevant for the study.

An environmental assessment of a PSS can in principle have three different scopes, illustrated in Figure 5. Which of these scopes apply depends on the purpose of the assessment, as defined in Step 1. For each of the three scopes, the nature of the reference system will be different, as follows:

- **PSS consequences:** The purpose of the study is to perform a system-level assessment, where the reference system can be defined as the baseline situation, without the PSS. The focus is on analysing the changes caused by introducing a PSS to the reference system. Based on the analysis of the PSS and the reference system, relevant scenarios are defined, upon which the environmental assessment can be performed.
- **PSS comparison:** The purpose is to compare the PSS with a predefined alternative. The reference system is equal to this alternative, which can either be the "non-PSS" option (e.g. the traditional product-sale business model) or an alternative PSS solution. As in a comparative LCA, the comparison is based on a common functional unit and functional equivalence needs to be established.
- **PSS optimisation:** The purpose is to evaluate different design options within the PSS. In these cases, the reference system could be defined as the PSS itself, since from the customer perspective, no changes are directly visible – the customer perceived value is considered unchanged. In contrast to the other two scopes, where the reference system can be seen as external, the reference system here is internal.

PSS consequences can be seen as the most comprehensive study scope in terms of evaluating the environmental performance of a PSS. For this scope, the reference system needs a thorough exploration, in order to identify the relevant substitutions (alternatives displaced by the PSS).

The following sub-steps aim to support such an exploration. Also for a PSS comparison or PSS optimisation study, Step 2 is relevant, as it provides understanding of and potentially new ideas to the PSS under evaluation. The following sub-steps will also help confirm that the relevant study scope has been chosen for the analysis.

If more than one application was considered in the goal definition, the reference system might be different for each scenario and should be assessed individually in the following steps.

Definitions

Reference system: The baseline situation that is altered by the PSS under study or is compared to the PSS under study. Can be either internal (a variant of the PSS itself) or external (a comparable alternative or the affected contextual system), depending on the study scope, see below.

PSS study scopes:

PSS optimisation: the reference system is internal. The purpose is to assess variants of the PSS itself.

PSS comparison: the reference system is a pre-defined comparable alternative.

PSS consequences: the reference system is the contextual system affected by the PSS.

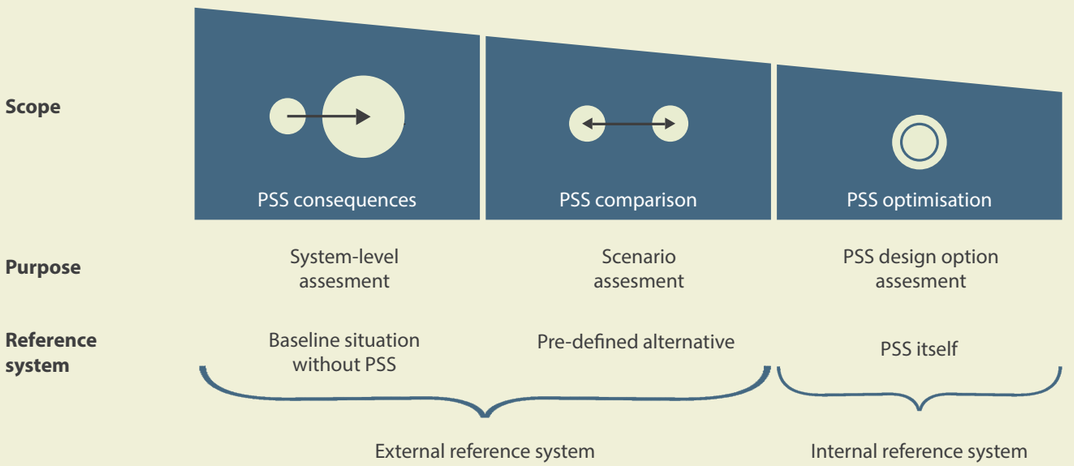


Figure 5 Scopes for environmental assessment of PSS

2.2 PSS support and substitutions

Classify the PSS based on what it is intended to support and use this to describe the reference system and the product system(s) that the PSS substitutes.

In this guide, three types of PSS support are distinguished:

Activity support:
The PSS supports or replaces an activity on behalf of the customer.

Product support:
A product is supported through life cycle services or offered as a service (e.g. through leasing or pay-per-service-unit).

Platform support:
Products and services are offered on a platform for customers to use e.g. through subscriptions or short-term rentals.

Other classifications of PSS exist. A traditional way of categorising a PSS is related to the business model logic (what the PSS delivers and what customers pay for). See Box 5 on page 25 on how to link to the PSS support classification used in this guide. A PSS business model might incorporate more than one type of support. It is recommended to keep these as separate PSS scenarios, in order to support the interpretation of the study results.

Start by reflecting on the profile of the reference system. Which activities and products are dominating in terms of environmental impacts? See also tip in Box 4. Based on this, consider which activities and/or product elements the PSS will substitute or change.

Use the following explanation of the three types of PSS support to describe the reference system and the substitutions.

Definitions

Product system: Collection of processes, which deliver the product and service flows required to obtain the specified functionality, and which model the life cycle of a product.

Substitution: The alternative product system(s) displaced by the PSS under study.

Activity support
Describe the reference system as the activity without the PSS support.

For example, for a laundry service for households, the reference system would be the households doing their laundry themselves. Another example is "eco-driving"[3] , where a fleet of trucks is supported, in order to operate more efficiently. The reference system is the truck operation, without the PSS sup-port. For both cases, only the use stage of the product system in focus (textiles and trucks, respectively) is directly influenced by the PSS. However, indirect effects might occur in other life cycle stages. For example, for a laundry service, the changed laundering procedure might either prolong or shorten the lifetime of the textiles. If this is the case, the substitution is defined as a **single product system**, since the whole life cycle of the products (in this case the textiles) needs to be considered in the study (Figure 6). If it can be argued that only the use stage of the product system is affected, it may be defined that the PSS substitutes a **single life cycle stage** (Figure 6). This will enable that only the direct influenced activity (in this case the laundry process) is in focus in the study.

[3] *Eco-driving: A fleet of trucks is supported, in order to operate more efficiently. The PSS includes: installing and maintaining monitoring software in the trucks that monitor fuel consumption and guide the truck drivers to eco-efficient driving, training programmes for truck drivers, and reward schemes for continuous improvement.*

Product support
Describe the reference system as the product system without PSS support.

Examples of PSS product support are maintenance services, upgrade services and take-back services. PSS product support can also be related to a change in ownership, where the customer pays for product use instead of owning the product. In this case, the reference system can be described as the individual ownership of the product.

For a PSS focused on product support, the PSS influences the whole life cycle of the product system in focus and the substitution is a **single product system.** However, even though the assessment of a PSS focused on product support starts with a mapping of the product system in focus, it might be necessary to expand the scope and assess **multiple product systems** (Figure 6).

This happens when the product is retained or taken back at the end-of-use and therefore resides with the PSS provider, when the product is disposed of. In these cases, the PSS provider can have an incentive to ensure that the products and materials are being reused, re-manufactured or recycled in a way that is most beneficial – also from an environmental perspective.

A product that can no longer fulfil its original functionality can take different end-of-use routes that need to be included in the assessment. This implies that the product system(s) that the second-hand product or material substitutes in the subsequent life cycles need to be included in the assessment.

For more information on how to model different end-of-use options, see Appendix 2.

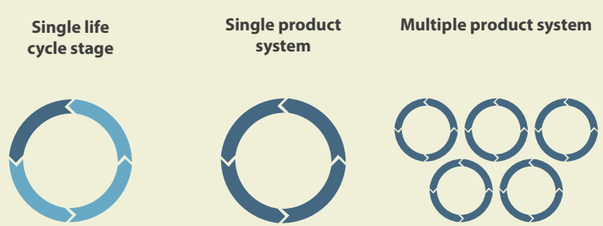


Figure 6 Consider whether the PSS is substituting a single life cycle stage, a single product system or multiple product systems

Box 4 *Tip* - Which life cycle stages are dominating?

Consider which life cycle stages are dominating for the product system in question. This will help guide to what extent the PSS supports the most important life cycle stages. In general, for energy-consuming products with long life cycles, such as cars and cargo ships, the use stage is dominating, and focus should be on reducing the energy consumption during use. For products with no or low impacts during use and/or short life cycles, focus should be on extending the useful life of the product and materials.

Platform support
Describe the reference system as the situation without or before introducing the PSS, encompassing all relevant substitutions.

When a PSS is supporting a platform, the PSS provider has limited control over the different product systems that the PSS substitutes.

An example could be a free-floating car-sharing system in a city[4], where the PSS is a substitute for many different transport means, such as public transport, own cars, rented cars or even bikes or walking. The reference system would be the transport system of the city, without or before the introduction of the car-sharing system.

Another example could be a streaming service for music or movies, which both displace physical CDs/DVD being bought or rented, but which also displace totally different means of entertainment, such as TV, video games or even reading a book. The reference system is the way customers would entertain themselves, without or before the introduction of the streaming service.

This type of PSS support is considered the most complex to analyse, since **multiple product systems** are substituted and will need to be assessed individually. An important part of this type of study is to analyse the alternative behaviour of the customers, both in terms of mapping the number of relevant substitutions and to what extent the different substitutions occur. This can be done using customer segmentation and survey methods. However, such analyses can be resource-intensive and therefore need to be based on assumptions and existing market knowledge, asking for a scenario approach in the quantitative part of the evaluation process.

Only in cases, where it can be argued that a platform-based PSS is predominantly used to displace one other product system, can it objectively be argued to compare the PSS to a **single product system** in the assessment (for example, a survey shows that 80% of the customers of a TV streaming service use the service as a substitute for cable TV).

Subjectively, it might be included in the study goal to assess the PSS from a single customer perspective (e.g. customers who would otherwise use cable TV), leading to the study scope being a PSS comparison. However, even in these cases, it is recommended that the study includes an evaluation of to which extent this type of substitution occurs, compared to other customer segments, in order to argue on the objectivity of the study.

[4] Free-floating car-sharing system: Energy-efficient cars are offered as subscription or short term rentals within the city-centre. The term "free-floating" refers to the fact that customers can drive wherever they need to go and then terminate the rental of the car by simply returning it within the same delimited area, using one of the authorized spaces. The aim is to reduce pollution and the need for parking spaces within the city centre.

Box 5 ***Supplementary information*** **- PSS business model categories**

A common way to categorise a PSS is related to the business model (what the PSS delivers and what customers pay for).

The most dominant way of describing PSS distinguishes three main categories, bridging a pure product and a pure service in the following order: [5]

- **Product-oriented PSS**: products are sold to the customer and services are added over the life cycle, in order to support the product. Examples include maintenance agreements and take-back services.
- **Use-oriented PSS:** the customer does not own the product but pays for product use, e.g. through leasing and renting schemes.
- **Result-oriented PSS**: the customer pays for the product outcome or an overall result delivered where the product and service elements are the means for providing the result.

Figure 7 shows how the three types of PSS business models usually relate to the three types of PSS support defined in this guide. The links are based on what the PSS is affecting.

[5] Tukker: Eight types of Product–Service System: Eight Ways to Sustainability Experiences from SusProNet. Business Strategy and the Environment. 2004

For a **result-oriented PSS,** products and services are combined to fulfil a predefined result, e.g. providing clean clothes in the case of a laundry service. The PSS intends to support an activity (e.g. laundering clothes) and will affect the products and service elements (e.g. washing machines, drying process, delivery service, etc.) used to deliver the result (e.g. clean clothes).

For a **product-oriented PSS,** services are added to support a product in one or more life cycle stages, post-production ("after gate"). If the PSS only influences the product operation and it can be argued that no other life cycle stages than the use stage are affected, then the PSS supports an activity. If the useful lifetime of the product or the end-of-life treatment is affected, the whole life cycle of the product needs to be taken into account and the PSS supports the product.

Lastly, for a **use-oriented PSS,** the product also plays a central role, however, instead of owning the product, the customer pays for the function of the product. If the PSS simply facilitates a change in ownership, so that the product merely stays as property of the PSS provider, while the customer abandons ownership end e.g. leases the product instead, then the PSS supports the product.

However, a use-oriented PSS might also support a platform. In these cases, the product is offered on a platform for customers as an alternative to a range of other ways of fulfilling the same need. This would be the case for a free-floating car-sharing system.

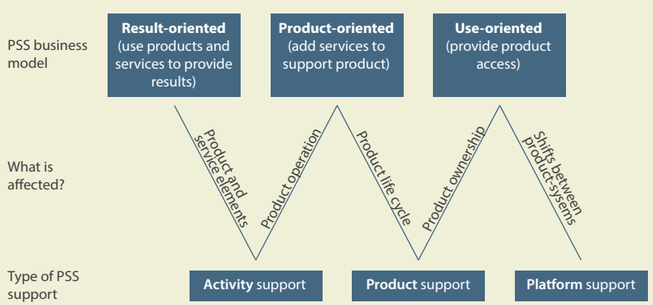


Figure 7 PSS business models in relation to type of PSS

2.3 PSS potential

Consider, qualitatively, if the PSS has a potential to reduce environmental impacts compared to the reference system. Describe the PSS strategy(ies) and explain their impact reduction potential.

Offering a PSS is no guarantee for environmental improvements. Examples of the opposite are not uncommon. As exemplified in the introduction, if a phone subscription that includes the leasing of a mobile phone involves getting the newest smart phone every year, the PSS is likely to be environmentally worse, compared to traditional product-sales.

However, many PSS strategies have a potential for environmental improvements, and they are easily identified, as they have often triggered the study in the first place. For example, a company offering laundry services to private households will have a clear assumption that they can wash the clothes more efficiently than the average household. Or a municipality offering a free-floating electric car-sharing system in the city centre will assume that this leads to less traffic-based pollution.

Fig 8 exemplifies six common PSS strategies and the environmental impact reduction potentials linked with each. Note that more than one PSS strategy may be utilised within the same PSS.

Appendix 4 presents PSS cases for each of the six strategies.

1. Activity support - operational support
Operational support is when the PSS provider supports the operational stage of a product system. This is especially relevant for energy-consuming products with long lives, such as trucks, ships and power plants. The PSS provider can offer valuable support, in order to make the system run as efficiently as possible. The environmental reduction potential is therefore termed **"direct resource efficiency"**. The previously introduced case of "eco-driving" is an example of the PSS strategy *operational support*.

2. Activity support – optimised result
Activity outsourcing as such is no guarantee for environmental improvements. However, when a PSS provider takes over an activity on behalf of a customer, this can be combined with the strategy of providing the result in a more optimal way, using more efficient equipment and procedures.

This type of PSS strategy is termed *optimised result*. The impact reduction potential materialises itself **indirectly through shift in the product and service elements** within the system. The laundry service is an example that has this type of potential.

3. Product support – product sharing
Leasing and renting of products do not necessarily lead to environmental improvements (e.g. leasing a car instead of owning it does not by default make any difference), but when a PSS provider combines retained ownership with product sharing, there is a potential for **optimised product utility through intensified use,** ultimately resulting in fewer products being produced to fulfil the same demand. A number of households sharing hand-tools or lawnmowers are an example of product sharing as a PSS strategy. The specific case of lawnmowers is exemplified in Case 3 in Appendix 4.

4. Product support – maintenance
Product maintenance can both be offered as after-sales services and be part of a leasing/renting scheme. Maintaining a product throughout its life cycle can lead to **product longevity and to reduced resource consumption in the use-stage.** In the latter, correct maintenance ensures that the product operates optimally, so that products that use energy or other resources (e.g. support materials or chemicals) minimise their consumption.

Maintenance as a PSS strategy includes preventive maintenance, repair service, upgrades, refurbishment, etc., all of which will lead to the product staying functional, updated, attractive, etc. leading to **product longevity.**

5. Product support – take back for re-use, re-manufacturing or recycling
As with maintenance, take-back services can be offered as an after-sales service. In cases where the PSS provider keeps ownership of the product throughout its use, as in the case of leasing, the PSS provider automatically needs to deal with how to handle the product after end-of-use. When strategies such as reuse, re-manufacturing, or recycling are initiated they can lead to environmental improvements. If the product is reused directly into the same use, it will have the same effect as **product longevity** from the perspective of the customer.

However, end-of-use strategies often entail that the products or materials are being re-directed into new product life cycles. This basically means that the products or materials substitute (part of) other product systems, which can be both new (virgin) versions of the same product/material (e.g. when second-hand aluminium substitutes virgin aluminium) or very different product systems (e.g. when worn-out textiles are used as insulation material). In these cases, the impact reduction potential arises **indirectly through product system substitution**, as it depends on the systems that are substituted by the second-hand product/material, see also Appendix 2.

6. Platform support – sharing platform
Lastly, sharing platforms enable radical shifts in consumption patterns. A free-floating car-sharing system and online movie and music streaming are such examples. In these cases, the impact reduction potential comes **indirectly through product system substitutions**, as it depends on the product systems displaced by the sharing platform.

For example, if a car-sharing system substitutes driving in a privately owned car, this will lead to fewer cars needed. In contrast, if it substitutes people using bikes or public transport, it will lead to more people getting access to a car and does not as such lead to impact reductions.

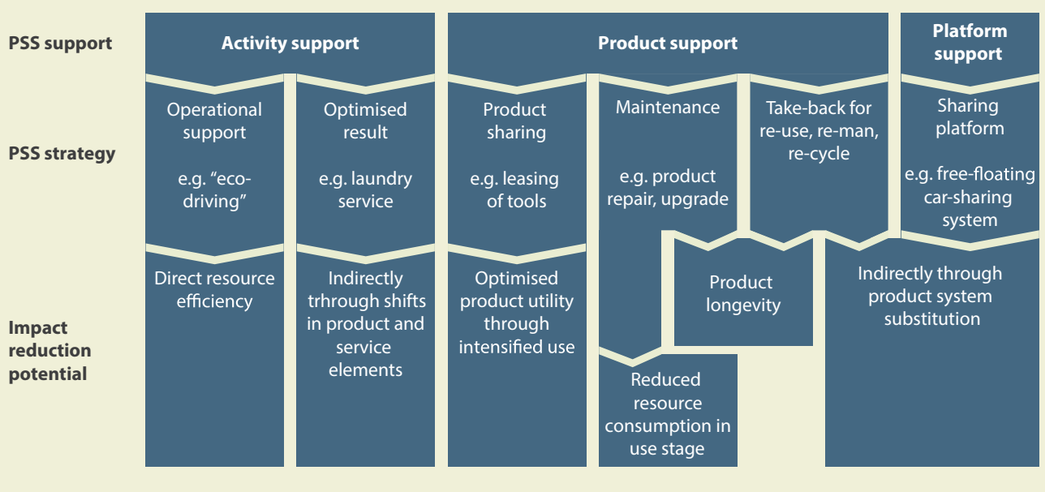


Figure 8 Examples of PSS strategies and impact reduction potentials

2.4 Definition: Systems to be analysed

Decide the systems to be analysed, in terms of relevant PSS scenario variations and the reference system(s) they will be compared with.

Use the learnings and conclusions from the previous steps to support the decision:

- **Step 1: Goal definition.** How many application scenarios were decided as being relevant to include in the study, taking into account the study purpose and time and resources available?

  Laundry service example: It was decided to focus on household applications and not professional (industry) customers.

- **Sub-step 2.1: Study scope and reference system.** Which study scope was relevant: PSS consequences, PSS comparison or PSS optimisation?
  For *PSS optimisation*, the systems to be analysed will be two or more variations of the PSS. Describe each of the PSS variations and how they differentiate.
  For *PSS comparison*, the PSS is compared with one or more predefined alternatives. Describe the PSS and the compared alternative(s).
  For *PSS consequences*, describe the reference system and list all identified substituted product systems.

  Laundry service example: The starting point was PSS consequences, since the study would include identifying which comparable alternative use-scenarios would be most relevant to assess.

  When exploring the reference system, it was decided to compare with three comparable alternatives of household laundering, which the PSS would substitute: Households taking their laundry to a laundrette or a similar shared facility; households using their own washing machine and a tumble dryer; and households using their own washing machine but air-drying their textiles.

- **Sub-step 2.2: PSS support and substitutions.** Is the PSS supporting an activity, a product and/or a platform?
  For *activity support*, describe whether the PSS substitutes or influences only the activity, or if the whole life cycle of the product system in focus is to be included in the assessment.
  For *product support*, describe the product system(s) that the PSS supports, including how it influences the product system life cycle.
  For *platform support*, describe all substituted product systems considered relevant to include in the assessment.

  Laundry service example: The PSS supports an activity (from dirty to clean clothes). It was decided to assume that the textiles' useful lifetime is not altered by changing to the PSS and thus the study focuses on the laundering process, looking only at the use stage of the textiles. As such, the PSS substitutes a single life cycle stage of the product system in focus (the textiles).

- **Sub-step 2.3: PSS potential.** In this sub-step the impact reduction potential of the PSS was qualitatively explored. It may be decided to include different PSS strategies to evaluate their impact reduction potential quantitatively during the next steps of the assessment. If this is the case, explain the included variations of the PSS and how the reference system might differentiate for each of them.

  Laundry service example: It was decided to only include the PSS strategy "optimised result", where the PSS supports the activity of laundering the clothes. However, in the result communication, it will be recommended to further explore if the service provider could also offers to repair clothes (PSS strategy "maintenance") and help ensure an optimal end-of-use treatment of worn-out textiles (PSS strategy "take-back for recycling").

To summarise, end this sub-step by listing and naming the scenarios that will be included upfront in the assessment. Supporting tips are provided in Box 6.

If the study is constrained in terms of time and resources, start with a base scenario and go through the next steps where the "hotspots" and data availability will be revealed, before deciding on further scenarios. This will support the iterative nature of the study.

In the next Step 3, the comparability between the PSS and the substituted product system(s) within the reference system will be assessed.

Box 6 *Tip* - When to include multiple scenarios upfront in the assessment?

When is it relevant to assess different variations of the PSS?

- When the study scope is PSS optimisation. However, also for a *PSS consequences* or *PSS comparison* study, it might be relevant to include different variations of the PSS, especially if the study is done as part of a design process, where the PSS is not yet fully defined. Also, internal variations of the PSS may be included upfront in the assessment, to explore optimisation options (e.g. the laundry service facility with and without heat recovery installed). Alternatively, such variations can be included as scenarios in Step 6 during result evaluation, in order to show optimisation potentials.
- When a PSS business model (e.g. a product rental offer) incorporates more than one type of PSS support and/or more than one PSS strategy.

When is it (usually) relevant to assess different variations of the reference system?

- When the study goal is to assess more than one application scenario.
- When the study scope is PSS consequences.
- When the PSS supports a platform.

SUMMARISING QUESTIONS

- Which scope is defined (PSS optimisation, PSS comparison or PSS consequences)?
- Is the PSS supporting an activity, product or platform, and how does this affect the complexity of the ref. system (relevant product systems to include in the study)?
- Which environmental impact reduction potentials can be identified based on the intended PSS strategies?
- Which systems to be analysed is it decided to include in the subsequent evaluation?

3 Comparability assessment

"How to compare?"

The purpose of Step 3 is to ensure that the systems chosen for analysis are comparable.

First, the functionality of the systems is defined, including defining an appropriate overall "functional unit" (sub-step 3.1), which makes up the starting point for comparisons between the PSS and its reference system.

This is followed by subdividing the systems (sub-step 3.2), representing "How" the functional unit is fulfilled.

Lastly, potential differences in the utility and value between the compared systems are qualitatively assessed, representing "How well" the functional unit is fulfilled.

This is done in order to identify potential causes of rebound effects (sub-step 3.3).

Both the PSS designer and the LCA practitioner profiles are needed in this step.

PSS designer

LCA practitioner

3.1 System functionality and Functional Unit

Describe the overall system functionality and define an appropriate functional unit upon which the comparison will be based.

Start by describing the functionality of the PSS and its reference system: What common functional outcome is delivered by them? See Box 7 for supplementary information on the difference between *function* and *system functionality*.

Based on the described system functionality, define the **functional unit**.

The functional unit is a description of the functional outcome in a measurable way, typically in terms of a specification of its quantity (how much?), duration (for how long?) and - if relevant - a location (where?).

In contrast to product-centred LCA studies (e.g. assessing different types of light bulbs), an LCA study on a PSS has the advantage that the functionality of the PSS is usually easy to define, since a PSS (e.g. a lighting service) is designed based on supporting the customer's need (e.g. "the need for light").

This knowledge can be used to describe the system functionality (e.g. "provide illumination").

Based on this, an appropriate functional unit could be: "provide annual illumination of a 12 m^2 office room with 30 lux". Here, the duration is one year, the amount is 30 lux and the location is an office room (inside a building).

When formulating the functional unit, make sure that it encompasses enough to be able to capture the functionality of the PSS and each of the substituted product systems within the reference system. The functional unit should be descriptive and reflect the activities that the PSS encompasses.

It is important not to "lock" the functional unit onto a parameter that might change as a result of the PSS. If, for example, the frequency of the service is expected to change, this should be variable, without having to change the functional unit.

In the example, the PSS might change the type of lightbulbs and how many hours they are turned on. The amount of light bulbs needed for one year of illumination would then be the **reference flow**. As such, the reference flows are the amount of products and services per functional unit.

While the functional unit should be defined broadly enough to be constant, the reference flows may vary between the compared scenarios.

Use the following examples as inspiration regarding how to specify the functional unit in relation to the three types of PSS support.

Activity support
For activity support, the functional unit can often be narrowed down to representing the activity affected by the PSS.

Laundry service example: The functional unit could be "the annual laundering of clothes for the average household". The duration of one year is important to include, since this enables that changes in how often the clothes is laundered can be reflected in the reference flows. Since the functional unit only describes the activity of laundering, only the sub-activities needed for laundering have to be included (washing, drying, etc). As such, it is assumed that the lifetime of the textiles are the same in both scenarios.

However, if the PSS causes a change in the durable lifetime of the clothes, this needs to be reflected in the functional unit, which should be changed to "The provision of one years' worth of clean clothes for the average household". This would enable that the amount of clothes that need to be produced and disposed of can vary and that processes of producing and waste-handling the clothes are included.

Product support
For product support, the functional unit should be able to capture changes in the life cycle of the product system in focus.

An example could be the case of a shared lawnmower. The functional unit could be "Mowing of 4800m^2 lawn (corresponding to the total lawn of 8 households) for 10 years". Again, the functional unit is defined in a way so that the changes caused by the PSS are taken into account, when defining reference flows (e.g. how many lawnmowers are needed during the 10 years). Also, the frequency of mowing the lawn is flexible here, within the functional unit.

Platform support
For a PSS supporting a platform, the functional unit needs to capture all the substituted product systems in the reference system.

Car-sharing system example: For a free-floating car-sharing system in the hypothetical city "Greentown", the overall functional unit could be: "The annual transport need of X commuters working within the city of Greentown", with X specifying the amount of commuters transitioning to the car-sharing system. The overall functional unit can then be broken down to sub-systems representing each of the alternative commuting options (product systems) that the car-sharing system substitutes.

Note, that for some of the comparisons, there will not be a one-to-one substitutability between commuting option.

For example, some of the commuters that previously used their own car might now use the car-sharing system in combination with public transport.

For this group of commuters, the comparison would be between commuting with private car (in reference system scenario) and commuting with public transport and car-sharing system (in the PSS scenario).

While in principle, the changes in all relevant alternatives could be related directly to the overall functional unit, the reason for dividing the functional unit into sub-systems is to be able to interpret the results better and capture differences in the reference flows.

For example, when changing from public transport to a car-sharing system the commuting distance might change. Thus, for each substituted product system the reference flow for the compared scenarios must be specified (in Step 3.2).

Definitions

System functionality: Describes what the system should provide, in order to fulfil the user's need = a description of the system requirements.

Functional unit: Quantified performance of a product system for use as a reference unit (ISO 14044).

Reference flow: Measure of the outputs from processes in a given product system, required to fulfil the function expressed by the functional unit (ISO 14044).

Box 7 *Supplementary information* - Function vs. system functionality

LCA as a method is traditionally product-centred.

LCA guidelines for expressing the functional unit are often based on specifying the "function" of the product (sometimes called the product's service) in a measurable way. In this guide, we use the term "system functionality" instead, to describe the system requirements, in order to fulfil the user's need.

As such, the "function" describes what the system can provide, while the "system functionality" describes what it should provide or support.

3.2 System subdivision - "How"

Specify "How" the functional unit is fulfilled by subdividing the system for each of the compared scenarios.

Subdivide the system into the components, which enable the system functionality.

The purpose of this sub-step is to make sure that the required processes are represented in the comparison between the PSS and the reference system. For example. a laundry service would not deliver wet clothes back to the customer. Therefore, the drying process will need to be included in both the PSS and in the reference system.

Processes that are eliminated or changed by the PSS can potentially lead to **avoided impacts**. In contrast, the added products, services and support systems on which the PSS relies, will lead to **induced impacts**.

Use the following examples as inspiration regarding how to subdivide the system for the three types of PSS support.

Activity support
Divide the overall activity into sub-activities and mark which are avoided (removed), changed or induced (added) by the PSS.

Laundry service example: Specify that the clothes need cleaning, drying, folding, (and for the PSS packing and transportation) etc.

Product support
Map all activities over the product system life cycle, from raw material, production, and use, to end-of-use and mark which are avoided (removed), changed or induced (added) by the PSS.

Shared lawnmower example: Specify that the lawnmower needs to be produced, maintained, fuelled and the sharing system needs administration. Finally, at end-of-use, the lawnmower needs to be redeployed or waste-handled.

Platform support
List all the product system constellations that the PSS substitutes. Subdivide each of these into activities.

Car-sharing example: Specify the different commuting options included in the PSS and substituted in the reference system (e.g. cycling, private car-driving, public transport use, combined train transport and car-sharing, etc.).

Each of these can be further subdivided into activities (e.g. in the PSS 20km of train and 3km of car-sharing substitute 19km of private car in the reference system).

The system subdivision lays the basis for the process mapping during Step 4, where a visual diagram (a flowchart) will be created. The system subdivision may be supported by using tools such as storyboards or life cycle galleries, see Box 8.

Box 8 *Tip* - Use product life galleries or storyboards to support the system subdivision

A **storyboard** is a tool derived from motion picture production and often used in service design, as a way to visually depict an experience or interaction among people and objects.

Through a series of drawings or pictures, the activity or product life cycle is broken down into specific components over time.

A **product life gallery** is a visual poster telling the product's life cycle story.

The poster may include:

- a description of each life cycle stage, including inputs and outputs of materials, products and services;
- a mapping of the important stakeholders and their interaction with the product;
- an overview of environmental concerns, e.g. by creating a **MECO** chart, listing **M**aterials, **E**nergy, **C**hemical and **O**ther uses for each life cycle stage.

Both tools have the advantage of being visual and may help facilitate discussion amongst relevant stakeholders, to ensure that all important aspects of the system in focus are taken into account.

3.3 Utility, value and rebound effects - "How well"

Identify relevant consumption factors affecting the utility or perceived value of the PSS, and consider if these imbalances might lead to rebound effects.

Besides supporting the functional unit by subdividing the system, also "non-functional" performance characteristics must be captured, to ensure that the comparison is carried out on an equal basis.

When comparing different options for needs fulfilment, the compared alternatives will most likely have differences, in terms of "how well" the need is fulfilled. This is influenced by the **utility** of the solution and how the customer perceives the **value** of the solution.

While the utility of a solution can be evaluated objectively, the actual value of a solution is a subjective judgement, which depends on customer preferences, see Box 9 for examples.

Definitions

Utility/value: Expresses "how well" the need is fulfilled, also taking "non-functional" quality aspects into account, when expressing the system performance.

Utility: Objective judgement.

Value: Subjective judgement.

Both utility and value are affected by **consumption factors**, which will depend on the system under study. For example, changing from owning a car to a car-sharing system would require that the "value of ownership" and "feeling of freedom" were compromised and replaced by other benefits such as saved money.

Use the list in Box 10 as inspiration, to identify relevant consumption factors for the systems to be analysed. Note that the list provided is not exhaustive.

Box 9 *Example* - Difference between utility and value

Consider comparing using a bike or a car to commute to work.

If the distance is 40km, the utility of the car is bigger than if the distance is 2km, due to time savings etc.

However, the person commuting 2km might choose the car because of other parameters, such as image, comfort or habit – the perceived value of the car is greater than the bike.

The contrary might also be the case, where the person commuting 40km chooses the bike because it provides an opportunity to exercise.

Box 10 *Tip* - Inspiration list of common consumption factors

Money: When the PSS is more or less costly than the alternative.

Time: When the PSS is more/less time consuming than the alternative.

Space: When (elements of) the PSS take up more or less space than the alternative.

Technology: When the PSS affects the availability of specific technologies or materials (e.g. when streaming services lead to people no longer owning CD or DVD players).

Skills: When the PSS requires more or less skills than the alternative.

Information: When the PSS requires more or less information than the alternative.

Access: When the PSS is more or less available than the alternative.

Responsibility: When the user feels more or less responsible for the PSS than the alternative.

Convenience/comfort: When the PSS is more or less convenient or comfortable than the alternative.

Risk and safety: When the PSS is considered more or less risky or safe than the alternative.

Perception/image: When the PSS is considered more or less attractive than the alternative.

Identifying and assessing relevant consumption factors has two purposes:

- **Substitutability:** Ensure that the compared systems are actually substitutable, from the perspective of the customer. If the utility or perceived value of an option is much lower than the alternative, it is not likely that the customer will choose it. Measures might need to be taken to make the alternatives comparable in the eyes of the customer, which again might change previous assumptions regarding the substitutability between systems or add processes not identified so far.
- **Rebound effects:** Ensure that differences in constrained consumption factors are captured, since these will likely trigger rebound effects.

A **rebound effect** is the negative, unintended environmental impacts that may arise due to behavioural or systemic responses to a change in a system. As such, rebound effects entail that the actual impact savings from an improvement are less than expected.

A rebound effect can also be "negative" in the sense that it increases the expected savings. Such effects can be referred to as **secondary** (environmental) **benefits**, see figure 9.

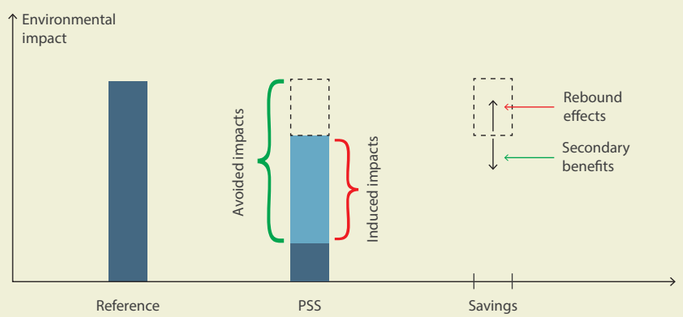


Figure 9 Comparing a PSS with a reference system in terms of environmental impact. Processes that do not change in the PSS and the reference system will have the same impact (the dark part of the PSS bar). When the avoided impacts are greater than the induced impacts, the PSS can be said to result in impact savings, represented by the dotted area. Rebound effects (illustrated by the red arrow) will lead to a decrease in anticipated savings, while secondary benefits (illustrated by the green arrow) will lead to an increase in anticipated savings.

Rebound effects occur when the improvement provides incentives for customers to consume more. Secondary benefits occur when the improvement avoids customers using or buying more.

These responses occur when the improvement option liberates or binds a constrained consumption factor, such as money or time.

The size and impact of the rebound effect depends on how the consumption factors differ between the compared systems, see Box 11 for examples.

Definitions

Avoided impacts: When a PSS replaces or reduces the need for processes in the reference system, this leads to avoided impacts.

Induced impacts: When a PSS introduces or increases the need for processes in the reference system, this leads to induced impacts.

Rebound effect: When the impact savings from an improvement are less than expected, because of behavioural or systemic responses.

Secondary benefit: Same as "negative" rebound effect: When the actual impact savings from an improvement are higher than expected, because of behavioural or systemic responses.

Two types of rebound effects can be distinguished (see Figure 10):

- **Direct rebound effects** occur as a direct response to a change. A common example is when people buy a more fuel-efficient car but increase how much they drive, so that the absolute savings in fuel are minimal or even negative.
- **Indirect rebound effects** occur as an indirect response to a change, by increasing consumption in other areas. Using the same example, the saved money from the fuel-efficient car might be spent on more consumption of other goods or services. In this case, the rebound effect will depend on how the money is spent.

An example of a secondary benefit would be if a fuel efficient car also motivates the user to drive less. During the functional unit definition, it was already discussed how the reference flow (e.g. the amount of kilometres travelled) could change between the compared systems. This would be equal to capturing the direct rebound effects that often occur when introducing a PSS.

However, taking the time to consider which consumption factors might be affected will help identify rebound effects not included in the assessment so far.

Box 11 *Example* - Rebound effects in PSS

Which consumption factors will be relevant for the PSS under study is highly case-dependent. For example, for transport, time has proven to be a constraining factor. If people save time on transport, they tend to transport themselves more.

For product sharing, access plays a role. If people share household tools, such as drills or lawnmowers, they cannot use them at the same time. If the PSS is very inconvenient, customers might use the system less than expected – the assumed substitutability of the compared systems may not be realised in practice. Furthermore, rental systems can make products available for users, who did not previously have access.

Another case is after-sales services, such as preventive maintenance. As companies get better at offering and supplying the service and as the service becomes more readily available for customers, they will often start using the service more – maybe even before the service is actually needed.

Responsibility is another common factor in PSS. People often tend to use products less carefully, when they don't own them. At the same time, they tend to have higher expectations, in terms of comfort or quality. In a car-sharing system, customers might be unsatisfied if the car is very dirty inside, but at the same time care less about the state of the car when leaving it for the next user. This would require extra cleaning of the car, compared to privately owned cars.

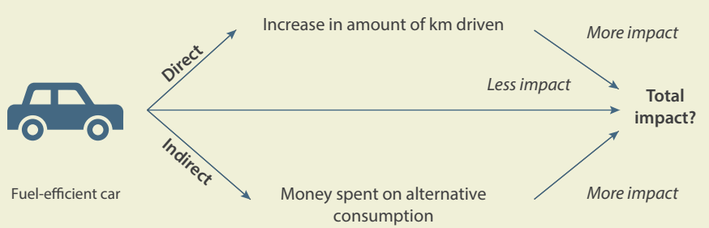


Figure 10 Difference between direct and indirect rebound effects from a more fuel-efficient car. Adapted from the International Handbook on the Economics of Energy, edited by Joanne Evans and Lester C. Hunt. 2009

Identifying rebound effects equals identifying constraints - what prevents or liberates the customer using more or buying more.

Differences in economic costs will always be relevant, especially for consumers, who will tend to spend the money saved elsewhere. As an indirect rebound effect, price differences are also the most common to try to include in LCA studies.

In these cases, the saved money is spent on alternative consumption, which can either be specified or assumed to be average consumption. So-called Input-Ouput-based LCA models exist, which model the environmental impacts of average consumption, see also Appendix 3.

Assessing the price difference in comparison to the expected savings will indicate if it will be relevant to quantify the economic rebound effect in Step 5.

Assessing the environmental impact of indirect rebound effects is not straightforward and can easily be seen as outside the scope of the assessment.

However, a qualitative evaluation of differences in the consumption factors between the compared systems is recommended, in order to support the interpretation of the quantified results and at least identify if rebound effects are likely to occur.

If the study is done to support a design process, this evaluation will also reveal if the PSS and the presumed substitutions are so different in their performance that it can be argued that the substitution is unlikely to occur (e.g. if the PSS costs twice as much or takes up twice as much time). See tip in Box 12.

Before moving to Step 4, revisit Steps 1-3 and consider if any changes should be made to the defined systems to be analysed, based on the comparability assessment.

Try to make a qualitative judgement of whether or not it is likely that the proposed PSS will entail environmental benefits, reflecting on:

- Activities or product systems that the PSS *induces* (the PSS' dependencies);
- Activities or product systems that the PSS *avoids* (the PSS' substitutability);
- The risk of *rebound effects*.

Box 12 *Tip* - Mitigate rebound effects in the design process

While quantifying the actual environmental impact of the rebound effects can be very difficult and uncertain, simply identifying the differences in the consumption factors can become very useful when designing or optimising the PSS. If these differences can be mitigated, e.g. by influencing the perceived value of the environmentally preferable option, this would in principle also mitigate the rebound effects.

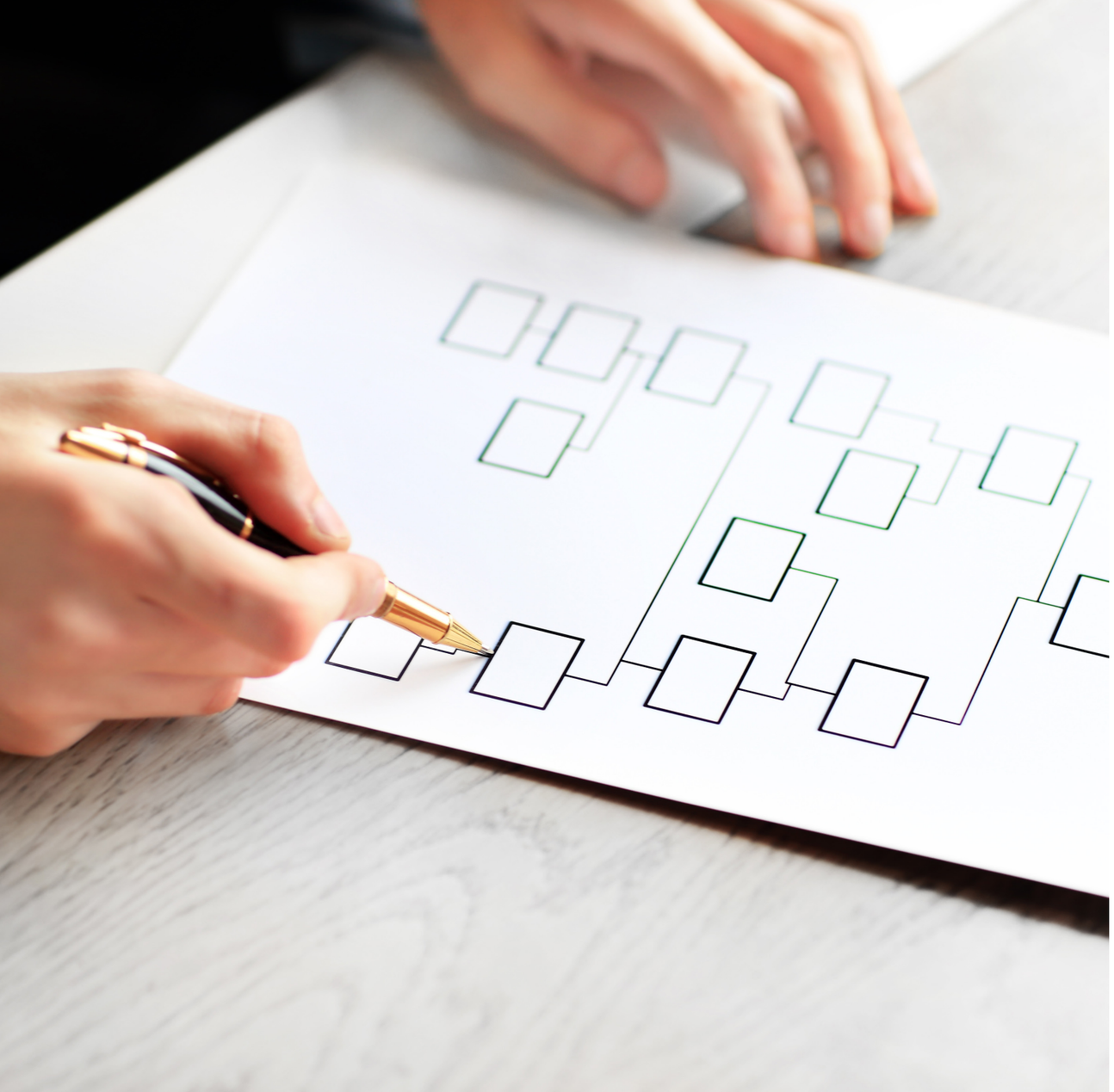
Therefore, if the study goal includes providing recommendations for the design of the PSS, identifying and assessing the consumption factors can be very fruitful.

If the PSS has the potential to reduce the environmental impact through efficiency measures, how can the economic value of the PSS be increased to compensate for the cost savings? For example for the "eco-driving" case, how can the PSS facilitate that money saved from fuel savings is spent on less environmentally burdensome activities that would still be perceived as valuable to the customer?

Maximising the value creation for the target customers can lead the way to ensure so-called eco-efficiency gains, where the environmental impact decreases while the market value increases (sometimes also referred to as "decoupling economic growth from resource consumption and environmental impacts").

SUMMARISING QUESTIONS

- What is the common functionality of the systems to be analysed?
- What is defined as the common functional unit of the compared systems?
- Which sub-systems are needed in the PSS and the reference system, respectively?
- Which consumption factors are expected to change between the PSS and the reference system and what can be expected in terms of potential rebound effects or secondary benefits that might be caused by these changes?
- Does the comparability assessment give rise to changing the previously defined systems to be analysed?



4 Process mapping

"What to measure?"

The purpose of this Step is to guide the inventory data, gathering in the subsequent quantitative Step 5.

The process mapping creates an overview of all data inputs required. This is done individually for each of the systems to be analysed.

First, a visual overview of the processes is created in a flowchart (sub-step 4.1).

Then, the system boundary for each of the compared systems is defined, ensuring consistency in completeness and modelling approach, between the compared systems (sub-step 4.2).

Lastly, the impact categories included in the quantitative assessment should be specified, since this might influence the data gathering (sub-step 4.3).

The "LCA practitioner" has the most significant role in this step, but should be supported by the "PSS designer" profile.

PSS designer

LCA practitioner

4.1 Flowchart

From the system subdivision specification (sub-step 3.2), create visual flowcharts for both the PSS and the reference system, in order to provide an overview of all the processes and product/service flows needed to fulfil the functional unit.

In a flowchart, activities (e.g. washing of clothes) are called **processes** and are represented as boxes, while **product and service flows** (e.g. water, detergent, electricity, transport service etc.) are the inputs and outputs from the processes and are represented by arrows. *Note that in traditional LCA terminology, both product and service flows are termed "product flows".*

Processes (e.g. "clothes washing") have inputs of products or services (e.g. "washing machines") which are linked to processes (e.g. "production of washing machine", "transport by truck" etc.). The size of the reference flow(s) determines how much is needed of each process to fulfil the functional unit. See also tip in Box 13.

Elementary flows are input or output flows originating or ending up in the environmental system. Examples are natural resources, extracted from the ground or emissions to water or air.

Figure 11 shows the flows to and from a process delivering a single product or service output.

Since mapping the whole system can be rather complex, it can be useful to break down the flowchart to create a better overview, for example by having one or more flowcharts per life cycle stage.

Another option is to create a more simplified visual diagram, showing only the main processes. Remaining product and service flows could be provided in lists or tables, supplementing the visual diagram.

Creating the flowchart will often be an iterative process. If visual mapping tools such as storyboards were used during the PSS design process or to support the system subdivision (sub-step 3.2), these can often be used as a starting point when creating the flow chart.

Box 14 exemplifies two different types of flow charts.

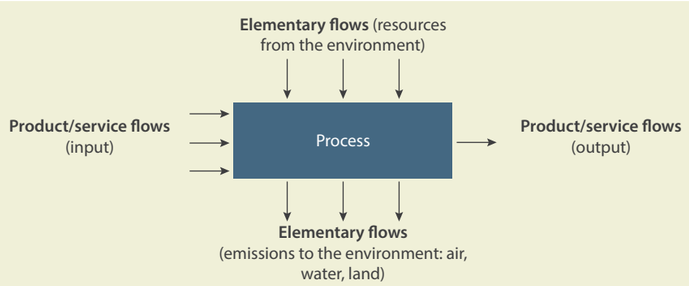


Figure 11 Product/service flows and elementary flows to and from a process

Box 13 *Tip* - Highlight processes leading to induced and avoided impacts

Added processes or where volumes are increased, compared to the substituted system, will lead to induced impacts. Highlight these processes in the flowchart. In the laundry example, an added process would be transportation to and from laundry. A process where volumes would potentially increase is the electricity use from drying, since this will occur more often, compared to home-based laundering.

Similarly, when creating the reference systems' flowchart, highlight displaced processes or where volumes are reduced by the PSS, as they will lead to avoided impacts. For example, in the laundry case, it is assumed that the washing process will be more efficient, leading to less use of water and energy.

In this way, a qualitative preliminary assessment of the causes for induced and avoided impacts is possible and the data gathering and quantification in Step 3 will help confirm or refute these assumptions.

Box 14 *Supplementary information* - Two types of flow charts

Life cycle flowchart

A horizontal mapping of the product system life cycle from cradle to grave. Especially relevant for a *product support PSS*, where the life cycle of the product plays a central role. Figure 12 shows a generic life cycle chart.

For each life cycle stage, inputs and outputs (including materials, energy, transport services etc.) are mapped. All supporting products and services will have a life cycle flowchart of their own, which may be extracted or black-boxed in the visual chart.

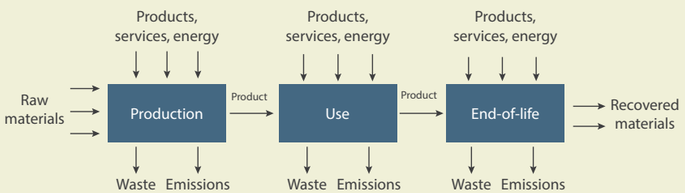


Figure 12 Generic life cycle flowchart

Process tree

A vertical mapping of all product and service flows directly related to the functional unit. Especially relevant for *activity support PSS*, which is composed of sub-activities, and *platform support PSS*, which is composed of multiple product systems. In this type of chart, the reference flow for each process is easily visualised. In Figure 13, a segment of a process tree for a laundry service is shown.

Note, that for this type of chart, all life cycle stages are mapped as inputs. For example both the production and end-of-life of the truck needed for transport are modelled as inputs (in a life cycle database, this will often be included in a single process). Also, the process of waste water treatment is modelled as an input to clothes washing (it is the process of washing clothes that requires that waste water is treated).

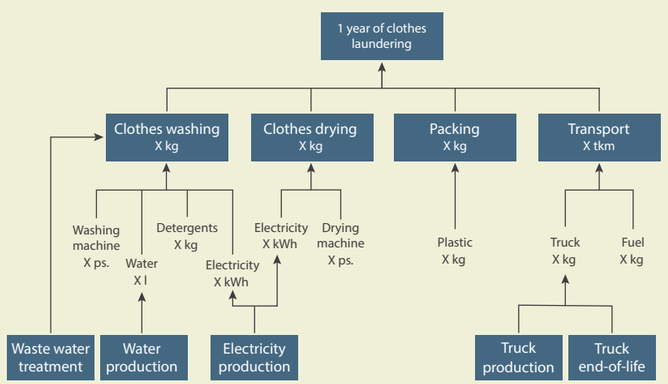


Figure 13 Segment of a process tree for a laundry service

4.2 System boundary

Define the system boundary by evaluating if any of the identified processes can be left out of the assessment.

Delimiting the amount of processes included in the study can be both necessary and practical, in order to complete the first iteration of the study. Further iterations may expand the system boundary to ensure a higher level of detail in the analysed systems.

Delimitation: Unaffected processes
Unless it is of interest to quantify the total impact of the systems, it is only necessary to include the processes that differ between the compared systems. Processes that are unaffected and therefore equal in the compared systems will not contribute to the difference in performance and hence can be black-boxed and left out of the assessment.

In the laundry example, all processes related to the laundry process change and need to be included. However, if no changes occur in the amount of clothes being produced or in the way it is produced, the clothes production can be left out. *Note, that this delimitation would already have been established in Step 2.*

Another example could be that it is discovered that the detergents are very similar in both laundry processes - both in terms of their production, amount used, and the subsequent disposal in the sewage system. These processes are therefore left out in the comparison.

Delimitation: Cut-off criteria
Processes might also be left out based on so-called cut-off criteria, which assume that the process contributes insignificantly to the overall environmental impact.

According to the ISO standard on LCA (ISO 14044) several cut-off criteria are used in LCA practice to decide which inputs are to be included in the assessment, such as mass, energy and environmental significance. Examples of inputs that are typically left out include: services, such as administration (accountants, lawyers, IT services) and capital goods, such as infrastructure and buildings. These are left out under the assumption that they have minor contribution to the overall result. Note, however, that studies show that this is not always the case, and especially for PSS that depend on these types of inputs, it is recommended to keep them within the system boundary, at least in subsequent iterations of the study. See Box 15 for an example.

When comparing systems, it is important to keep in mind that the same level of completeness/cut-off criteria are applied for the systems under comparison.

The system boundary is also affected by the choice of how to model multifunctional processes (processes that have more than one product/service output). See Box 16 for more information.

Box 15 *Example* - The importance of including services - the case of Eco-driving

In the case of "Eco-driving", besides the monitoring system, the PSS consists mainly of training seminars and consultancy, which could be perceived as having an insignificant environmental burden. However, when including the inputs on which these services rely such as travel and IT equipment, it would show that impacts related to these inputs make up a significant part of the total PSS induced impacts.

Box 16 *Supplementary information* - Multifunctional processes

During the process mapping, you will probably encounter multifunctional processes (processes that have more than one product/service output). An example is a wool t-shirt, which requires wool from sheep. The process "sheep production" delivers both wool and meat, and the wool should not account for all impacts associated with "sheep production". For these types of processes, the modelling approach needs to be decided.

The methodological choice will also influence the system boundary. The ISO standard on LCA has a hierarchy of how to deal with processes shared with other product systems:

1. **Subdivide** the process by function.
2. If subdivision is not possible (as would be the case in the example above), **expand the system** to include the additional functions related to the co-products. In the example, it would be to include the function of the meat.
3. Only if this is not possible, apply **allocation,** where input and output flows are split between the co-produced products.

In the next step, during data gathering, it is briefly discussed how the inventory data are influenced by the modelling approach decided.

4.3 Impact categories

Lastly, decide the environmental impact categories to be included in the assessment.

Impact categories may have been decided earlier, maybe already in the goal definition. Otherwise, choosing relevant impact categories is important for the interpretation of the results and will depend on the type of product system(s) in focus and what is of concern for the intended audience of the study.

Appendix 1 provides guidance on how to choose impact categories.

If a narrow range of impact categories (or only one) is chosen for the quantitative part of the assessment, it is recommended to state whether other impact categories have been identified as relevant during the previous steps.

This information can be used in Step 6 with regards to how well the results represent the overall environmental performance of the system and to recommend further work needed.

SUMMARISING QUESTIONS

- Which processes (activities) are needed to fulfil the functional unit?
- Which processes are assumed to lead to induced and avoided impacts?
- Are there processes that are unchanged between the compared systems and can they be left out?
- Are other cut-off criteria applied?
- Which approach is chosen for handling co-products from multifunctional processes?
- Which impacts categories will be measured?

5 Quantification

"How to measure?"

In this step, the data are gathered for each process included within the system boundary, and the quantitative results are generated.

Performing the data gathering (sub-step 5.1) and calculating the results for a PSS (sub-step 5.2) can in principle be done by following the LCA procedure, as described in ISO 14044. As such, if the LCA practitioner is experienced, the activities in this step will be well-known and the reader can skip it.

For novel practitioners, the sections provide a brief introduction to the life cycle inventory (LCI) phase and life cycle impact assessment (LCIA) phase of LCA, with emphasis on important aspects for assessing PSS.

The main competence profile involved in this step is the LCA practitioner.

LCA practitioner

5.1 Data gathering

Gather the inventory data for each process included in the assessment.

Gathering the inventory data is often the most time-consuming task in an LCA study. See tip in Box 17 on how to focus the data collection.

Inventory data are connected to two aspects in the established flowchart:

- Quantities of the product/service flows (how much?).
- Data for each individual process (what?).

Flow quantity (How much?)
Flows connect all processes, and are in the end related to the reference flow(s). The flow quantities are the amount of product or service needed from each process to fulfil the functional unit.

An example could be the amount of electricity used by washing machines for each of the laundry service scenarios ("how much" electricity), measured in kWh. A product/service flow can be quantified through measurements, calculations and/or estimations, often in combination.

For simplicity, this guide distinguishes between two extremes for defining the flow quantities: **actual data**, and **assumptions**; with "proxies" being somewhere in between. While actual data can be measured (or to some extent calculated), assumptions rely on estimates.

Assumptions are necessary, when actual data are not available. To reduce the level of uncertainty, assumptions can be based on measured or calculated data from other existing (similar) systems, through projections, expert opinions etc. Assumptions should somehow be justified and when they have high variability, it should be considered if different scenarios (e.g. best case, worst case and most likely) need to be modelled, in order to support the interpretation of the results (Step 6).

Process data (What?)
The process data are the product/service input flows and elementary input and output flows per unit of product/service output for each individual process.
In the previous example, the process data would model the electricity production ("what" electricity production?) in order to calculate the environmental impact per kWh produced.

For each process, decide between two data source options: model the process using **primary data**, or model the process using **secondary data** sources, e.g. drawn from existing LCA databases.

Taking into account the complexity and uncertainty, which often characterises PSS assessments, there will often be a high dependency on LCA databases, in order to ensure the required completeness and consistency in the assessment. However, some degree of primary and original data will always be needed for the processes identified as most important within the decision-making context (the so-called foreground system) see also Box 18.

Furthermore, the decision on how to model multifunctional processes will influence the inventory data, see Box 19.

Consider how the chosen modelling approach affects the inventory data.

Box 17 ***Tip*** **- How to focus data collection so as not to get lost in the detail**

Compared to an LCA of a simple product (e.g. a water container or a light bulb), assessing a PSS will often require that the level of detail in terms of data precision is compromised, in order to ensure the required completeness and consistency between the compared systems.

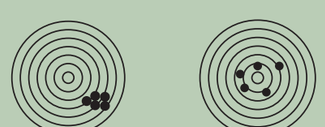
This guide supports evaluations with a relatively high uncertainty in terms of data **precision** (how large variations in the results), as long as the **accuracy** (how close to the true value) is appropriate for the defined study goal and scope.

There are three reasons for allowing a high tolerance in terms of data precision, also taking time and resource limitations into account:

1. This guide supports not only evaluations of established PSS solutions, but aims to support evaluations of pre-implementation as well, including assessing different design options. In these cases, the assessment will to a large extent be based on assumptions and will include several scenarios.
2. For multiple application scenarios and for platform support PSS, the assessment will include numerous product systems, and a high level of detail for all of these will often not be applicable.
3. A PSS often relies on many inputs, both in terms of products, services and support systems. This complexity requires a higher focus on completeness, often at the expense of data precision.

These conditions will influence the data collection, which to a larger extent will have to be based on estimates and secondary data (data collected in previous studies, e.g. data found in LCA databases).

While this might introduce uncertainty in terms of data precision, focusing on choosing the best representative data and modelling approach should help provide meaningful results.



High precision, low accuracy

High accuracy, low precision

Box 18 ***Supplementary information*** **- Foreground vs. background system**

Building on the established flowchart, a distinction between the **foreground system** and **background system** can be made.

Processes in the foreground system are those within the sphere of influence of the decision-maker, while processes in the background system are those drawn upon, but that are not under direct control or decisive influence of the decision-maker. While data for the processes in the foreground system can be gathered from the actual suppliers, producers, service providers and customers, processes in the background system often use data from other LCA studies, such as from LCA databases.

Box 19 ***Supplementary information*** **- Modelling multifunctional processes**

Multifunctional processes were explained in Box 16 in Step 4.2, where the example of a sheep farm producing both wool and meat was used. Another example is combined heat and power production, where only the electricity is used by the product system. How inventory data are calculated depends on the modelling approach decided.
If using system expansion, data must be gathered for the products that are substituted by the co-products not used in the product system under investigation.

This is called the *substitution approach*, in which the alternative system substituted by the co-product is simply subtracted from the investigated system, in order to balance the input and outputs (illustrated in Figure 14). If allocation is applied instead, the inventory data for the multifunctional process are partitioned through a rule that reflects the underlying physical relationships between them (e.g. mass or energy content) or through other relationships such as economic value.

Figure 14 The substitution approach. Adapted from the original ISO 14041:1998 (which was merged with ISO 14042 and 14043 into the current ISO 14044 in 2006)

Lastly, decide if inventory data in the background system should be modelled using average data or marginal data.

Average data represent the "market mix", whereas marginal (or incremental) data represent the actual affected technology. While the marginal data can be argued to represent the actual consequence of a change better, it can be challenging to identify the correct marginal technology and the results can change drastically if the technology changes.

In general, marginal data should be used to model changes when the accuracy is important, i.e. when the choice of data is important for the results and conclusions of the study.

Note that the data gathering is an iterative process, where better quality data can be collected for the important processes in the system, see tip in Box 20.

Box 20 *Supplementary information* - Where to place the effort in data collection?

When deciding where to place the effort in terms of collecting better quality data, Figure 15 can be useful to consider.

Emphasis should be put on collecting better data for processes that have a high sensitivity (influence on the results is high) and where the uncertainty in the initial data is high.

As an example, the first screening of a laundry process shows that energy consumption during the washing process has a high influence on the results.

Effort is therefore put on collecting better data on the actual energy consumption ("How much"), including to which extent it varies, as well as the modelling of the electricity production ("What").

Appendix 3 provides an explanation of Input-Output-based LCA, in contrast to Process-based LCA and the combination, termed Hybrid LCA, which has the benefit of ensuring completeness as well as data precision, with a high influence on the results.

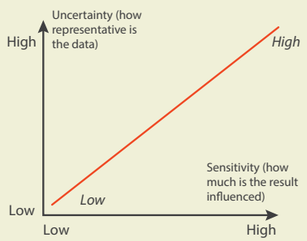


Figure 15 Prioritising data collection

5.2 Calculations

Perform calculations based on the gathered data.

Usually, an LCA software tool will be needed to collect and analyse the data, especially since PSS assessments will often draw on the LCA databases readily available in these tools.

The summarised calculations can be made on the inventory level (leading to a life cycle inventory (LCI) result) or - more commonly - through performing a life cycle impact assessment (LCIA), where each inventory flow is translated into environmental impacts.

For example, the amount of minerals consumed and the amount of CO_2 emitted would be two LCI results, while mineral extraction potential (for the impact category *resource depletion*) and global warming potential (for the impact category *climate change*) would be the corresponding characterised results of the LCIA.

The LCI result merely summarises the inventory results in relation to the functional unit and does not say much about the potential environmental impact.

Most environmental assessments would therefore require an LCIA, which is also a requirement in the ISO standards on LCA.

The LCIA method chosen will determine how inventory data are characterised. Remember to state the LCIA method used.

SUMMARISING QUESTIONS

- Which processes will require primary data and which may rely on secondary data?
- Which data sources are used?
- Is allocation applied and if so, by which criteria?
- Which assumptions are most uncertain and should be subject to sensitivity analysis?
- In the case of conducting an LCIA, which method is applied?
- Is an LCA software utilised?

6 Interpretation and recommendations

"What to conclude?"

In this step, the calculated results are evaluated in terms of their validity.

The quantified results are interpreted in relation to the goal of the study (sub-step 6.1), and together with the qualitative results from Steps 2, 3 and 4, the overall study results and conclusions are communicated to the intended audience (sub-step 6.2).

As a last sub-step (6.3), the results can optionally be supported by recommendations, addressing potential areas of improvement.

All three competence profiles need to be involved in this final step.

Strategic decision-maker

PSS designer

LCA practitioner

6.1 Results evaluation

Evaluate the results in terms of their validity.

The result evaluation might include completeness checks, sensitivity checks, and consistency checks as described in the ISO standard 14044.

What needs specific attention in regards to evaluation of a PSS, are the parameters that have a high influence on the results and at the same time have high uncertainty (e.g. in the case of unverified assumptions or high data aggregation). The result evaluation can be supported by a scenario analysis, where the purpose is to evaluate different options, where parts of the product system are changed, see example in Box 21.

Using parameters and varying these can also be used to find optimums or break-even cases, in order to argue under which circumstances the PSS is environmentally superior.

Box 21 *Example* - Laundry service

In the case of the laundry service, the household habits in terms of the drying behaviour might have been hard to gather data on. In these cases, it is recommended to perform a sensitivity check by formulating a worst case (all users dry their clothes in tumble dryers) and best case (all users hang their clothes out to dry), in addition to the most likely case used in the assessment.

6.2 Results communication

Present the overall study results, taking into account both qualitative and quantitative findings.

How the results of the assessment are presented depends on the intended audience and the application of the results. The results should be presented in a relevant, transparent, and illustrative way.

Inspiration on what to include in a report is found in Box 22.

Start by recapping the goal definition and ensure that the results of the study actually answer to the study purpose.

Supplement the quantitative results with a qualitative description, stating the main learnings from the study, especially from the activities performed during Steps 2, 3 and 4, as well as main limitations and assumptions influencing the results.

The overall findings of the study should help conclude under which circumstances the PSS under study leads to environmental impact savings or not. Three main aspects should be highlighted:

- **The PSS' dependencies (induced impacts):** Does the PSS depend on new support systems, infrastructure and services, which are added, compared to the reference system? Are any of the related processes left out of the assessment, which could jeopardize the results?
- **The PSS's substitutability (avoided impacts):** Does the result depend on the PSS' ability to substitute specific products systems and has the study revealed any concerns about their substitutability?
- **Rebound effects:** Is there a risk that the PSS will increase the demand for the products/services (direct rebound effect) or other consumption (indirect rebound effect)?

Boxes 23 and 24 provide examples of communicating avoided and induced impacts and rebound effects. Lastly, supplement the result communication with recommendations for further work needed. This may include:

- If more iterations are necessary to enable conclusions and answer to the study goal.
- For which processes, more or better data could or should be gathered.
- Which further scenarios could be assessed.

Box 22 *Tip* - What to include in the result communication?

The following aspects may be included in the report or presentation of the study result:

- The stated study goal
- The type of study scope (PSS consequences, comparison or optimisation)
- The type of PSS support (activity, product or platform)
- The PSS strategy(ies) and their impact reduction potential
- The defined systems for analysis and assessed scenario variations
- The functional unit
- The consumption factors identified that might cause rebound effects
- The quantified results in the shape of a visual chart, comparing the PSS and the reference system (variations may be included to show different scenarios)
- A statement of the main parameters that influence the results
- An evaluation of whether the results are significant (will the proposed improvements lead to statistically significant impact or do they lay within the uncertainty of the results?)
- Under which circumstances the PSS has the largest impact-saving potential (for multiple scenarios, which performs the best and why?)
- The most important processes contributing to induced impacts within the PSS (which ones are added and which have the largest impacts within the PSS?)
- The most important causes of avoided impacts in the reference system (which processes should the PSS influence or substitute to reduce impacts?)
- A discussion of chosen impact categories, including if impact categories were identified as relevant but not assessed for various reasons
- Potential trade-offs between impact categories (e.g. if the PSS has higher metal depletion potential but lower global warming potential)

Box 23 *Example* - Laundry service

Avoided impacts come from the laundry service being more efficient, due to upscaling and sharing of equipment, while induced impacts come from increased transport (to and from the laundry facility), increased energy for drying of clothes, and packaging.

The assessment shows that overall impact savings are achieved when comparing the PSS and the reference system.

However, the customer will save time on clothes washing, which could lead to the clothes being washed more often, potentially leading to a shortened lifetime of the clothes due to of increased abrasion.

On the other hand, the PSS is more expensive, so the customers have to spend more money, meaning that less money is available for alternative consumption (secondary benefit).

These considerations are recommended to include in future work, to see under which circumstances the PSS has higher impacts than the reference system.

Box 24 *Example* - Eco-driving

Consider the example of a PSS for "eco-driving". The avoided impacts come from reduced fuel consumption, while induced impacts come from the products (e.g. monitoring equipment) and the activities needed for realising the fuel savings (e.g. training sessions, which includes travel etc.).

For the impact category, such as climate change, the saved fuel decreases the amount of CO_2 equivalents emitted, while the PSS-induced activities add CO_2 equivalents.

The impact savings are the avoided impacts subtracted from the PSS induced impacts.

The identical elements of the reference system and the PSS were not included (e.g. the impact of truck production and end-of-life handling).

It is expected that the customer's expenses for the PSS elements will be less than the cost savings from the saved fuel, and this difference will most likely lead to a rebound effect.

This rebound effect can either be stated as a study limitation, qualitatively assessed (by investigating how the saved money is or could be spent), or it could be quantified. The choice will depend on time and resources available, as well as the stated goal definition.

6.3 Recommendations (optional)

If the purpose of the study is to provide suggestions for improvements, use this final sub-step to provide recommendations, based on the findings.

The type of recommendations will depend on the study purpose and might include the following:

Design recommendations
The study will often have identified areas with potential for design improvements within the PSS. The purpose of this guide is not to provide an extensive list of ecodesign options for PSS.

However, as inspiration, **product design** improvement could include:

- Design for repairability and upgradeability
- Design for dismantling and material recycling
- Design for improved maintenance and operation

In terms of **process design**, recommendations could include optimising processes with a relative high impact. An example could be optimising route-planning for collecting clothes in the case of the laundry service, in order to reduce the transport need.

Unexplored PSS strategies
In sub-step 2.3, the employed PSS strategies were identified. However, the PSS setup might be expanded to include other strategies. As such, the evaluation might inspire to conduct a subsequent evaluation of the effect of employing more strategies.

For example, could the laundry service include a take-back service for used textiles and would that lead to environmental improvements, compared to the alternative end-of-use treatment?

Mitigating rebound effects
In Step 3, the potential causes of rebound effects were identified. Examples include:

- The PSS led to cost savings
- The PSS helped customers save time
- The PSS provided easier access to products
- The PSS was more comfortable

These changes in consumption factors would most likely lead to rebound effects, in terms of increased consumption.

Even though the environmental impact of these rebound effects might not be quantified, it could be part of the recommendations to provide suggestions as to how they might be mitigated.

If the PSS is a cheaper solution than the alternative, could value be added (e.g. extra services that add intangible experiences), in order to allocate the saved money back to the PSS and avoid the rebound effect?

In the case of the car-sharing system, how can the system be supported to attract private car owners and not people currently riding bicycles, who could perceive the car-sharing system as more comfortable and time saving?

PSS support and lobbyism
In many cases, ensuring a successful implementation of a PSS will require support systems and perhaps even political support.

For example, in the case of a car-sharing system, ensuring environmental improvements equals ensuring that it is primarily current or potential car-owners who use the system. This entails that a successful car-sharing system within a city is supported by the public infrastructure.

In some cases, regulations challenge a potential PSS solution because of different price structures, compared to traditional business models. Even though this does not directly affect the environmental performance of the PSS, it might affect its adoptability. The evaluation of the PSS might reveal such issues and it could be part of the recommendation to suggest which regulatory hurdles need to be overcome and which positive consequences this might have for the environmental potential.

SUMMARISING QUESTIONS

- How are the results evaluated in terms of validity, sensitivity and uncertainty?
- Which parameters are varied in order to perform sensitivity checks and/or scenario analysis?
- What can be concluded in relation to the study goal, considering both the qualitative and quantitative findings?
- Which recommendations are proposed based on the overall study?
- How to mitigate the rebound effects?

Glossary

Product/Service-System (PSS): Product(s) and service(s) combined in a system to deliver required user functionality.

Product: A physical good (e.g. a computer) or a non-physical good (e.g. a piece of software) provided to the customer for him/her to make use of.

Service: Activity performed on behalf of the customer.

Reference system: The baseline situation, which is altered by the PSS under study or is compared to the PSS under study. Can be either internal (a variant of the PSS itself) or external (a comparable alternative or the affected contextual system), depending on the study scope, see below.

PSS study scopes:

PSS optimisation: A study scope, where the reference system is internal. The purpose is to assess variants of the PSS itself.

PSS comparison: A study scope, where the reference system is a pre-defined comparable alternative.

PSS consequences: A study scope, where the reference system is the contextual system affected by the PSS.

Avoided impacts: When a PSS replaces or reduces the need for processes in the reference system, this leads to avoided impacts.

Induced impacts: When a PSS introduces or increases the need for processes in the reference system, this leads to induced impacts.

Rebound effect: When the actual impact savings from an improvement are less than expected, because of behavioural or systemic responses.

Secondary benefit: Same as "negative" rebound effect: When the actual impact savings from an improvement are higher than expected, because of behavioural or systemic responses.

Impact category: Classification of environmental issues of concern, to which life cycle inventory analysis results may be assigned (ISO 14044). E.g. "carbon dioxide (CO_2) emissions" are assigned to the impact category "climate change".

Intended audience: Stakeholders who will make use of the study result, including the decision-makers who will be able to influence the result.

Study commissioner: Stakeholder who initiates and finances the study. Can be different from the intended audience.

PSS Business models:

Result-oriented PSS: The customer pays for the product outcome or an overall result delivered, where the product and service elements are the means for providing the result.

Use-oriented PSS: The customer does not own the product but pay for product use, e.g. through leasing and renting schemes.

Product-oriented PSS: Products are sold to the customer and services are added over the life cycle, in order to support the product.

Types of PSS support:

Activity support: The PSS supports or substitutes an activity on behalf of customer.

Product support: A product is supported through life cycle services or offered as a service (e.g. through leasing agreements).

Platform support: Products and services are offered on a platform for customers to use e.g. through subscriptions or short-term rentals.

PSS strategy: The strategy embedded in a PSS offer, through which the customer is supported.

PSS potential: When a PSS strategy has the potential to lead to environmental impact reductions.

Product system: Collection of processes, which deliver the product and service flows required to obtain the specified functionality, and which model the life cycle of a product.

Note that this definition is slightly different from the definition in the ISO 14044 standard on LCA.

Substitution: The alternative product system(s) displaced by the PSS under study.

Note that the term substitution is also used in LCA when modelling the individual processes constituting the product system. In the case of a multifunctional process (when a process has more than one product output e.g. as in the case of combined heat and power production) the substitution is the alternative product displaced by the by-product.

System boundary: A set of criteria specifying which processes are part of a product system (ISO 14044).

System functionality: Describes what the system should provide, in order to fulfil the user's need = a description of the system requirements.

Function: Describes what the system can provide = a description of the performance characteristics.

Note that in other LCA guidelines, the term function is normally used instead of system functionality, which is the term used in this guide when expressing the functional outcome of a PSS.

Functional unit: Quantified performance of a product system for use as a reference unit (ISO 14044).

Reference flow: Measure of the outputs from processes in a given product system, required to fulfil the function expressed by the functional unit (ISO 14044).

Utility/value: Expresses "how well" the need is fulfilled, also taking "non-functional" quality aspects into account, when expressing the system performance.
Utility: Objective judgement.
Value: Subjective judgement.

Consumption factor: Driver that influences the utility and value of a solution and therefore might trigger rebound effects.

Appendix 1 Impact categories

If not predefined by the intended audience, choosing impact categories should be based on an informed decision.

If following the ISO standard on LCA, the selection of impact categories is intended to reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration. As such, it is recommended that all impact categories that are found to represent an area of environmental concern related to the product system being studied are included in order to identify potential trade-offs between impact categories (e.g. if the PSS leads to a decrease in greenhouse gas emissions but an increase in mineral depletion or toxicity).

The table on the right provides an overview of the most common impact categories used in LCA (adapted from the LCIA method ReCiPe). For an explanation of each impact category, see e.g. Acero et al, LCIA methods - Impact assessment methods in Life Cycle Assessment and their impact categories, GreenDelta, 2017, www.openlca.org.

Note that other impact categories than those listed here might be considered as well, potentially also including economic or social impacts.

How to simplify communication and delimit impact categories?
For a study covering a broad range of impact categories, communication may be simplified by translating impacts into "end-points" covering the so-called "three areas of protection": **Human health**, **Ecosystems** and **Resource availability.**

These three can further be translated into a single score using weighting. Even though this might ease communication, the approach is problematic, since weighting requires value choices (which environmental impacts are more important) and it also becomes difficult to trace which environmental issues the PSS improves or contributes to. Even though choosing a broad range of impact categories is recommended, it is also acknowledged that choosing a few and well known impact categories can reduce complexity and ease the data gathering as well as communication.

A recommended approach when assessing PSS is to focus on the impacts that are the most relevant for the systems under study, taking both the reference system and the PSS into account. Choosing which impacts are the most relevant can be done through examination of existing LCA studies of the product system in focus together with industry-specific reports on environmental issues, regulations, and concerns.

Climate change is a commonly used indicator (often expressed as a Carbon Footprint) and for some product systems this provides an acceptable metric. This would be the case for product systems, where there is a strong correlation between impact on climate change and other impacts of concern. However, impacts to be aware of that often have poor correlation with climate change are: **resource depletion, toxicity** and **land use.**

Note however, that including indirect land use change in the greenhouse gas inventory will often improve the correlation between climate change and land use.

Examples of product systems with a strong correlation between impact categories are infrastructure-related products such as buildings and power plants and transportation systems. These have a high correlation between processes contributing to climate change (mainly from fossil fuel for energy production) and processes contributing to impacts on toxicity and resource depletion (e.g. from steel production). However, for other product systems such correlations may be poor, and if it is of interest for the intended audience, it is recommended to include other relevant impacts to support decision making. If only a few or a single impact category is included in the assessment, it may be supported by argumentation of correlated impact categories and/or suggestions on which impact categories could be included in future work.

Since this guide is intended to also support more streamlined assessments in contrast to a full LCA approach, it is acknowledged that simplified measurements such as the MECO approach (measuring the amount of Materials, Energy, Chemicals and Other impacts) can be useful, as long it is in line with the study purpose.

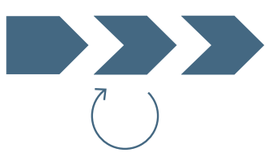
For more information about MECO, see Pommer et al: Handbook on Environmental Assessment of Products, The Danish Environmental Protection Agency, 2003.

Impact category	Impact indicator	Main elementary flows of concern	Examples of characterisation units (*in ReCiPe 2016)
Acidification	Increase of the acidity in water and soil systems	Ammonia (NH_3), Nitrogen oxides (NO_X), Sulphur oxides (SO_X)	Kg SO_2 equivalent*
Global warming	Disturbances in global temperature and climatic phenomena	Carbon dioxide (CO_2), Methane (CH_4), Dinitrogen monoxide (Nitrous oxide) (N2O), CFC-gasses, etc.	Kg CO_2 equivalent*
Resource depletion/scarcity *Sub-categories:* Mineral resource scarcity Fossil resource scarcity Water consumption	Decrease of resources (renewable and non-renewable)	Mineral use (copper, gold etc.), Use of fossils (oil, gas, coal), Water use	Kg CU equivalent (mineral consumption)* Kg oil equivalent (fossil fuel consumption)* m^3 (water consumption)*
Ecotoxicity Freshwater ecotoxicity Marine ecotoxicity Terrestrial ecotoxicity	Biodiversity loss and/or extinction of species	Heavy metals, Toxic organic chemicals	Kg 1,4-DBC equivalent*
Eutrophication Freshwater eutrophication, Marine eutrophication	Increase of nitrogen and phosphorus concentrations, in natural water systems which causes formation of biomass (e.g. algae)	Ammonia (NH_3), Nitrogen oxides (NO_X), Nitrates (NO_3-), Phosphorous (P)	Kg P equivalent (freshwater)* Kg N equivalent (marine)*
Human toxicity	Cancer, respiratory diseases, other non-carcinogenic effects and effects to ionising radiation	Various chemicals releases	Kg 1,4-DCB equivalent*
Ionising radiation	Health effects of the radiation (health decline, cancer, illnesses, etc.)	Radionuclides (radiation types α-, β-, γ-radiation and neutrons)	Kg U235 equivalent kBq Co-60 to air eq*
Land use Agricultural land occupation Natural land transformation Urban land occupation	Species loss, soil loss, amount of organic dry matter content, etc.	Land use	m^2a (square metre of land integrated over time) Annual crop eq*
Ozone layer depletion	Increase of ultraviolet UV-B radiation and number of cases of skin illnesses	CFCs, Halons , HCFCs	Kg CFC-11 equivalent*
Particulate matter	Increase in different sized particles suspended on air (PM10, PM2.5, PM0.1) causing health problems such as cardiovascular and respiratory tract diseases	Particulates, Ammonia (NH_3), Nitrogen oxides (NO_X), Sulphur oxides (SO_X)	kg PM2.5 eq*
Photochemical oxidation Human damage Ecosystem damage	Smog increase	Carbon monoxide (CO), Sulphur dioxide (SO_2), Nitrogen oxides (NO_X), NMVOC (non-methane volatile organic compounds), etc.	kg NO_X eq.*

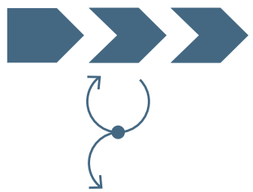
Appendix 2 Modelling different end-of-use options

When a PSS includes end-of-use strategies that either increase product longevity or extend the use of products or materials into multiple use cycles, it becomes relevant to include the effect of these in the assessment. Even though many terms exist covering reuse, re-manufacturing, and recycling processes, we here narrow down to four end-of-use routes. The table on the right provides a suggestion of how to model the avoided impacts for each end-of-use routes. Each route is illustrated with a symbolic figure showing the three overall stages of a product life cycle: production, use and end-of-life.

1 Direct product reuse (same function, same use context)
The product is retained or taken back after use, potentially repaired, cleaned, refurbished/upgraded or re-manufactured and sent back into the same use. The PSS ensures that the reused product has the same value as the new product and therefore it displaces a new product.

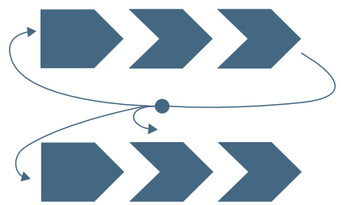


2 Product redistribution (same function, new use context)
The product is sold as a second-hand product for the same type of use. It might be treated in some way first (as with direct reuse) in order to increase the value. The second-hand product has a lower value than a new product and therefore only partly displaces a new product.



3 Indirect reuse into new applications (new function, new use context)
The product is given a new purpose after end-of-use. The term up-cycling is sometimes used when the new application represents a higher use (has a higher value) compared to if the product/material was used for its original purpose. However, also for products where it is not possible to use the recycled material as a replacement of the same virgin material (as is the case for most textiles), it can be a strategy to reuse the product/material in new applications (e.g. use the worn out textiles to produce building material). The reused product is not replacing the same type of product but another product.

4 Material recycling
After end-of-use, the product undergoes end-of-life treatment, in which material is recovered and reused for the same or new applications. The displacement potential depends on material quality and second hand market conditions.



Note, that these end-of-use routes are usually seen as alternatives to landfilling or waste incineration. When compared to waste incineration, potential energy recovery from the incineration should be included in the assessment. In some countries, waste is an important input for producing electricity and heat and the waste substitutes other ways of producing the energy.

Also note that this appendix is only about assessing the avoided impacts from end-of-use strategies. The impacts caused by processes such as repairing, refurbishing and recycling the products/materials into new uses should be accounted for when modelling the *induced impacts* from the PSS.

End-of-use route	Subsequent product function	Subsequent use context	How to model	Notes
1 Direct product reuse	Same	Same	Similar to improved product maintenance, direct product reuse may lead to product longevity resulting in fewer products needed to fulfil the functional unit.	*If a re-manufactured product is not replacing a new product, but is sold at a lower value or in a different market, this is "product redistribution" not "direct reuse".*
2 Product redistribution	Same	New (second-hand market)	If the buyers of the product are known, the assessment can include investigating to which extent... 1. *...The product displaces a new product* (the buyer buys the second-hand product instead of a new): On the market this reflects that the demand for second-hand products is higher than the supply. "Decreased lifetime" or "loss in technical properties" is used as a proxy to distribute impacts between first and subsequent use cycles. 2. *...The product increases utility* (e.g. the buyer uses the product as an extra product, which he would not have bought if this option was not available). On the market this reflects that the demand for second-hand products is lower than the supply. No credit is given to the PSS provider, who will bear the full burden of the environmental impact. If the product's second-hand use and the market conditions are unknown, *"value correction"* can be used as a proxy to distribute impacts between life cycles. In example, if a car-sharing company sells the cars after 2 years at 50 % of the price of a new car, they account for 50 % of the impact from car production and end-of-life treatment.	*Note that social impacts are not considered here. Making products and technologies available for people who did not previously have access can have positive social effect as well as positive indirect environmental effects.*
3 Indirect reuse into new applications	New	New (market of the displaced product)	The study includes identifying the products that are being substituted and assessing the environmental impact of the alternative, substituted product in order to quantify the avoided impacts.	
4 Material recycling	-	-	How recycling is modelled in LCA is highly debated, but in principle the guidelines for product redistribution can be followed when the recycled material can be used for the same purposes as the virgin material, while principles for reuse into new applications can be used for materials that are recycled into new applications.	

Appendix 3 Process, Input-Output, and Hybrid LCA

When gathering inventory data for the background system, two distinct approaches in LCA exist.

A process-based LCA builds the data "bottom up" for each process by identifying the inputs to the process (primary inputs) then the inputs to that input (secondary inputs) and so on.

In contrast, an Input-Output (IO)-based approach uses economic input-output tables for countries and regions, published by national statistic agencies, coupled with environmental data such as emissions and resource use to understand environmental impacts on a sector level.

Utilising IO-based data for LCA purposes can be seen as a "top-down" approach, since all flows between sectors in the economy is by default taken into account.

Limitations of the process-based approach
While the process-based approach allows for more precision than the IO-based approach, it can be time-consuming and third-order inputs and beyond can easily be "forgotten", resulting in so-called cut-off errors where a significant part of the system is excluded from the system boundary, leading to an underestimated environmental impact.

Limitations of the IO-based approach
For the IO-based approach, the main limitation is the sector aggregation, since the number of sectors represented in the model depends on the data availability from statistical agencies.

This results in lack of precision, since sectors may be too heterogeneous to correctly reflect a particular process or product.

Other limitations include data age (data are often several years old), limited coverage of environmental indicators (often limited to certain resources and emissions), and price sensitivity (transactions are typically in monetary units).

Hybrid approach
IO-based models are continuously improved to mitigate the above mentioned limitations, i.e. by creating hybrid databases, which combines IO-based data with mass-flow analysis in order to eliminate price sensitivity and by disaggregating sectors by combining different data sources.

LCA software such as SimaPro, but also open access data sources such as eiolca.net provides access to IO-based databases.

A hybrid LCA aims to combine "the best of the two worlds", in order to ensure the level of completeness as well as the level of precision required for the study.

A hybrid LCA can be conducted in a *tiered approach*, where the "holes" in the process-based LCA is filled using IO-based data.

It can also be conducted in an *embedded approach*, where an IO-based process is modified by changing inputs in order to make the process more representative.

The three approaches are summarised in the table at the right.

Method	Description	Main advantage	Main disadvantage	Recommended application
Input-output LCA	Top-down approach, where economic input-output tables are combined with environmental data on sector level Product/Service flows are calculated per monetary unit	Completeness	Sector aggregation	Covering "hard to get data", e.g. for service sectors, which would otherwise have been omitted (financial data can be used as input data) Creating rough estimates ("hot-spot" analysis) to understand the orders of magnitudes Country and sector-level assessments Quantifying rebound effects based on average consumption, taking the whole economy into account
Process LCA	Bottom-up approach, where processes are build input by input, assessing environmental impacts Product flows are calculated per physical unit (Kg, kWh, km etc.)	Precision	Time- and resource intensive	Simple product-level assessments
Hybrid LCA	IO-based data and process-based data are combined Hybrid database: Services are in monetary units and physical products are in physical units (kg, kWh) based on combining IO-data with mass flow analysis on a meta level Hybrid approach: a product system or process is built on combining IO-based data and process-based data in either an embedded (starting from the IO-based data) or tiered (starting from the process-based data) approach	Combines overall completeness with precision for specific processes where primary data are available and/or data uncertainty is high	Can cause double-counting and inconsistency between data sources	Assessment of complex product systems and organisational LCA (in order to cover all upstream impacts)

Appendix 4 Case examples

In this appendix, a series of PSS case examples are introduced – one for each of the PSS strategies presented in step 2.3. The descriptions are a combination of hypothetical and real PSS solutions.

Case 1: PSS for hull cleaning of tanker ships

PSS support: *Activity support*
PSS strategy: *Operational support*

During the operation of a ship, a part of the hull is always immersed in the water, and therefore marine organisms accumulate on it. This undesirable accumulation of micro-organisms, plants, and animals is termed marine biofouling, and the result is increased fuel consumption due to generated roughness. To prevent marine biofouling, hulls are equipped with antifouling systems.

The most important part of the antifouling system is the antifouling paint that provides a low-friction, ultra-smooth surface to prevent settling, while dispersing a mix of toxic biocides to hinder fouling. Tanker ships are repainted every five years when in dry-dock, after which the antifouling system is supposed to protect the vessel.

In many cases, however, aggressive fouling might develop on the hull, due to high fouling pressure especially in warm waters, low sailing speeds, and paint detachment caused by mechanical damage or incorrect paint application. In these cases, in-water hull cleaning is required.
During hull cleaning, the hull is cleaned by a team of divers using hull cleaning machines that brush the hull.

The PSS under study is offered by the paint provider as a performance agreement. Through the PSS, the provider monitors the performance of the hull and suggests when and how a hull cleaning should be conducted in order to ensure that the paint performs. If the cleaning is done in the wrong way or too often it will damage the paint.
The purpose of the study is to evaluate the potential environmental impact savings from the performance agreement, where hull cleanings are initiated whenever the ship's fuel penalty is above a certain threshold. The threshold has been determined through a cost/benefit analysis on economic costs.
The study evaluates the avoided impacts from reduced fuel consumption vs. induced impacts from the extra hull cleanings, including the materials and energy used for the cleaning process as well as the potential changes in the toxic impact on the marine environment.

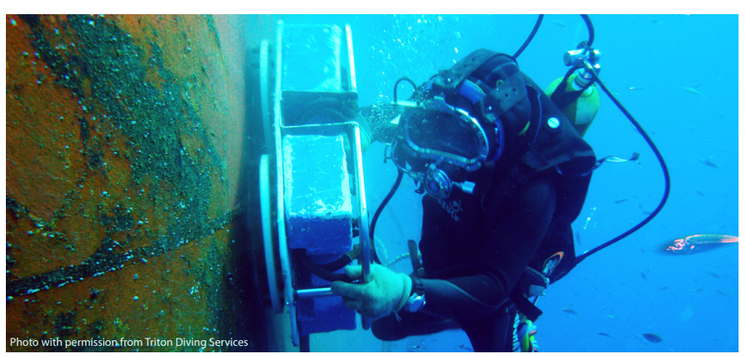


Photo with permission from Triton Diving Services

Since the PSS only influences the operational stage of the paint, the substitution is a single life cycle stage.

Study scope: *PSS optimisation*

Functional unit example: *Monitoring and cleaning the hull of a medium range tanker vessel throughout the five year life cycle of the antifouling paint.*

Case 2: PSS for cleaning of hospital floors

PSS support: *Activity support*
PSS strategy: *Optimised result*

A PSS is offered, where hospital floors are cleaned using a special cleaning system. The cleaning system involves the use of special fibre mops, which makes it possible to increase the level of hygiene while eliminating the need for chemicals and reducing water consumption. The mops are washed and dried at the PSS provider's own industrial laundries. Embedded tags (RFID) are used to trace the mops, eliminating unintended waste during use.

The PSS provider has commissioned an LCA study comparing their cleaning system with the traditional way of cleaning hospital floors using traditional cotton mops and where local laundering machines are used to wash and dry the mops.

Since the PSS influences the whole life cycle of the mops, the substitution is a single life cycle.

Study scope: *PSS comparison*

Functional unit example: *Cleaning of 100 m^2 of hospital floor in one year.*

Case 3: PSS for shared lawnmowers

PSS support: *Product support*
PSS strategy: *Product sharing*

Eight households in a residential area are considering if they should purchase a PSS involving a shared lawnmower and repair/service contract for 10 years as an alternative to each owning an individual machine.

Prior to their purchase, they want to know what a sharing-system would imply in terms of carbon footprint and costs.

In order to compare different options, the households have contacted a company that offers PSS for lawnmowers.

Two versions of the PSS are offered: One where a normal sized lawnmower (similar to the privately owned) is shared and replaced with a new every second year. And one where a large sized lawnmower is maintained throughout all 10 years.

Since the PSS influences how many lawnmowers and the type of lawnmower that needs to be produced, the study needs to take the full life cycle of the lawnmowers into account, and the substitution is a single product system.

Study scope: *PSS comparison*

Functional unit example: *Mowing of 4800m^2 lawn (corresponding to 8 households) for 10 years.*

Case 4: PSS for maintenance of truck tyres

PSS support: *Product support*
PSS strategy: *Maintenance*

A truck tyre manufacturer offers its customers a predictive maintenance service based on condition monitoring.

The solution relies on a set of sensing devices, which is able to collect and transmit real-time condition data of the tyres. After analysis, the system will provide maintenance advice. The aim of the solution is to prolong the tyres' lifetime and optimise the maintenance operations to improve truck productivity.

The company is interested in a study that compares the traditional maintenance service, which requires regular inspections and maintenance of all tyres, with the condition-based monitoring PSS, which can predict breakdowns based on the real condition of each tyre and help the customer make a judgment as to whether or not a repair is needed.

Through this strategy of predictive maintenance, the use-stage of the tyres may be extended, resulting in avoided impacts from a decreased demand for tyre production and thereby raw material and waste handling.

However, induced impacts will arise from the monitoring system and sensors that needs to be installed and operated. Since the PSS influences the whole life cycle of the product (the tyre) the substitution is a single product system.

When defining the system functionality and the functional unit, the functionality of the PSS is to improve the truck productivity per mileage and the functional unit needs reflect the truck's transport function.

Study scope: *PSS comparison*

Functional unit example: *Operation of a 80,000 lbs truck for 50,000 miles on average "on/off road condition" (a mixture of improved secondary and aggressive road surface).*

Case 5: PSS for reuse of hospital textiles into new applications

PSS support: *Product support*
PSS strategy: *Take-back for reuse and recycling*

An industrial laundry company is offering a PSS to hospitals, where the laundry company owns the textiles used for e.g. uniforms and linen.

They deliver clean textiles to the hospitals and pick up the laundry after use. Since the laundry company has the ownership of the textiles, they are also responsible for the production and end-of-use handling.

In the assessment, the company is interested in evaluating the environmental impact of different end-of-use routes that the textiles can take.

One of the options includes using the warn-out textiles to produce plates, which can be used in furniture such as shelves and tables.

The study should not only include an assessment of the substituted product systems from the refurbished material, but also how different end-of-use options might influence the production and use stage of the textiles, e.g. if the textiles need to be of a certain homogeneous quality.

Since the study investigates different end-of-use options, the substitution is multiple product systems.

Study scope: *PSS consequences*

Functional unit example: *Provision of 1000kg of clean hospital textiles for 1 year. (Note that "hospital textiles" needs to be subdivided since different applications will have different requirements).*

Case 6: Bike-sharing system

PSS support: *Platform support*
PSS strategy: *Sharing platform*
A municipality of a large capital city is offering a public, electrical bike-sharing system for the city commuters, locals and tourists. Prior to the introduction of the bike-sharing system, the municipality mapped out the transport patterns of the city commuters and based on a survey, commuters were asked to state how they would prioritise between different modes of transport, if they had the option to commute by public electrical bikes.

Based on this survey, the municipality would like to know – for the customer group commuters – how the carbon footprint from commuting would change for the commuters stating that they would change to the bike-sharing system.

Since the PSS influences many commuting options, the substitution is multiple product systems.

Study scope: *PSS consequences*

Functional unit example: *5000 citizens commuting for one month => 200,000 trips (corresponding to 40 trips/month/user).*

A selection of relevant material

Workbooks in the PROTEUS series
Mougaard et al.: **Maritime Branch Analysis**. Technical University of Denmark (DTU), 2013. 87 p.
Andersen et al.: **PSS Business Models.** Technical University of Denmark (DTU), 2013. 64 p.
Apitz et al.: **PSS Organisation.** Technical University of Denmark (DTU), 2013. 60 p.
Andersen et al.: **PSS Partnerships.** Technical University of Denmark (DTU), 2013. 60 p.
Avlonitis et al.: **PSS Readiness Manual.** Technical University of Denmark (DTU), 2013. 48 p.
Finken et al.: **PSS Tool Book.** Technical University of Denmark (DTU), 2013. 78 p.

Sustainability workbooks:
McAloone et al.: **Environmental improvement through product development: A guide.** Danish Environmental Protection Agency, 2013. 48 p.
Eco-I Manual: Eco-innovation implementation process. UN Environment and DTU, 2017.
Eco-I Manual: Agri-Food Supplement. UN Environment and DTU, 2017.
Eco-I Manual: Chemicals Supplement. UN Environment and DTU, 2017.
Eco-I Manual: Metals Supplement. UN Environment and DTU, 2017.
Eco-I Manual – Templates. UN Environment and DTU, 2017.

PSS Articles:
Pagoropoulos et al.: **Economic and Environmental Impact Trade-Offs Related to In-Water Hull Cleanings of Merchant Vessels.** Journal of Industrial Ecology, 2017.
Haase et al.: **Product/Service-System Origins and Trajectories: A Systematic Literature Review of PSS Definitions and their Characteristics.** In: Procedia CIRP, Vol. 64, 2017.
Pigosso et al.: **Maturity-based approach for the development of environmentally sustainable product/service-systems.** In: CIRP - Journal of Manufacturing Science and Technology, Vol. 15, 2016.

Sustainability articles:
Kjær et al.: **Challenges when evaluating Product/Service-Systems through Life Cycle Assessment.** In: Journal of Cleaner Production, Vol. 120, 2016.
Kjær et al.: **Application of Environmental Input-Output Analysis for Corporate and Product Environmental Footprints—Learnings from Three Cases.** In: Sustainability, Vol. 7, No. 9, 2015.
Pigosso et al.: **Characterization of the State-of-the-art and Identification of Main Trends for Ecodesign Tools and Methods: Classifying Three Decades of Research and Implementation.** In: Indian Institute of Science. Journal, Vol. 94, No. 4, 2015, p. 405-427.

See also:
PROTEUS project: www.proteus.dtu.dk
Ecodesign-related research at DTU: www.ecodesign.dtu.dk
Circular Economy Implementation in the Nordic Industry: www.circitnorden.dk
Making the Transition to Circular Economy: www.matche.dk
UNEP Eco-Innovation Manual: www.eco-innovation.org

Notes

A six-step approach for evaluating the environmental performance of Product/Service-Systems through LCA methodology

The Technical University of Denmark
Department of Mechanical Engineering
Anker Engelundsvej 1, 101A
DK-2800 Kongens Lyngby