Safe by Design – A design approach for dealing with hazardous substances in products

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De aanwezigheid van zorgwekkende stoffen in producten maakt de transitie naar een circulaire economie moeilijk. Zorgwekkende stoffen zijn schadelijk voor het milieu en de volksgezondheid. Daarnaast beperken ze de mogelijkheid om producten, componenten en materialen opnieuw te gebruiken of te recyclen. Een voorbeeld zijn de water- en vlekafstotende chemicaliën in kleding en voedselverpakkingen (PFAS), die intussen overal in het milieu (en in mensen) worden teruggevonden.

Het Safe-by-Design-concept probeert al in de ontwerp- en ontwikkelingsfase van een product de kwalijke effecten van zorgwekkende stoffen te voorkomen. Safe-by-Design is erop gericht om producten te ontwikkelen die veilig kunnen worden geproduceerd, gebruikt én hergebruikt in een circulaire economie. Onderzoek verricht door chemici en risico-analisten leidt echter nog nauwelijks tot toepassing van Safe-by-Design binnen de (circulaire) ontwerppraktijk. Deze studie zet een eerste stap om tot daadwerkelijke toepassing door ontwerpers te komen. Hiervoor is onderzocht hoe in het verleden is omgegaan met producten die zorgwekkende stoffen bevatten. Dit is gedaan met literatuuronderzoek, interviews met deskundigen, levenscyclusanalyse en risicobeoordeling. De inzichten uit deze studies vormen de basis voor Safe-by-Design-strategieën en een methode voor ontwerpers om een geschikte strategie te kiezen.

Bij deze studie staan de volgende onderzoeksvragen centraal:

a) Waarom en op welke manier worden zorgwekkende stoffen gebruikt in producten? Wat weten we over de effecten en risico’s van deze stoffen gedurende de levensduur van producten?
b) Hoe kunnen we al tijdens de ontwerpfase de risico's van zorgwekkende stoffen tijdens productie, gebruik en hergebruik elimineren?
c) Hoe kan de juiste balans worden gevonden tussen duurzaamheid, veiligheid, prestaties en kosten wanneer we te maken hebben met zorgwekkende stoffen in producten?

Gewerkt is aan producten die relevant zijn voor de Nederlandse economie, die verschillende zorgwekkende stoffen bevatten, en die diverse Safe-by-Design-strategieën illustreren. De volgende stoffen en producten zijn gebruikt om de methode op te stellen: 1) weekmaker in oplaadkabels; 2) weekmaker in PVC vloeren; 3) microplastics uit landbouwfolie; 4) koelmiddel in koelkasten; en 5) water- en vlekafstotende stoffen in outdoor kleding. De methode is vervolgens getest met: 6) microplastics uit synthetisch textiel; 7) polyurethaanschuim in slaaphulpmiddelen en ademhalingsapparaten; en 8) water- en olie-afstotende stoffen in voedselverpakkingen.

De gevonden strategieën kunnen worden ingedeeld in drie groepen: de zorgwekkende stof **vermijden/elimineren**; het gebruik en/of de uitstoot van de zorgwekkende stof **reduceren;** en het **beheersen/voorkomen** van de uitstoot van en blootstelling aan zorgwekkende stoffen.

Op basis van de resultaten is een Safe-by-Design-methode ontwikkeld. Deze methode stelt ontwerpers en ingenieurs in staat om de combinatie van product, stoffen en context grondig te analyseren voor alle fasen in de levenscyclus van het product. De ontwerper kan dan een goed onderbouwde selectie maken van de te volgen strategie (**vermijden/elimineren**, **reduceren** of **beheersen/voorkomen)** en die vervolgens toepassen in het productontwerp.

Deze studie laat zien dat ontwerpers een belangrijke rol hebben bij het ontwerpen van veilige(r) producten. Voorbeelden van mogelijkheden van ontwerpers voor veiliger ontwerpen zijn het gebruiken van andere materialen, andere manieren om de functie van een product te vervullen of de zorgwekkende stof zo in te sluiten dat de blootstelling aan schadelijke stoffen en/of de emissie van dergelijke stoffen wordt voorkomen. Toepassing van een strategie leidt echter niet altijd tot een veilig product. In het geval van reduceren wordt een product veiliger, maar niet per se veilig. Elimineren kan leiden tot nieuwe risico’s. Een holistische benadering is daarom noodzakelijk. Het onderzoek liet ook zien dat er sprake is van een aanzienlijk gebrek aan gegevens, waardoor methoden als levenscyclusanalyses en risicobeoordelingen van blootstellingsscenario’s maar in beperkte mate gebruikt kunnen worden. Communicatie en samenwerking tussen ontwerpers, leveranciers en experts op het vlak van risicobeoordeling en levenscyclusanalyse is daarom belangrijk.

Public Summary

The transition to a circular economy is challenged by the presence of hazardous substances (also known as substances of concern) in products. An example is the presence of water and stain-repellent chemicals (known as PFAS) in textiles and food packaging. Hazardous substances may harm the environment and human health, and pose limitations on the reuse or recycling of products, components, and materials. The Safe by Design concept proposes the inclusion of safety considerations from early design and development stages. The goal of Safe by Design is to develop products that can be safely produced, used, and reintroduced into a circular economy. While the topic of Safe by Design is commonly researched by chemists and risk analysts, its application in (circular) product design practice is limited. This study makes a start at bridging this gap by researching and evaluating different Safe by Design strategies applied to five products containing hazardous substances. Insights from these case studies will be used to develop guidelines for designers to deal with hazardous substances in products.

This study focuses on the following research questions:

a) How and why are hazardous substances used in products? What is known about their effects throughout the lifecycle of products and on the circular economy?
b) How can risks from hazardous substances be eliminated or managed through design throughout the lifecycle of products and when a product or parts of it go through several lifecycles?
c) How can tradeoffs between sustainability, safety, performance, and cost be balanced when dealing with hazardous substances in products?

The case studies were chosen for their relevance to the Dutch economy and their potential to illustrate a variety of SbD strategies, chemicals, and applications. The selected cases include: 1) Plasticizers in charging cables, 2) Plasticizers in vinyl flooring, 3) Microplastic release from agricultural mulch films, 4) Refrigerant in household refrigerators, and 5) Water and stain repellent substances in synthetic textiles (outdoor garments). A detailed investigation of the five case studies was conducted through desk research, expert interviews, screening Life Cycle Assessment, and Risk Assessment.

We investigated the function of the hazardous substance in the product as well as its physicochemical inclusion. Potential emissions/exposure scenarios throughout the product lifecycle were identified and prioritized. Safe by Design strategies that have been, are, and could be used to deal with the hazardous substances were then identified. The relevant strategies were classified into three groups: Avoid/Eliminate the hazardous substance, Reduce the use of the hazardous substance and/or its hazardous emissions, and Control/Prevent hazardous emissions and/or exposure to the hazardous substances. An assessment of the strategies showed a diversity of tradeoffs (e.g., loss of performance) and newfound risks (e.g., flammability). The investigation illustrates substantial knowledge and data gaps (and unavailability) that limit the application of methods like screening Life Cycle Assessment and Risk Assessment in the public domain. This is not only a problem for designers, but a challenge for analysts in general when analyzing and assessing hazardous substances in products.

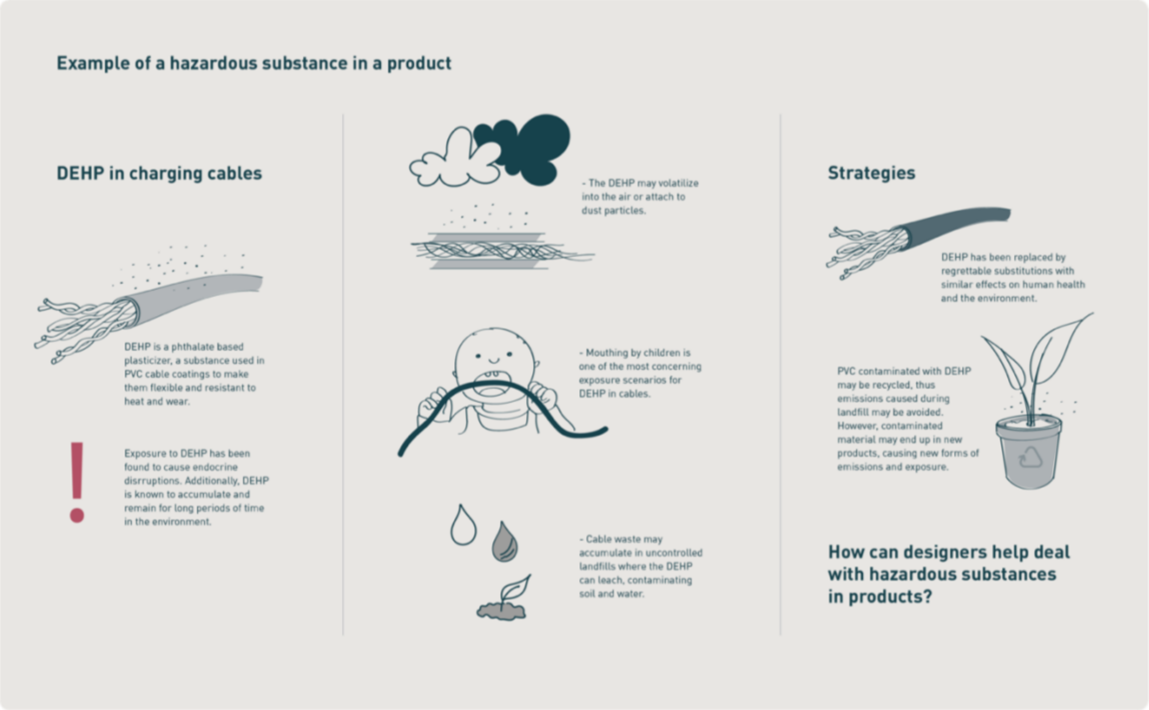
Insights from in depth analysis of the case studies, and further investigation of approaches in the industry and other fields were used to develop guidelines for designers to deal with hazardous substances in products. This resulted in the Safe by Design approach which guides designers and engineers through a thorough analysis of the product-substance combination and its context at all stages of the product lifecycle. The results of this analysis can then be used to inform the designer when selecting or combining the above-mentioned strategies (Avoid/Eliminate, Reduce, and/or Control/Prevent). These strategies are then assessed by the designer, guided by a set of recommendations and suggested methods. This assessment can also be performed in collaboration with Risk Assessment and Life Cycle Assessment experts.

The approach was tested internally with respect to workflow logic, effort needed, and limitations. This was achieved using the additional cases: 1) microplastic release from synthetic textiles, 2) polyurethane foam in sleep and respiratory care devices, and 3) water and oil repellent substances in food packaging. This evaluation showed that a basic understanding of the hazardous substance in the product could be gained by following the approach, allowing designers to understand the problem and identify action points. However, the availability and specificity of information to perform the analysis of the product-substance combination, the assessment of emission/exposure scenarios, and the assessment of the identified Safe by

Design strategies was variable. This indicated that the functionality and specificity of the approach may vary. The proposed approach currently assumes working mostly with qualitative data. The results should be treated as estimations to guide following steps of the development process, and facilitate the communication and collaboration between designers, Risk Assessment and Life Cycle Assessment experts, and suppliers.

Overall, results show that designers can play an important role in the design of safe and safer products. Examples of this include dealing with drawbacks of the substitution of materials and chemicals (e.g., by compensating for a loss of performance by reinforcing certain component sections), the development of alternative value and function propositions to avoid the use of a particular substance (e.g., providing alternatives ways to charge electronics to avoid the use of cables), or the prevention of emissions or exposure to a substance through specific characteristics of the product (e.g., hermetic systems that prevent the emission and exposure to refrigerants in cooling products). Safe by Design strategies were found to have different scopes in resulting in safe products; those avoiding or eliminating the use of hazardous substances may result in safe products if no other unintended consequences are generated. However, strategies to reduce the use and/or emissions of a hazardous substance, or strategies to avoid/prevent emissions and exposure, may result in a safer product, but not a safe one.

The widespread use of Safe by Design in practice was found to critically depend on the collaboration between product designers and other stakeholders in the supply chain, the development of comprehensive, organized databases, and the development of analytical tools catering to the needs of product designers. This project involved a close collaboration between design researchers, Risk Assessment, and Life Cycle Assessment experts. While data limitations afforded very preliminary evaluations of substance-product combinations, regular in depth discussions deepened the understanding of the safety issues in the product and the role of the disciplines involved. This suggests that although the right data for safety and sustainability evaluations is often not easy to find, resourcefulness in finding approximations and openness to other disciplinary perspectives can often yield substantial results that can inform the development of solutions to deal with hazardous substances in products.



DEHP is a phthalate based plasticizer, a substance used in PVC cable coatings to make them flexible and resistant to heat and wear.

Exposure to DEHP has been found to cause endocrine disrruptions. Additionally, DEHP is known to accumulate and remain for long periods of time in the environment.

- The DEHP may volatilize into the air or attach to dust particles.

- Mouthing by children is one of the most concerning exposure scenarios for DEHP in cables.

- Cable waste may accumulate in uncontrolled landfills where the DEHP can leach, contaminating soil and water.

DEHP has been replaced by regrettable substitutions with similar effects on human health and the environment.

PVC contaminated with DEHP may be recycled, thus emissions caused during landfill may be avoided. However, contaminated material may end up in new products, causing new forms of emissions and exposure.

Graphical Abstract. Example of a hazardous substance in a product. The case of DEHP in charging cables.

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i. List of abbreviations

EC – European Commission
EU – European Union
CE – Circular Economy
SoC – Substance(s) of Concern
SbD – Safe by Design
ECHA – European Chemicals Agency
RIVM – Rijksinstituut voor Volksgezondheid en Milieu (Dutch National Institute for Public Health and the Environment)
PBT – Persistent Bioaccumulative and Toxic
vPvB – very Persistent and very Bioaccumulative
ZZSs – Zeer Zorgwekkende Stoffen (Substances of very high concern)
pZZS – Potentieel Zeer Zorgwekkende Stoffen (Potential substances of very high concern)
REACH regulation (Registration, Evaluation, Authorization and Restriction of Chemicals)
CLP – Classification Labelling and Packaging of chemicals
POP – Persistent Organic Pollutants
LDPE – Low density polyethylene
LLDPE – Linear Low-Density Polyethylene
GWP – Global Warming Potential
EoL – End of Life
CFC – Chlorofluorocarbons
HCFC – Hydrochlorofluorocarbons
HFC – Hydrofluorocarbons
ODS – Ozone Depleting Substances
ODP – Ozone Depleting Potential
HFC 134a – 1,1,1,2-Tetrafluoroethane hydrofluorocarbon
RSLs – Restricted Substances Lists
MRSLs – Manufacturing Restricted Substances Lists
LCA – Life Cycle Assessment
RA – Risk Assessment
DEHP – Bis(2-ethylhexyl) phthalate
PVC – Polyvinyl Chloride
PUR – Polyurethane
PFAS – Per and polyfluoroalkyl substances

ii. Reading guide

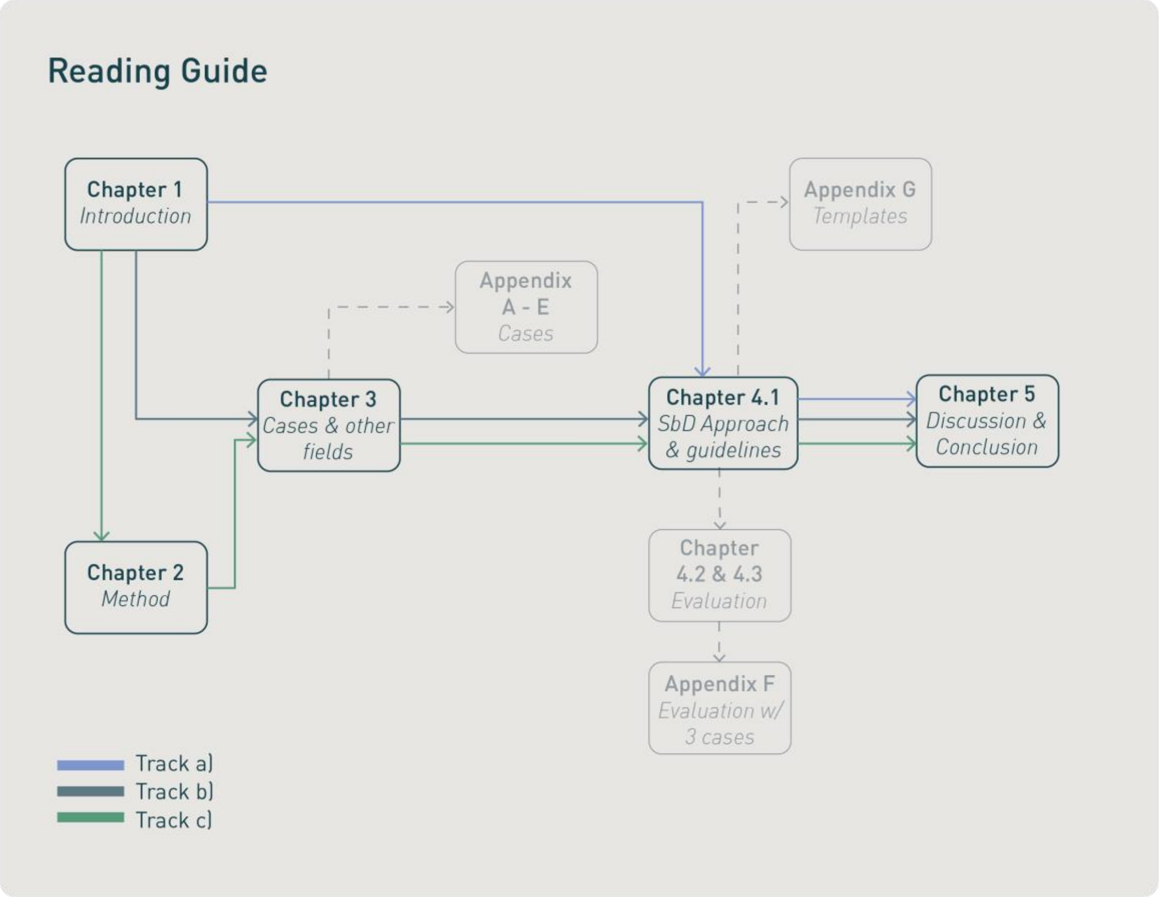
This reading guide supports the readers in quickly finding the information they find most relevant and accommodate for limited reading time availability. Three different tracks are suggested:

Track a – For readers with limited time and mostly interested in the Safe by Design approach and guidelines. Includes the introduction (Chapter 1) for general background of the project and goes directly into the proposed SbD approach/guidelines (Section 4.1). It then finishes with the discussion and conclusion which includes several recommendations and reflections.

Track b – For readers interested in how Substances of Concern have been used and have been dealt with in the products of the selected case studies. This track includes the introduction (Chapter 1) and then goes into the results obtained from the investigation of the five case studies and approaches in other fields and industry (Chapter 3). Optionally, the reader can choose to read the in depth version of the case studies (Appendixes A – E). These appendixes include detailed information about the product-substance combinations, the research and evaluation of emission/exposure scenarios throughout the entire lifecycle, in depth descriptions of the identified Safe by Design strategies, and the assessment of these strategies using Life Cycle Assessment and Risk Assessment where possible. The track then details the Safe by Design approach and finalizes with the discussion and conclusion (Chapter 5).

Tack c – For readers interested in the project's methodology and process, the results, and the evaluation steps of the Safe by Design approach. This track advises reading all chapters of the report. Optionally, Appendix F can be consulted for readers interested in the complete version of the evaluation of the Safe by Design approach with the three additional cases (including microplastic release from textiles, Polyurethane foam in respiratory care devices, and PFAS in food packaging).

*** It is recommended that designers wanting to apply the proposed Safe by Design approach make use of Appendix G, where detailed instructions and examples are provided, as well as fillable templates.**



1. Introduction

1.1 Background and introduction

The circular economy (CE) revolves around three principles: 1) Eliminate waste and pollution, 2) Maintain the value of resources and products, and 3) Regenerate nature [1]. The European Union (EU) has developed an agenda to transition towards a circular economy [2], which emphasizes the need for products designed to meet CE principles by making them more durable and fit to be reused, repaired, refurbished, recycled, or reintegrated into nature. With this in mind, any product that harms human health or the environment throughout its lifecycle, including multiple use cycles and end-of-life treatments, does not meet the CE principles. To avoid harmful impacts, safety should be explicitly addressed in circular product design.

The Safe by Design (SbD) concept proposes the inclusion of safety considerations in early stages of the development process. The aim of SbD is to avoid health and environmental hazards stemming from hazardous substances, materials, and associated processes throughout the life cycle(s) of products to make them fit to be safely reintroduced in a circular economy [3], [4]. The SbD approach has different research aspects to it in a diversity of fields including, for example, biotechnology, nanotechnology, chemistry, civil engineering, chemical engineering, aerospace engineering, and software engineering amongst others. Each discipline has a different perception and approach to safety, and deals with a variety of present risks through different strategies and methods for risk management [5]. For product design, two aspects have been highlighted: safety in repairs and dealing with substances of concern (SoC) in products [6].

Substances of concern (substances that may have harmful effects on human health and the environment) are used in a variety of consumer products (clothing, electronics, toys, etc.), often without designers and users being aware of their presence. Although some are currently regulated to avoid or reduce their presence in specific applications, many others remain in use and can be hazardous for the environment and human health. With the transition to a CE, products containing SoC will have to be designed or adapted to mitigate their presence or avoid their release, and prevent exposure during production, use, reuse, and at all other stages of the product life cycle(s), including end of life. An informed and better management of SoC in the early stages of the product development process can potentially reduce the hazards and risks posed by SoC. However, awareness, information, and methods for designers to consider the safe use of substances are currently limited.

This study focuses on the elimination or management of SoC in product design and has as a main goal to d*evelop design guidelines that support designers when (re)developing products with substances of concern, in order to mitigate or manage the risks they impose with the aim to design products that are safe to fit a circular economy*. This goal suggests that the scope of design concerning SbD is not limited to making improvements to the product itself, but also considers the design of elements in its context, its corresponding infrastructure, and the design of new alternatives.

To achieve this goal, three research questions are addressed:
RQ 1. How and why are SoC used in products? What is known about their effects throughout the lifecycle of products and on the circular economy?

RQ 2. How can the risks and hazards posed by SoC in products be eliminated or managed through design, considering the entire lifecycle of the product and when a product (or parts of it) goes through consecutive lifecycles (manufacturing, use, reuse, recycling, remanufacturing, etc.)?

RQ 3. How can tradeoffs between sustainability, safety, performance, and cost be balanced when dealing with SoC in products?

1.2 Definition of SoC for this project

Different institutions such as the European Chemicals Agency (ECHA), and the Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM) have different definitions, classifications, and inclusion criteria for their lists of SoC.

The European Chemicals Agency (ECHA), classifies SoC as Substances of very high concern (SVHC), defined as those that may have harmful effects on human health and the environment, and meet the criteria proposed in Article 57, of the REACH regulation [7], [8]. These can include substances that are Carcinogenic, Mutagenic, or toxic to Reproduction, Persistent, Bioaccumulative and Toxic (PBT), or very Persistent and very Bioaccumulative (vPvB), [8].

The RIVM also classes substances of very high concern (Zeer Zorgwekkende Stoffen (ZZS) in Dutch), however these are identified through a broader scope [9], which not only considers the criteria proposed by REACH, but also includes substances listed under the Classification Labelling and Packaging of chemicals (CLP) regulation [10], and the Persistent Organic Pollutants (POP) regulation [11], amongst others. Additionally, the RIVM has a list of potential ZZS (pZZS), which includes substances that possibly meet the criteria of ZZS but are still under research to classify them as such [9], [3].

Thus, an agreed, definitive definition of SoC does not exist. For this study the definitions are too limited to specific criteria set by different organizations, which do not consider a broader scope of potential pollutants. For this reason, for this study, the following definition for chemical pollution proposed by Rockström, J. et al. [12] forms guidance: *Primary types of chemical pollution include radioactive compounds, heavy metals, and a wide range of organic compounds of human origin which adversely affect human and ecosystem health*. This definition was found to be suitable from a CE perspective as it allows for the inclusion of a larger array of compounds of human origin (e.g., plastics), that can be emitted from products, concentrating in ecosystems, and having detrimental effects on human health and the environment. This definition also provides the notion that SoC are not necessarily added as such but might also be formed during use or at end-of-life. This can include substances emitted by products, but that are not yet classified or identified as SoC or emerging contaminants. Table 1 presents the definition and classification of SoC proposed for this study, considering different scenarios in which they may be present or released throughout the lifecycle of products.

Table 1. Definition and classification of SoC in products used in this study.

SoC present in the product – intentionally added to their composition *(e.g., additives such as phthalates in flexible PVC)*	**SoC unintentionally generated by the product – byproducts generated throughout Use/EoL** *(e.g., microplastics released from agricultural mulch films)*	**SoC used or added temporarily to the material or product for additional functions but not intended to be present in the end product – intermediates** *(e.g., formaldehyde added to textiles to reduce creases)*

2. Approach and methods

A detailed analysis was performed to identify historical, existing, and possible SbD strategies in a number of specific product-substance combinations to review their advantages and drawbacks in the context of the product. These results have been used to deliver a first set of guidelines for designers to eliminate or deal with SoC in products. This study was conducted using different analysis methods, including desktop research on the five selected case studies, interviews with experts, Risk Assessment, and Life Cycle Assessment, all are described in detail below.

2.1. Preliminary definition of strategy types

Based on an initial screening research of strategies used to deal with SoC in each one of the 5 case studies, 3 main types of strategies to deal with SoC in product design were identified, Table 2.

Table 2. Proposed classification of SbD strategy types

Avoid / Eliminate	**Reduce**	**Control / Prevent**
Any action that avoids the use of the SoC. Any form of modification to the product that removes the SoC. Any form of chemical/material substitution by a compound with comparable functionality.	Any action or modification of the product that results in a) and/or b): a) A reduction of the overall content of the SoC in the product. b) A reduction of emissions of the SoC in any stage of the lifecycle.	Any action or modification of the product that results in a) and/or b): a) The prevention of emissions of the SoC in any stage of the lifecycle b) The prevention of exposure to the SoC in any stage of the lifecycle.

2.2. Detailed investigation of five case studies

Five existing product-substance combinations were selected as case studies to investigate how and why SoC are used in products and to further understand how they have been, are, and could be dealt with. This to find relevant insights to build a framework or approach that designers can use when dealing with SoC.

2.2.1 Selected case studies and rationale for selection

The case studies were selected based on the findings from an initial project executed as a prelude to this study, with the goal to select ten product-chemical substance combinations relevant to the Dutch economy that have the potential to illustrate a variety of SbD approaches [13].
The general criteria for the selection of the case studies included:

1. Variety in the type of products and applications/fields.
2. Variety in the type of Substances of Concern. Considering the previously defined classification of substances of concern for this project as mentioned in Table 1.
3. Suitable to demonstrate a variety of SbD strategies (see Table 2).
4. Relevant to the Dutch economy and relevant to the field of product design.

The selected five case studies are summarized in Table 3.

Table 3. Selected case studies

Case	Specific Rationale	Function of the SoC
Case 1 - DEHP in charging cables	- Expected to have a variety of SbD strategies due to its ban.	Plasticizer
Case 2 - DEHP in PVC flooring	- Expected to have a variety of SbD strategies due to its ban. - Opportunities for comparison in SbD strategies considering the use of the same SoC in distinct applications.	Plasticizer
Case 3 - Microplastic release from agricultural mulch films	- Substitution with biodegradable is already available. Opportunity to investigate the effects of these EoL alternatives.	Microplastics are part of the composition of the material. The film is used to protect crops and generate microclimates
Case 4 - HFC 134a as a refrigerant in household refrigerators	- Expected to have a large variety of SbD strategies due to current regulation on the production, transportation, design, disposal, and recycling of cooling equipment.	Refrigerant
Case 5 - PFAS in synthetic textiles, outdoor garments	- Expected to have a variety of SbD strategies due to the ban of some PFAS types.	Oil and water repellency treatments

2.2.2 Product-substance combinations - desktop research and interviews with industry experts

Desktop research

The five case studies were investigated in depth through desktop research as well as through interviews with experts, whenever possible.

The desktop research for each case was performed following a set of steps:

1. The SoC present in the product was analyzed to understand its context, nature, applications, regulatory status, and its potential hazards to human health and the environment.
2. The product-substance combination was investigated to identify the function of the SoC in the product, the presence of the SoC in the product, and the related manufacturing processes.
3. The emission/exposure scenarios per life cycle stage of the analyzed product were investigated. During this step three additional aspects were considered and noted:
    - The mechanisms in which the SoC is released:

        i. Volatilization - The transition of a chemical substance into the vapor phase, resulting in emission into the ambient atmosphere [14].
        ii. Leaching - The loss of a compound from a material or carrier into a liquid (solvents, water, saliva), which could result in the contamination of groundwater, surface water, and saliva [15][16].
        iii. Migration - The transfer of a compound to another medium when in direct contact (e.g. transfer to the skin upon contact) [17].
    - The inputs that could aggravate (increase the amount or rate at which they are released) the release mechanisms, for example:
        i. UV light
        ii. Chemicals
        iii. Mechanical input
    - And the different exposure routes, for example:
        i. Ingestion
        ii. Skin contact
        iii. Inhalation
4. The identified emission/exposure scenarios were analyzed and evaluated to prioritize them and identify those that are most concerning based on their effects to human health and/or the environment. This was done through qualitative analysis of the information found through literature, and other methods, such as risk assessment to identify concerning human health and ecological risks, The qualitative assessment of the emission/exposure scenarios was done by identifying those that are specifically and repeatedly mentioned in literature or reports as most concerning. The use of risk assessment is further described in section 2.2.3.
5. The identified SbD strategies that have been, are, and could be currently used to deal with the SoC in question were listed. Each one of these strategies was then assessed in a qualitative way and quantitatively whenever the available data allowed it. For the qualitative assessment all advantages, disadvantages, uncertainty, and tradeoffs mentioned in literature, reports, and company reports or websites for each alternative were listed and analyzed. Risk Assessment and/or Life Cycle Assessment were used for the qualitative evaluation. The use of these quantitative methods in the assessment of strategies is further discussed in section 2.2.4.
6. The main insights for designers were summarized, as well as the identified challenges and limitations specific to the case study.

The investigation of the case studies was limited to the available information. Some cases have clear knowledge gaps or lack specificity to the particular SoC product-substance combination. In some instances generic information about a substance, or group of substances, was used to build the case (e.g., PFAS was researched as a group).

The desktop research for each case was performed by using the following search queries:

a) Search of the substance in several databases/lists to identify its nomenclature(s), known applications, function, known hazards, and regulatory status. The lists include ECHA's information on chemicals, SIN List, Material Wise, Pub Chem.
b) Further reading was then done on the identified relevant regulations and relevant annexes.
c) Search for literature was done using the following code combinations in search engines, including Google Scholar, Science Direct, and TU Delft Library:
    - Name(s) of the substance + in + Name(s) of the product (i.e., Household refrigerators) / Product category (i.e., Cooling equipment)
    - Emissions + of + Name(s) of the substance
    - Emissions + of + Name(s) of the substance + from + Name of the product / Product category
    - Production/manufacturing + of + Name of the product / Product category
    - Waste management + of + Name of the product
    - Hazards + of + Name(s) of the substance
    - Risk assessment + of + Name(s) of the substance
    - Function + of + Name(s) of the substance + in + Name of the product
    - Alternatives + for + Name(s) of the substance
    - Identified Alternatives (each of them searched separately)

d) Snowballing from the identified references through the queries, was done to find other relevant sources.

Interviews with industry experts

To support the investigation of the case studies and to expand in the identification of strategies used in the industry to deal with SoC in products, several semi structured interviews with industry experts were conducted, see Table 4. These interviews were prepared with a set of questions formulated to complement the information found during the desktop research and fill remaining information gaps from it. The interviewees were then questioned regarding specific alternatives or solutions to SoC in the researched application. The answers obtained during the interview were directly transcribed as a response to the question into an electronic document. These answers were further analyzed later to compare the results to those obtained from the desktop research, and complete gaps whenever possible.

The questions used to provide structure to the interview are as follows:

1. Has (Name of the company) used (Name of the SoC) in their products in the past or currently? In which applications?
2. What is the function of the (Name of the SoC) in the (Name of the product / Product category)?
3. What is the expected lifetime of (Name of the product) in (Context of use)?
4. What actions has (Name of the company) taken to avoid/eliminate, reduce, or control/prevent (Name of the SoC) in their products?
    a. Replacement of substance. What are the advantages and disadvantages of replacement (design changes, cost, convenience, lifetime)?
    b. Replacement of material. What are the advantages and disadvantages of the replacement (design changes, cost, convenience, lifetime)?
    c. Controlling monitoring EoL. Are there any actions from (Name of the company) in this area?
    d. Other (i.e., reevaluation of essentiality, informing consumers). What are the consequences of these strategies (design changes, cost, convenience, lifetime)?

Table 4. Interview with experts per case

Case	Interviews	Month / Year
Case 1 - DEHP in charging cables	Dutch cable manufacturer	March 2022
	Dutch recycler	March 2022
Case 2 - DEHP in PVC flooring	American flooring products manufacturer	April 2022
Case 3 - Microplastic release from agricultural mulch films	Plastic Film manufacturer	April 2022
Case 5 - PFAS in synthetic textiles, outdoor garments.	Sport clothing manufacturer	June 2022

2.2.3 Assessment of emission/exposure scenarios – Risk Assessment

SoC in products can cause a variety of ecological and human health risks throughout the product life cycle. These risks must be prioritized for potential design solutions. SoC cause risk in specific environmental compartments i.e. air, freshwater, marine, soil, wastewater (which may subsequently be released to waterbodies, while sewage sludge can be applied to soils), which in turn may affect some proportion of organisms in that environment. Three kinds of risks may occur due to SoC: ecological risks (risks due to chemical substances to specific species or the whole ecosystem), human health risks (e.g. occupational workers in production and waste handling facilities or consumers could be exposed to SoC through inhalation, dermal, oral, or combined routes of exposure during the performance of specific activities) and public health risk (caused by indirect exposure of the general population to chemicals that are persistent and mobile in the environment).

It is beyond the scope of a screening exercise to carry out a rigorous risk assessment for each case. The focus is on exploring if the most concerning risks through the product life cycle can be pinpointed using literature sources. To this end, the ecological, human health and public health risks along the lifecycle were prioritized quantitatively (if possible) or qualitatively based on the literature and presented as a heat map, see Table 5. Quantitative risk estimations are typically available as ratios (risk quotient compares exposure with hazard or margin of safety which is the inverse).

Table 5. An example of Heat Map Thresholds for Risk Prioritization. The Risk Quotient is zero in the absence of risks, while values larger than 1 indicate a significant risk. The Margin of Safety Scale is 200 in the absence of risks, while values exceeding 100 indicate significant risks.

Risk Quotient	**Color**	**Margin of Safety**
0- 0.1	🟩	190-200
0.11-0.2	🟩	180-189
0.21-0.3	🟩	170-179
0.31-0.4	🟩	160-169
0.41-0.5	🟩	150-159
0.51-0.6	🟩	140-149
0.61-0.7	🟩	130-139
0.71-0.8	🟩	120-129
0.81-0.9	🟨	110-119
0.91-1	🟧	100-109
Risky, 1-10	🟥	Risky,90-99
Risky, 11-20	🟥	Risky, 80-89
Risky, 21-30	🟥	Risky, 70-79
Risky, 31-40	🟥	Risky, 60-69
Risky ,41-50	🟥	Risky ,50-59
Risky ,51-60	🟥	Risky ,40-49
Risky, 61-70	🟥	Risky, 30-39
Risky ,71-80	🟥	Risky ,20-29
Risky, 81-90	🟪	Risky, 10-19
Risky, 91-100	🟪	Risky, 1-9
	⬜	Beyond defined limits (over 200)

In the case of emerging contaminants like microplastics in Case 3, where physicochemical properties, hazard and exposure are poorly understood or uncertain, information from probabilistic risk assessment (PRA) studies was used [18].

Exposure limits are sometimes prescribed for specific chemicals in occupational settings, which can also provide an indication of risks. This approach is used for risk prioritization in Case 4. While HFC 134a is used in controlled settings, an emergency situation (e.g. leak, repair) may warrant exposure. It is important to note that exposure limits are not developed for specific activities but as a general occupational standard to guide risk management. Moreover, exposure limits are not available for consumer exposure.

2.2.4 Assessment of selected, identified SbD strategies per case - Risk Assessment and Life Cycle Assessment

The purpose of this assessment is to explore the possibilities and challenges of applying RA and LCA to screen alternative designs, making use of SbD strategies and select the most promising ones. The general approach followed for assessing the identified SbD strategies is described below.

Define and evaluate a baseline scenario via screening LCA: The salient environmental impacts for the use of the SoC in the product are evaluated via a screening LCA. A functional unit is defined based on function or mass (or translatable to mass, e.g. phone cable length in Case 1). LCA inventories like Ecoinvent, USLCI and the literature are searched for data to perform an LCA. If a SoC is missing in the commonly available Life Cycle Inventories, tools estimating environmental impacts on a mass basis from the results of past projects or tools using machine learning (e.g. CLICC, Hotspot scan, IDEMAT) are used. The literature is also scanned for existing studies that can help evaluate the baseline scenario.

Define and evaluate the effects of a SbD strategy via screening LCA/RA/Other Analysis: The analysis is framed for the SbD strategy in terms of setting up the LCA framework. A screening LCA is performed using

LCA inventories like Ecoinvent, USLCI and the literature and the effect of the strategy is evaluated. Each SbD strategy may lend itself to a different functional unit. For example:

- In the case of a substitution strategy, alternative chemicals to SoC may be compared in terms of function or mass.
- In the case of an elimination strategy, scenarios with reduced or no concentration of SoC are compared.
- In the case of longer service life, the functionality has to include the notion of an increased service life.

In the case of substitution strategies, Predictive RA approaches based on the structure of chemical can assist designers in avoiding regrettable substitutions of SoC as certain chemical groups are associated with toxic effects. One such tool is RIVM's ZZS similarity tool, which provides chemicals that are structurally similar to those on the ZZS list and may therefore exhibit similar toxicity profile. The Chemical Abstracts Service (CAS) number, an identifier assigned to all chemicals, is used as an input to the RIVM ZZS similarity tool to find chemicals that designers must be cautious to use as a substitute. This tool cannot be used for SoC that have a complex chemical nature (e.g. nanomaterials, where toxicity can vary by particle size and morphology) or SoC produced during the product lifecycle (e.g. microplastics). Not all SbD strategies are amenable to be evaluated using screening LCA or RA (e.g. the risk or impact reduction due to restricting or regulating the use of an SoC). In those cases, back of the envelope calculation or qualitative evaluation (QE) is used.

Indicate most promising SbD strategy: The most promising and feasible strategies are indicated on the basis of the quantitative and qualitative information. The limitations of the analysis are considered.

2.3. SbD approaches in other fields and industries

To further inform this investigation and the development of SbD guidelines for designer, two additional things were investigated: the way SoC (e.g., hazardous chemicals) have been approached by other fields (e.g., Green Chemistry), and the SbD approaches used by the industry to deal with SoC. Approaches should not be mistaken for strategies. In the context of this research, SbD strategies constitute direct development actions to deal with a certain SoC in a given product. Approaches are considered supporting tools, processes, sets of guidelines, or principles, that can be applied to guide professionals when dealing with SoC in products.

The investigation regarding the approach of the industry was partly informed by the results obtained from the case studies, were certain strategies and mechanisms were identified. These were further researched through literature, specifically focusing on company reports. The approach in other fields was investigated through desktop research, focusing on the fields and concepts of Green Chemistry, Green Engineering, and Safer Chemicals, to identify strategies, methodologies, and tools used.

The desktop research for approaches in other fields was performed following a set of steps:

1. Search for literature was done using the following codes in search engines, including Google Scholar, Science Direct, and TU Delft Library:
    a. Green Chemistry
    b. Green Engineering
    c. Safer Chemicals
    d. SoC in the circular economy
    e. Safe by Design
2. Snowballing from the identified references to find further sources.

The desktop research for approaches in the industry was performed through the analysis of the previously identified alternatives applied by the industry in the case studies. These solutions and companies were further researched. The research focused on finding public company reports on their frameworks and sustainability related actions. The results from the interviews were also further analyzed to inform this identification of approaches.

2.4. Development of SbD guidelines for designers

An initial SbD approach for designers was developed as the result of the investigation of the case studies.

The analysis guidance included in the approach was developed by mimicking the structure followed to research each case study during this project. The list of possible SbD strategies to select from was developed by mapping all identified strategies of the case studies together and classifying them using the proposed preliminary classification. Then, the steps proposed for designers to assess selected strategies were developed mimicking the qualitative assessment performed throughout the case studies. The proposed set of steps and methodologies are displayed in the form of templates, which designers can fill out and follow. This format was developed with the intention of providing designers with a structured step by step approach.

The approach first provides guidance for designers to analyze product-substance combinations in depth. It then provides a variety of possible SbD strategies to select from to target identified concerns. It finalizes by providing designers with guidelines to assess their selected strategies to understand their relevance, benefits, and potential drawbacks/tradeoffs.

2.5. Evaluation of the SbD approach with 3 additional cases

An internal evaluation of the proposed SbD approach for designers was performed by the main researcher of this project by applying the developed method to 3 additional case studies, see Table 6. The selection of these case studies followed the same general criteria established for the in-depth 5 case studies.

Table 6. Additional case studies used for the evaluation of the approach

Case	Specific Rationale	Function
Case 6 - Microplastic release from synthetic textiles	- Opportunities for comparison in SbD strategies considering the use of the same SoC in distinct applications.	Microplastics are part of the composition of the textile. Synthetic textiles are used as an alternative to natural fibers. Synthetic textiles can be modified to obtain added functions.
Case 7 - Polyurethane foam in apnea masks	- Relevant implications for product architecture.	Sound dampening.
Case 8 - PFAS in food packaging	- Opportunities for comparison in SbD strategies considering the use of the same SoC in distinct applications.	Water and oil repellency properties.

The evaluation of the approach was done by the main researcher of this project, following the steps indicated in the fillable templates to 1) Identify any problems with the proposed workflow, 2) Obtain an estimate of the amount of time/effort necessary to complete the steps, and 3) Identify challenges designers may encounter when filling up the necessary data for the analysis and performing the assessment steps.

The results of the evaluation serve as guidance for the development of future iterations of the approach, as well as to find limitations and challenges that require further research and development efforts.

3. Results: Case studies and approaches in other fields and industry

This section presents a brief summary of the results found during the investigation of the 5 case studies and the results of the investigation of approaches in other fields and industry.

3.1. Cases

Each case summary briefly presents the product-substance combination, including its context, information about the substance (its function, presence in the product, relevant regulations, and hazards), most relevant emission/exposure scenarios, a summary table of all identified safe by design strategies to deal with the SoC in question, a summary of identified benefits and drawbacks, and a set of insights for designers derived from the case.

The detailed results of the research of each case can be found in Appendixes A – E. These appendixes include detailed information about the product-substance combinations, the research and evaluation of emission/exposure scenarios throughout the entire lifecycle (qualitatively and quantitatively, using RA whenever possible), in depth descriptions of the identified SbD strategies, and the assessment of the application of these strategies (qualitatively and quantitatively, using RA and LCA whenever possible).

3.1.1 Case 1 - DEHP in charging cables

Background on DEPH in cables

The topic of this case study is DEHP (also known as Bis(2-ethylhexyl)) used as a plasticizer in charging cables. Plasticizers are synthetic chemicals used to increase the flexibility and workability of plastics (most commonly used in flexible PVC [23], [24]). DEHP, is added to cable mantles to make them flexible, insulating, heat resistant, and add to their durability [16], [24], [18], [26], [27], [28]. DEHP in cables is considered an interesting historic case, because DEHP has been used at a large scale in cables (resulting in 11000 ton of Waste from Electrical and Electronic Equipment (WEEE) annually) [19], [20] and is banned in the EU since 2021 by the REACH regulation (Registration, Evaluation, Authorization and Restriction of Chemicals), [21], [22]. This allows to investigate how industry, and specifically design, dealt with this ban, and which strategies were deployed to eliminate DEHP.

DEHP is the most common member of the class of phthalates. It has been classified as a substance of concern since human exposure can cause endocrine disruption, deformities in the reproductive system, increased risk of premature birth, and cancer risk [16], [29]–[31]. Additionally, phthalates are considered bioaccumulative and ubiquitous environmental contaminants, which means they can be found almost anywhere in the environment, air, soil, and water. Humans, birds, fish, mammals and soil organisms are all exposed to the effects of DEHP [16], [30], [31].

Most relevant emission/exposure scenarios

DEHP is not chemically bound to the molecules of the polymer (PVC), making it possible for it to be released from the material into the environment throughout the lifecycle of the products that contain it [16]. This can occur through a number of mechanisms, including volatilization, leaching, and migration.

This study found the production of the DEHP and cable, the use phase, and the landfill of the cable to be the most concerning emission/exposure scenarios. During production, industrial activities can discharge DEHP directly into the sewages as well as releasing volatilized DEHP in air particles and dust [16].

The increasing accumulation of contaminated charging cable waste in landfills is a concerning emission scenario, since DEHP can leach and evaporate resulting in the contamination of air, soil, groundwater, and surface water [15], [16]. For this reason, strategies such as recycling may be useful in overcoming this accumulation. The WEEE Directive of the EC [32], has as an objective the collection and proper disposal of electronic devices, to recover the resources from those products and avoid the release of hazardous substances and their landfilling. However, cable waste recycling was found to be mostly interesting for the recovery of metals (due to their high value) and not plastics. DEHP hinders the recycling possibilities of flexible PVC [33]. This is because phthalates remain in the composition of PVC after recycling, causing the plastic fraction to be sent to incineration or landfilling [33].

Concerning exposure scenarios include 1) Occupational exposure during the production of DEHP and manufacturing of cables, where workers are exposed through skin absorption and inhalation [29] [31], 2) Indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [16], and 3) Users, particularly and most concerningly children, can be exposed to DEHP through ingestion by chewing on the cable. Plasticizers are soluble in water and other media, in this case saliva [16],[34].

Design Insights

Found strategies, evaluating benefits and drawbacks

Table 7 provides a summary of the identified SbD strategies and their potential benefits and drawbacks according to literature and the RA, and LCA assessments carried out by the researchers when applicable.

Table 7. Summary of identified SbD strategies for DEHP in Cables

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with DEHP in cables				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential drawbacks
Avoid / Eliminate	Substitution of DEHP by another phthalate-based plasticizer	[QE] [LCA] [RA]	- Similar functional characteristics [int], [35]. - Similar cost [int], [35].	- Some phthalate-based plasticizers have a similar hazard profile to DEHP [RA], [36], [37]. - Unknown hazard profile for other phthalate-based plasticizers [23], [25]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [38]. - Some alternatives are currently regulated (DINP)[37]. - No clear winner, DPHP has the best environmental profile [LCA].
	Substitution of DEHP by a non- phthalate-based plasticizer	[QE]	- Some types have comparable functional characteristics to DEHP [int], [35].	- Unknown effects/ hazards for health and environment [int]. - Higher cost [int]. -Potential displacement of land for food production for biobased plasticizers [28] [16]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [38].
	Substitution of the cable material – (halogen free alternatives) PE, PP, PUR, PS, Rubber	[QE]	- No known hazards to health or the environment [39].	- Increased cost [39] [40]. - Processing is energy intensive [39] [40]. - Limitations in performance [39] [40].
	Delivering function differently - Wireless charging	N/A	- *No identified benefits since device operates through a cable of similar dimensions as common chargers. Strategy is mentioned as a possibility for further exploration.*	
Reduce	Cable type harmonization to USB -C and de-bundle the phone and charger, by regulation.	[QE] [est]	- Increase useful life of cables, decreasing env impact [est], [19], [20], [41]. - Reduce number of disposed cables. Decrease WEEE. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [15][16].	- Only applied to adapter. Cable under consideration [3], [15].
	Extending useful life – Repair with sleeves	[QE] [LCA]	- Increase useful life of cables, decreasing environmental impact [1]. - Repair sleeve has less environmental impact than purchasing a new cable [LCA]. - Reduce number of disposed cables. Decrease WEEE. Decrease of DEHP	- Safety could be an issue if the repair is not done correctly. - Only reduces the speed of accumulation of the SoC at EoL.

			emissions in EoL (Uncontrolled landfill being of most concern) [15][16].	
	Extending useful life – Durable cables. Reinforce sections that are prone to breaking, improve folding and portable options.	[QE]	- Increase useful life of cables, decreasing environmental impact [1]. - Reduce number of disposed cables. Decreasing WEEE. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [15][16].	- Only reduces the speed of accumulation of the SoC at EoL.
Control/ Prevent	Controlled / regulated recovery - WEEE Directive	[QE] [LCA]	- Controlled disposal and recovery could facilitate recycling.	- Recycling is hindered by the presence of plasticizers other additives [33], [42]. - Recycling of cables is focused on metal recovery and not plastics [int]
	Prevent exposure – preventing mouthing by children through the use of cover sleeves.	[QE]	- May protect children from direct exposure to DEHP and other substances through ingestion.	- Risks may vary depending on the composition of the material of the sleeves. More information is necessary.

Design strategies

Eliminating DEHP in cables has been mostly done through substitution. Since DEHP was restricted under REACH, the industry has been forced to substitute it with other types of plasticizers and/or materials. Substitution can be challenging, especially because the effects of these substitutions regarding safety, and their effects on human health and the environment are many times uncertain. This uncertainty may lead to regrettable substitutions as shown for example, in the assessment comparing DEHP to alternative phthalates. Additionally, current substitution options for DEHP present a diversity of other challenges including performance, durability, and increased costs.

Strategies under the category of reduce, focus in this case, on the extension of the useful lifetime of cables, and thus contribute to the reduction of cable waste generation to reduce the speed of the accumulation of DEHP and other harmful substances in landfills. Although these strategies may have a positive influence in reducing DEHP emissions, it is relevant to note they do not eliminate all the risks related to the substance during other stages of the lifecycle of the product, notable the use phase.

Role of designers

Reduce strategies related to the extension of the useful life of cables may influence the design of the product. Designers have clear opportunities to apply the identified strategies for extending the useful life of cables, such as making them stronger and resistant to manipulation, making cables repairable, and avoiding incompatibility issues. The implementation of policies, such as the standardization of charging ports and unbundling of phones and chargers, facilitate designers in clear priority setting regarding strategies. Additionally, designers can also play a role in identifying these types of strategies and possible beneficial changes in the design of a product to inform policy making.

Substitution strategies need further elaboration by designers to overcome tradeoffs at the cost of durability, performance, and comfort that currently result from switching to new additives and/or materials. Equally so, designers can also further explore the possibilities of modifying the cable design to prevent exposure, e.g., mouthing from children, and volatilization during the use phase.

Limitations and challenges

Existing substitute substances and materials for DEHP and flexible PVC are showed to have a number of performance limitations. In addition to this, it is unclear how information over substances is managed and communicated across all the stakeholders through the lifecycle of a product and some substitutes appear to have limited information on their benefits, drawbacks, and potential long-term effects on the environment and health. The information on the alternatives for DEHP is sometimes unclear and/or unavailable. In the case of phones and their chargers, some manufacturers [43], [44] have installed internal policies which require their suppliers to comply to restricted substances lists and/or provide full material declarations to support substitution decisions. However, existing options for the substitution come with a large number of tradeoffs or need further development to fulfill the expected environmental, public health, cost, and performance requirements.

3.1.2 Case 2 – DEHP in PVC Flooring

Background on DEHP in PVC flooring

PVC flooring belongs to a product group known as Resilient Floor Coverings. These products are specifically designed to meet different performance qualities, such as, resistance to wear, comfort, ease of maintenance and cleaning, acoustic dampening, and hygiene. Resilient floor coverings are available in a diversity of materials and forms and can be used in both residential and commercial applications [45]. Out of the 50.7Mt of plastic demand in Europe in 2019, 10% can be attributed to PVC, including mostly window frames, flooring, wallpaper, hoses, and cable coatings [46]. According to Vinyl plus [47], 7% of the annual PVC demand in Europe can be attributed to flooring.

DEHP is a plasticizer, see Case 1 (Chapter 3.1.1). In the case of flooring, PVC is plasticized to fulfill different functional requirements such as flexibility, dimensional stability, wear resistance, stain resistance, acoustic dampening, and comfort [45] [48] [49]. PVC flooring can have different configurations depending on its application. Homogeneous PVC flooring, is a single layer flooring material produced with a method called calendering, which is used to produce films and sheets by processing molten plastic through pairs of rollers [50]. Multiple-layer, or heterogeneous PVC flooring, is produced by laminating several films of PVC and other materials, such as glass fiber, wood fiber, printed layers, and polyurethane coatings. Lamination can be done with heat and or adhesives [51] [52].

Prior to being banned by the REACH regulation, DEHP was one of the most commonly used plasticizers in PVC flooring [8], [37]. Although phthalate based plasticizers have been identified as hazardous or are being investigated for health and environmental hazards [53], they continue to be the most commonly used type of plasticizers used in Europe [54].

Most relevant emission/exposure scenarios

Similar to the cable case (Case 1) this study found the production of the chemical and flooring, landfill, and use phase to be the most concerning emission scenarios. During production, industrial activities can discharge DEHP directly into the sewages as well as releasing volatilized DEHP in air particles and dust [16].

DEHP can volatilize into the air from plastic products, during the use phase, it is released into the air and dust of indoor environments with PVC flooring and/ or PVC wallpaper [26], [55], [31]. DEHP particles can be released into the air or attached to dust particles, levels appear to be higher in dust particles than in air [55]. Emissions of DEHP from flooring may increase by a number of factors, including higher temperatures and humidity [55]–[57].

DEHP hinders the recycling possibilities of flexible PVC [33]. This is because phthalates remain in the composition of PVC after recycling, which could risk reintroducing contaminated materials into the market. For this reason PVC waste from construction is recommended to be collected separately and incinerated in specialized incineration plants [33]. Even though PVC is highly recyclable, PVC waste is most commonly incinerated or sent to landfill [33], [58], [59]. The accumulation of products containing DEHP in landfills is concerning, since DEHP can leach and evaporate resulting in the contamination of air, soil, groundwater, and surface water [15], [16].

Concerning exposure scenarios include 1) Occupational exposure during the production of DEHP and manufacturing of PVC flooring , where workers are exposed through skin absorption and inhalation [29]

[31], 2) Indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [31], [16], and 3) Direct exposure of users to DEHP from flooring through inhalation of indoor air and contaminated dust, skin contact and ingestion [26], [34].

Design Insights

Found strategies, evaluating benefits and drawbacks

Table 8 provides a summary of the identified SbD strategies and their potential benefits and drawbacks according to literature and the RA, and LCA assessments carried out by the researchers when applicable.

Table 8. Summary of identified SbD strategies for DEHP in PVC flooring

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with DEHP in PVC flooring				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential drawbacks
Avoid/ Eliminate	Substitution of DEHP by another phthalate-based plasticizer DINP(Diisononyl phthalate) and DIDP (Diisodecyl phthalate).	[QE] [LCA] [RA]	- Similar functional characteristics [int], [35]. - Similar cost [int], [35].	- Some phthalate-based plasticizers have a similar hazard profile to DEHP [RA], [23], [36], [37]. - Unknown hazard profile for other phthalate-based plasticizers [23], [25]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [38]. - Some alternatives are currently regulated (DINP)[37]. - No clear winner, DPHP has the best environmental profile [LCA].
	Substitution of DEHP by a non-phthalate-based plasticizer like DINCH (1,2-Cyclohexane dicarboxylic acid diisononyl este).	[QE]	- Some types have comparable functional characteristics to DEHP [35].	- Unknown effects/ hazards for health and environment. DINCH does not appear to have public health effects but potential adverse effects on aquatic organisms [60], [61],[62]. - Higher cost [35]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [38].
	Substitution of material - Alternative polymers and bio composites PET, PUR, linoleum, rubber, and cork.	[QE] [LCA]	- No hazards to public health or the environment identified from these materials yet [39].	- Unclear benefits and tradeoffs over environmental effects and functional performance [63], [64].
Control/ Prevent	Preventing emissions with coatings and layered materials	[QE]	- Coated flooring presented lower emission rates of DEHP in indoor environments [56] and lower migration of DEHP into dust [55].	- Only targets the use phase. - Unknown composition of the coatings and their effects. - Additional materials may hinder recyclability.

	Controlling emissions by improving indoor air quality	[QE]	Ventilation systems, particle filtration systems, and cleaning flooring surfaces improve indoor air and reduce exposure to DEHP [26], [55], [31].	N/A
	Controlled recovery for controlled landfill and incineration of flooring waste	[QE]	- Avoids uncontrolled emissions from landfill and incineration [15], [16], [33].	N/A
	Recovery and recycling of post-installation flooring waste (scraps of flooring remaining after installation, this flooring has no signs of use)	[QE]	- Recycling can have the most environmental benefits for flooring materials [63]. - Avoids uncontrolled emissions from landfill and incineration [15], [16], [33].	- This strategy is mostly applied to internal recycling cycles (collected and recycled by the manufacturer to be used internally in the production of new products) [33], [42], [int]. Manufacturers only recover their own materials to have knowledge over the composition.
	Monitoring of materials and recycling of post-consumer waste (used flooring materials recovered from buildings)	[QE]	- Recycling can have the most environmental benefits for flooring materials [63]. - Monitoring of the composition of the flooring materials avoids the introduction of harmful additives. - Avoids uncontrolled emissions from landfill and incineration [15], [16], [33].	- Only possible to recycle products were it is certain that no DEHP or other harmful phthalates are present [65], [66]. If the presence of DEHP is confirmed or uncertain the recovered material cannot be used in the production of new flooring products.
Reduce	Increasing the useful life of flooring products -Product selection based on user requirements (level of comfort, acoustic properties, etc.).	[QE]	- Increase useful life can have a positive influence over environmental performance [63], [64]. - Guidance for buying decision can avoid early retirement due to failure or wrong product selection for a certain application [63]. The EN classification already in place [49]. - Reduce number of disposed floorings. Decreasing waste. Decrease of DEHP emissions during EoL (Uncontrolled landfill being of most concern) [15], [16].	- Only relevant to reduce the speed of the accumulation of DEHP in landfills.
	Increasing the useful life of flooring products	[QE]	- Increase useful life can have a positive influence over	- Unknown effects (water and energy demand for

	- maintenance and repair.		environmental performance [63], [64]. - Reduce number of disposed floorings. Decreasing waste. Decrease of DEHP emissions during EoL (Uncontrolled landfill being of most concern) [15], [16].	maintenance) and availability of repair components [63].

Design strategies
Like the case of DEHP in cables, substitution of the additive has been a common strategy to eliminate DEHP in PVC flooring. Uncertainty about the safety and potential effects of alternative phthalate and non-phthalate based plasticizers on human health and the environment can lead to regrettable substitutions of DEHP.

Although the cable case showed limitations to the strategy of substitution of the material, including limited performance and increased costs. The case of flooring showed several suitable material substitutions which are flexible without the need of a plasticizer, have the desired functional performance for certain applications and are currently commercialized.

Reduce strategies, such as informing product selection to avoid early retirement, and increasing the useful life of flooring through repair and maintenance, are only effective in avoiding DEHP (or other concerning phthalates) from accumulating in landfills. However, if further explored, and in combination with other strategies increasing the useful lifetime may have a positive influence over the overall environmental performance of flooring products. Control strategies appear to be limited to the development of additional products to prevent emissions or improve air quality. Additionally, those control strategies focused on the recovery and recycling of flooring materials, remain limited by the presence of DEHP.

Role of designers
Designers may have influence over the substitution of plasticizers and other chemicals in products if they are able to understand the product-substance combination, the properties, and potential effects of the SoC, and the functional requirements of the product. Additionally, designers must count with the knowledge to communicate with suppliers to either avoid regrettable substitutions or prevent emissions and exposure to limit the hazard of the substance in question.

Designers can also focus on the strategy of substitution of the material to achieve the functional, cost, and performance requirements of different applications whilst avoiding the use of PVC (and plasticizers) overall. Design can also play a role in strategies that aim to increase the useful life of flooring (Reduce strategies). By designing services that support customers in the correct purchase of a product companies could understand their customer needs better and avoid early retirement of products due to failure or inappropriate product selection. Additionally, designers can also develop systems that allow and facilitate the repair and maintenance of flooring products.

Decreasing emissions (Control/Prevent strategies) throughout the use phase was shown to be possible by the addition of top coatings or layers that avoid dust and air to be directly in touch with materials that contain DEHP. This can also be considered by designers in applications where eliminating DEHP or plasticizers overall is not possible for specific applications or functions.

Last, although designers may not have direct influence over strategies for a controlled EoL, incineration and recycling, and internal policies from manufacturers for monitoring of post-consumer waste for recycling, they may be involved in the design of the services that support those strategies (e.g., collection) or in the design of flooring products that can cope with the use of recycled materials.

Limitations and challenges
An important challenge when dealing with DEHP in flooring products is the transparent communication between chemical and polymer producers, and flooring manufacturers. Similar to the case of cables, PVC

flooring manufacturers are using strict policies to communicate their requirements to their suppliers. Such as adherence to restricted substances lists and issuing material declarations.

Although studies on the environmental impact of resilient floor coverings recommend the recycling of PVC flooring as the preferable option [63], the presence of plasticizers hinders the possibilities for safe recycling. To overcome this challenge, some companies have installed a closed loop recovery and recycling systems for post installation waste (not post- consumer), making sure only known materials (without DEHP) are used. In order to make it possible for post-consumer flooring waste to be recycled, DEHP and other harmful plasticizers need to be phased out or removed through chemical recycling. Additionally, monitoring systems need to be further developed to avoid other harmful chemicals and DEHP in older discarded products that may still contain them.

3.1.3 Case 3 – Microplastics release from agricultural mulch films

Background on microplastics and agricultural mulch films

Plastic mulching is an increasingly common agricultural practice that consists of covering agricultural soils with plastic films, commonly made of polyethylene, to create a barrier to avoid water evaporation, increase the soil temperature, protect soil from pests and contaminants, and control weed growth [67]–[69]. In 2016 there were 20 million hectares using plastic mulch films around the world, with China alone covering approximately 90% of that. Europe currently is estimated to cover up to 427,000 hectares. The plastic mulching global market was calculated back then to be 4 million tons, and expected to grow 5.6% every year [69], [70].

Low density polyethylene (LDPE) and Linear Low-Density Polyethylene (LLDPE) are commonly used to produce mulch films due to their flexibility, high impact resistance, ease of processing, low cost, and to reduce the weight of the film [67], [70], [71]. The films are produced by casting or blown film [72]. Additives are used to adjust the properties of the films, to withstand environmental conditions, modify their capacity to absorb and transfer solar radiation, to withstand mechanical degradation and increase their useful life [72]. These additives can include UV stabilizers, pigments, plasticizers, co-polymers [70], [72].

Although plastic mulching is found to have many benefits on product quality, growth, and yield of crops [67], [70], it has also been found to be a major contributor of secondary macro and microplastic release in terrestrial environments. This mainly due to its increasing and continuous use, to meet the growing global food demand, and the improper removal and disposal of the films [68], [69], [70]. Microplastics are defined as small plastic particles of less than 5mm in diameter, released into the environment from plastic products, while macroplastics are defined as plastic particles of greater than 5mm diameter [73], [74]. Microplastics can also be classified as primary or secondary based on their origin. Primary microplastics are purposely made small and introduced into products (e.g., microbeads in exfoliants and toothpaste). Secondary microplastics, are those resulting from the breakdown of larger plastic bodies through mechanical, chemical and/or UV degradation [73], [74].

Microplastics are ubiquitous contaminants, increasingly present in the environment as a result of the increased production, consumption, and low recovery rate of plastics. Due to their resistance to degradation, they can remain for long periods of time in the environment [69], [73]. Additionally, other pollutants are easily adhered to them and transported to different environmental compartments (water, soil, air) having different effects in the environment [73]. Macro and microplastics generated from plastic mulch films accumulate in the soil throughout time and may have long-term negative effects on soil quality, including damages to soil health, changes in humidity, modified PH, and loss of nutrients, long term yield reduction when films are not removed and disposed, and food contamination, all of which have implications for food security [69], [70], [75].

The effects of microplastics have been studied mostly in terrestrial and aquatic wildlife, identifying feeding and reproductive disruptions as well as metabolic disturbances [69], [73]. So far, humans have been found to be exposed to microplastics indirectly and directly through food, water, and air. Some of the studied health impacts include respiratory problems, cardiovascular diseases, and obesity but further research is necessary [73]. Exposure to plastic particles can also have a negative impact in health if the plastic is contaminated by hazardous additives, such as plasticizers and flame retardants, or adhered pathogens [73], with some of these identified as carcinogenic and endocrine disruptors [29].

Even though agricultural mulch films are large contributors to microplastic pollution [73], there are currently no regulations in place specifically applied to secondary microplastics, nor microplastics generated by them. However, some regulations focus on the reduction and management of plastic waste. Banning or controlling landfills, promoting recovery and recycling, and reducing the consumption of single use plastics are some examples of existing regulations that contribute to the reduction of microplastic pollution in Europe [32], [73], [76].

Most relevant emission/exposure scenarios

When microplastics are identified in an environmental compartment (soil, water, air) it is challenging to identify their origin due to the complexity of the sources [77], however, soil has been identified as one of the most relevant compartments for microplastic release with agricultural mulch films being the primary contributors [78].

This study found the use phase, uncontrolled recovery, and landfill to be the most concerning emission scenarios for microplastics release from agricultural mulch films. During the use phase (months or even years depending on the type of crop), agricultural plastic mulch films are exposed to environmental conditions that can contribute to their deterioration, including UV degradation and mechanical degradation, that cause the release and accumulation of microplastics in the soil [79].

The removal and proper disposal of plastic mulch films is a labor-intensive and expensive activity. In consequence, plastic mulch films are often left on agricultural areas where they break down into smaller plastic particles over time. Uncontrolled recovery has been highlighted as an issue of major concern in relation to the accumulation of microplastics in the soil in several publications [68]–[70], [75], [79]. The degradation of the film during the growing season also complicates its removal in its entirety [79]. The leftover of the film is sometimes buried and sometimes just left on the surface, alternatively, the film is burned in its entirety [67].

Although recycling is the preferred alternative to incineration and landfill, removed plastic mulch films are not suitable for the recycling process due to heavy UV degradation and high contents of contaminants (Films are only accepted for recycling with less than 5% of contaminants by weight with mulch films typically reaching 40 – 50%), including soil, vegetation, water, and agrochemicals, such as pesticides [67], [70], [75]. When recycling is not possible and incineration facilities are not available, mulch films are deposited in landfills where plastics accumulate and continue to degrade from macroplastics into microplastics [75]. Additionally, mulch films can also release additives and agrochemicals into the soil and water during landfill [70].

No direct exposure routes were found for microplastics from agricultural mulch films. Indirect exposure from contaminated soil and food is highlighted as a concerning exposure scenario [73].

Design Insights

Found strategies, evaluating benefits and drawbacks

Table 9 provides a summary of the identified SbD strategies and their potential benefits and drawbacks according to literature and the RA, and LCA assessments carried out by the researchers when applicable.

Table 9. Summary of identified SbD strategies for microplastic release from agricultural mulch films
Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with microplastic release from agricultural mulch films.				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential drawbacks
Avoid / Eliminate	Substitution of material for photodegradable and biodegradable mulch films	[QE]	- Could substitute the need of collecting the film after the harvest [67], [70], [75].	- Concerns about complete degradation [67], [70], [75], [79], [81], [82], [int]. - Photodegradable films degrade prematurely [67], [75]. - Biodegradable degrade faster into microplastics than PE films [79]. - Unclear effects on crops and soil quality [81], [82], [int]
	Substitution of material for paper mulch	[QE], [LCA]	- Eliminates microplastic release unless combined with PE [75].	- Lower durability [75]. - Higher costs than PE [75].
	Substitution of material for Biobased alternatives. (Straw, woodchips, living mulches)	[QE], [LCA]	- Eliminates the use of plastic mulch films and challenges related to recovery [75], [83], [84].	- Not suitable for all crops [75]. - Availability problems and quality cannot be guaranteed [83], [85], [84]. - Unclear effects on soil quality and yield [83], [84]. - Reduced efficiency over soil water conservation [84].
Control/Prevent	Reduce mechanical degradation – reduced use of machinery /automated input	[QE]	- Avoids the film from breaking/degrading during use, reducing microplastic release and facilitating its collection [68].	- Unknown limitations and consequences over production.
	Mulch recovery systems for proper waste handling	[QE]	- Collection avoids macro and microplastic emissions caused by leaving the film behind [68]–[70], [75], [79].	- Unknown costs and availability. - Unknown collection rates.
	Recycling of used agricultural mulch films	[QE]	- Reduction of microplastic emissions due to recovery [68]–[70], [75], [79]. - Some systems include cleaning steps to reduce contamination [86], [87].	- Challenges due to contamination with soil [67], [70], [75], [int]. - Unknown limitations, costs, collection rates, and availability.
Reduce	Reduce overall use – intermittent use and variation in crop types (crops that do not require mulching)	[QE]	- Reduces microplastic emissions. Fields with intermittent use have an important reduction compared to continuous use [68], [69] .	- Unknown limitations and consequences over production.

Design strategies

A large part of the strategies found in this case focus on the elimination of the substance by substitution of the material, with substitutes including biodegradable, photodegradable, and biobased alternatives.

Biodegradable (in soil) and photodegradable films were found to have unknown effects on soil health. Additionally, there are concerns regarding their complete degradation, and their early deterioration and release of microplastics. While biobased alternatives including paper, wood chips, and living mulches may have compatibility issues, lower durability, and unknown effects on health and the environment that need further research.

Strategies to recover and clean mulch films (Control/Prevent strategies) to make them fit for recycling are currently not widely available, leaving farmers with limited alternatives to avoid leaving the mulch film on the ground to deteriorate on its own. Additionally, these strategies fail to target the issue of deterioration and breakage of the film throughout the use phase.

Furthermore, strategies like reducing mechanical input (reduce the use of automated machinery or irrigation systems) and implementing the intermittent use of mulch films may not be feasible for all farms, possibly interfering with internal working practices, production volumes and necessary investments in people and equipment to counteract the absence of the film or the protection of its integrity.

Role of designers

Designers could have most influence on the design and development of collecting systems that reduce the effort and costs of this process. In addition to collection, the process of cleaning the film to facilitate recycling could be further explored. Current collection systems struggle with the deteriorated state of the film and are designed for existing mulch film designs. Films and collecting devices have been designed separately and not as a coherent system. Designers could further explore the design of the PE film to make adaptations that prevent its degradation, and a corresponding redesign of a collecting device. Although the influence of designers over biodegradable, photodegradable, and biobased alternatives, such as paper can be limited, the design of these films could be further explored to counteract some of the deficiencies caused by the substitution of the material, for example, increasing their durability and facilitating their installation.

Limitations and challenges

Existing options for the substitution of the material come with a large number of tradeoffs, some of which may have concerning environmental effects and several other currently unknown consequences. Some of the identified challenges include 1) Communication and transparency issues over the benefits and risks of alternative mulch film materials, 2) Lack of information over the long-term effects of substitute materials over soil health, human health, crop yield, etc., specifically for photodegradable and biodegradable mulch films, 3) Labor costs to remove the film, and 4) Higher costs of replacing materials.

The reduction of microplastic release from agricultural mulch films requires a great deal of innovation and development that considers the design of films and collecting devices as systems. The design of new mulching systems should avoid the focus on a specific emission scenario and consider the analysis of all stages of the lifecycle. Furthermore, improved communication between manufacturers, farmers and recyclers is needed to overcome all the presented challenges and scale up found solutions.

3.1.4 Case 4- HFC 134a in household refrigerators.

Background on the use of HFC 134a as a refrigerant

HFC 134a (also known as 1,1,1,2Tetrafluoroethane) is a gas, commonly used as a refrigerant and blowing agent for insulating foam in refrigerators [88], [89]. It is a part of the family of Hydrofluorocarbons (HFCs), currently the most used type of fluorinated gases [90], [91]. When used as a refrigerant, HFC 134a is contained and flows through the components of the hermetically sealed cooling unit of the refrigerator [92], [93]. When used as a foaming agent, HFC 134a remains contained within the cells of the polyurethane foam that forms the insulation walls of the refrigerator [92], [93].

Temperature exchange equipment, the category in which refrigerators fall in according to the WEEE Directive [32], accounted for 20.14% (10.8Mt) of the total global waste of electrical and electronic equipment (WEEE), which was estimated to reach 53.6Mt (Europe 12Mt) in 2020 [94]. The environmental impacts of temperature exchange equipment are specifically related to the ozone-depleting substances, and substances with high global warming potential (GWP), which are used as refrigerants and foam blowing agents [95]. These may be released into the environment throughout the lifecycle of refrigerators, with end of life (EoL) being the most concerning stage [95].

Prior to the Montreal Protocol in 1987 [96], and the Regulation (EC) No 1005/2009 [97], the most used substances for refrigerants and blowing agents in cooling equipment were Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), which were identified as ozone depleting substances (ODS) [90], [92]. Through regulation, these refrigerants have been replaced for Hydrofluorocarbons (HFCs), which are not ozone depleting substances but are greenhouse gases and have a high global warming potential (GWP) [90], [92].

Although HFC 134a is considered non-toxic and non-flammable (under normal temperature and pressure conditions), and no significant human health risks are expected from exposure to it (except for overexposure) [98], [99], its high GWP makes it an important contributor to radiative forcing, hence climate change [91],[100].

In 2016 the Montreal Protocol was amended to reduce greenhouse gas emissions, particularly focusing on reducing the production and use of HFCs [101]. In Europe, the Regulation (EU) (No 517/2014) [102] was implemented in 2014, establishing conditions to place fluorinated gases with high Global Warming Potential (GWP) in the market in certain applications and quantities, as well as regulating containment, transportation, leakage, recovery, and destruction. Due to this, manufacturers have found alternatives with lower GWP in comparison to HFCs, as well as implemented measures to comply with the regulations concerning the production, use and EoL of refrigerators and other cooling appliances [90].

Most relevant emission/exposure scenarios

Emissions of HFC 134a are mostly discussed in regard to leakages, which can vary over time and quantity, making them hard to quantify [93]. Out of the total HFC 134a emissions in the EU in 2005, it is estimated that 71% originate from refrigerant fluids and 8% from foams [93]. In general, HFC 134a is expected to be emitted into the atmosphere almost exclusively, where it is expected to remain for several years with an atmospheric lifetime of ~12 years [103]. Emissions into wastewater and water bodies are expected to volatilize. It is also not expected to accumulate in any form of organism nor to be absorbed by soil [99].

Exposure scenarios are normally of low or no concern [99]. In case of spillage it is recommended to wear personal and respiratory protection [99]. Overexposure via inhalation can cause central nervous system depression and cardiac sensitization [98].

Concerning emission scenarios include:

- Losses while filling up the hermetic cooling unit during production [93].
- Losses during the blowing process of insulation foams during production [93].
- Leakage from hermetically sealed cooling units during the use phase due to damaged, when frequently serviced, or when components are of low quality [93].
- Loses and leakage caused by inappropriate treatment and disposal of cooling and refrigerating equipment waste[104]. Including leakages during the process of extraction and storage of the refrigerant, accidental breakage or faulty operations and components, and the shredding of the foam components in uncontrolled environments, which causes the blowing agent to be released freely into the atmosphere [32], [92], [105], [93], [104].

Design Insights

Found strategies, evaluating benefits and drawbacks

Table 10 provides a summary of the identified SbD strategies and their potential benefits and drawbacks according to literature and the RA, and LCA assessments carried out by the researchers when applicable.

Table 10. Summary of identified SbD strategies for HFC 134a in refrigerators

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with HFC 134a in household refrigerators				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential drawbacks
Avoid / Eliminate	Substitution of HFC 134a as a refrigerant	[QE]	- Substitution with natural refrigerants and hydrocarbons may eliminate emissions of Ozone Depleting Substances (ODS) as well as substances with high GWP and long atmospheric lifetimes [106], [107].	- No substance found to fulfill All three following characteristics: no Ozone Depleting Potential (ODP), low Global Warming Potential, flammability, toxicity, and energy efficiency [91], [106], [108]. - Reduced energy efficiency could lead to an increased indirect environmental impact [91].
	Substitution of HFC 134a as a blowing agent	[QE]	- Substitution with hydrofluoroolefins (HFOs), and natural inert gases, such as CO2, nitrogen, and hydrocarbons may eliminate emissions of ODS as well as substances with high GWP and long atmospheric lifetimes [106], [107].	- Higher costs in comparison to HFCs and require changes in the production methods [107]. - Risk of explosion and high flammability in the case of HCs, making it challenging to use safely in the use phase and during recycling processes [104]. - No substance found to fulfill All three following characteristics: no Ozone Depleting Potential (ODP), low Global Warming Potential, flammability, toxicity, and energy efficiency [91], [106], [108].
Control/Prevent	Hermetic cooling units	[QE]	- If working as expected, hermetic systems can avoid emissions of refrigerant from the cooling system completely [93], [109].	- Leakage can occur due to faulty or loose components such as joints [93]. - Leakage can also occur when the system is serviced since it need to be punctured to re charge or release refrigerant [93].
	Leakage detection systems	[QE]	- Could detect and warn when leakages occur to be attended promptly [110].	- Only applied in commercial refrigerating equipment [110].
	Controlled recovery, WEEE and collection of refrigerants	[QE]	- Refrigerants are collected to be recycled of destroyed, avoiding emissions of improper disposal [32], [92], [104].	- Emissions can still occur during the extraction process, due to faulty components or operations, since the cooling system needs to be punctured [92], [105], [93].

				- Emissions can also occur when the cooling system breaks due to transportation or manipulation without care leakage [104].
	Collection of blowing agents	[QE]	- Blowing agents are collected during the shredding process to then be recycled or destroyed, avoiding emissions of improper disposal [32], [92], [104].	- Challenging process that can only be performed by specialized treatment plants due to explosion risk [92], [104].
	Improving systems for extraction and recharge of refrigerants	[QE]	- The inclusion of a valve could avoid the need of puncturing the hermetic cooling system and avoid leakages during servicing and recycling processes [92].	- The cooling system is hermetic by regulation [102]. - The valve could increase risks of leakage during the use phase [92].
	Strengthening or protecting the components of the cooling system.	[QE]	- Protecting these components could prevent leakage cause by breakage when the equipment is not transported or handled with care [92], [104].	- Unknown consequences of this strategy over additional materials, costs, and ease of disassembly.
Reduce	Reducing the amount of refrigerant gas.	[QE]	- Reducing the overall amount of refrigerant in a cooling system has been mentioned as a way of reducing emissions and facilitating recycling processes [92], [93].	- The reduction is limited, since the mass of the refrigerant influences the energy efficiency of the cooling appliance [92]. - Reduced energy efficiency could lead to an increased indirect environmental impact [91].

Design strategies

Regulations have largely influenced the strategies that are currently being implemented to deal with HFC134a (and refrigerants and foaming agents in general) in refrigerators. Establishing norms and standards to control, reduce and eliminate emissions from HFC 134a, throughout the lifecycle of the product (with a focus on EoL), incentivizing substitution, and defining the design of refrigerating equipment and their components, as well as their production and recycling processes. This can explain why most of the strategies found during this study focus on controlling and preventing emissions of HFC 134a, including improvements in the engineering of the cooling systems to reduce leakage, better containment strategies/engineering, and controlled recovery of refrigerants and blowing agents at end of life.

Substitution of both, refrigerants and blowing agents, is a repeatedly found strategy. Substitution, however, comes with different tradeoffs with recommendations and regulations requiring no ODP, low GWP, low/no flammability, low/no toxicity, and comparable or improved energy efficiency to existing systems. These tradeoffs need to be further analyzed to avoid potential consequences throughout the different stages of the lifecycle of the refrigerator and indirect environmental impact.

Role of designers
Although designers may not directly influence the substitution of the refrigerant/blowing agent, they can focus on facilitating the use of the alternative substances in the product. The analysis of substitution tradeoffs can provide designers with further information over points of improvement of the product design and engineering, or the processes and systems around it.

As an example, current substitution strategies are focusing on the use of natural inert gases including CO_2 and HCs, such as Cyclopentane. Some of these substances are not ODS and have 0 GWP but may pose other challenges regarding safety due to possible risks of explosion during the use phase and recycling phase. To make the use of these substances possible, designers and engineers must update the design of refrigerators to mitigate the newfound risks as well as meeting the energy efficiency requirements. Similarly, reducing the amount of refrigerant gas also provides a design challenge to guarantee the energy efficiency of the appliance.

Additionally, designers could further explore elimination strategies by substitution of function, an example is the exploration of alternatives to guarantee the insulation of refrigerators without the use of foams (and their foaming agents).

Strategies to control/prevent emissions of HFC 134a also appear to be strongly related to the design of specific components to avoid leakages. These are relevant strategies for designers to further analyze. For example, the addition of a designated valve for servicing and extraction of refrigerants poses a challenge of possible emissions during the use phase, touching upon topics of design for safe repairs. While strengthening the refrigerator components to avoid breakage during transportation and recycling processes, may pose a challenge to avoid the unnecessary use of additional materials.

Limitations and challenges
One of the challenges identified for this case is the management and analysis of the tradeoffs of substitution. No alternative to HFC 134a has been identified to fulfill all the following characteristics: no Ozone Depletion Potential, low Global Warming Potential, no flammability, no toxicity, and energy efficient. The use of an alternative with all mentioned characteristics would avoid indirect environmental impacts, increased costs in comparison to currently used substances and processes, and safety risks during the use phase and recycling processes.

One of the most mentioned challenges in other cases, is the communication across stakeholders in the supply chain, and availability of information over substances of concern and their alternatives. In the case of refrigerants, it is notable that regulation addresses specific information requirements over substances and defines specific guidelines for the different stakeholders to follow, about the design of refrigerating equipment and the corresponding processes, facilitating and standardizing communication across the supply chain.

3.1.5 Case 5 – PFAS (Per- and polyfluoroalkyl substances) in synthetic textiles – Outdoor apparel

Background on the use of PFAS in synthetic textiles
Per- and polyfluoroalkyl substances, also known as PFAS, are a large group of man-made chemicals, widely used in industrial and consumer applications since the 1940s [112], [113] (over 4000, with ECHA's database containing information of over 2,000 individual PFAS on the EU market [111]). The use of these chemicals has gained popularity due to their durable water, oil, and grease repellent properties, as well as their high thermal stability [112], [113], [114]. Their oil, stain, and water repellency qualities make PFAS especially popular within the textile sector, which studies have calculated to account for approximately 50% of the total global use [120]. A study estimated 45,000 to 80,000 tones of the total PFAS use in Europe are consumed in textiles, with home textiles accounting for 50-53% and consumer apparel 34-39%, other application categories include professional apparel and technical textiles [113], [117].

Some PFAS have seen an increase in global and local regulatory action in recent years due to human health and environmental concerns [112], [113], [114]. With local regulations and international agreements to phase out, control the production, reduce the placing on the market, and control the EoL of different sub-groups of PFAS [8], [111], [11], [115], [116]. PFAS are considered "forever chemicals" and have been found to be resistant to degradation, making them highly persistent in the environment; they are ubiquitous, being found in air, soil, water, plants, and organisms, and are also of concern due to their long-range mobility across the environment; they are bioaccumulative, and have been found to have diverse effects on wildlife and human health, including cancer, development effects during pregnancy, liver toxicity, reproductive harm, immunotoxicity, and endocrine disruption among others [112], [114], [117], [118]. In addition to regulatory and innovation actions to eliminate these substances, PFAS remediation has become a field of increasing interest to develop technologies that isolate and/or remove PFAS from contaminated environments [114]. PFAS have different characteristics and functions, making it challenging to study their specific potential human health and environmental risks, as well as identifying and classifying them [119].

The outdoor apparel sector uses PFAS to impregnate textiles and produce membranes that are dirt and water repellent to be used in shoes, jackets, backpacks and tents [120]. PFAS are released into the environment throughout all stages of the lifecycle of textile products, causing a number of exposure routes [117]. Even though a number of alternatives are available, including substitutes (e.g., paraffin and silicone based chemicals) and non-chemical alternatives (e.g., tight weaving) the use of PFAS in textiles prevails in certain applications [120]. Additionally, the presence of PFAS in textile products has been identified as a barrier to recycling and the circular economy, since they are difficult to trace and separate from textile fibers and may remain in products produced with contaminated materials [120].

Studies have found interest of a number of stakeholders across the textile industry in eliminating the use of hazardous substances, including PFAS, emphasizing the need for safe substitutions, classification and limited use, to lift the barriers for recycling and produce safe products for the circular economy [121].

Most relevant emission/exposure scenarios

PFAS are released from textile products in all environmental compartments (air, water, wastewater, soil) through several release mechanisms (volatilization, leaching, migration, mechanical wear of textiles) throughout the lifecycle [112], [113], [117], [122], [123], [124], [125]. The most concerning emission scenarios are, in order of relevance, production (chemical production and garment manufacturing), landfill, and use phase (wear and tear, laundering) [113]. People are directly exposed to PFAS through several possible channels, including inhalation, ingestion, and skin contact, with occupational exposure during chemical production, indirect exposure through contaminated water and food, and inhalation of indoor and outdoor air/dust being of most concern [122], [123]. In addition, PFAS continue to accumulate in organisms and in the environment adding to concerning indirect exposure scenarios.

Design Insights

Found strategies, evaluating benefits and drawbacks

Table 11 provides a summary of the identified SbD strategies and their potential benefits and drawbacks according to literature and the RA, and LCA assessments carried out by the researchers when applicable.

Table 11. Summary of identified SbD strategies for PFAS in textiles (outdoor garments).
Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with PFAS in textiles (outdoor garments)				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential drawbacks
Avoid / Eliminate	Substitute with per or poly fluorinated substances with shorter carbon chains	[QE]	- Lower environmental impact compared to long chain PFAS [113].	- Persistent in the environment, bioaccumulative and concerning water contaminants [112], [126], [127]. - Information about effects on human health and the environment remains unavailable [112].
	Substitute with non-fluorine containing	[QE]	- Similar water repellency to	- Oil and stain repellency remain low, not suitable for

	substances: Polyurethanes, Dendrimers, Silicones, Hydrocarbons, and paraffin		long and short chain PFAS [128].	high performance applications [126], [128]. - Durability of water repellency is a concern [129]. - Hazards and effects on human health and the environment are unknown for some alternatives [113]
	Substitute with non-chemical techniques: weaving and fiber control	[QE]	- High quality durable water repellency [113], [8]. - Self-cleaning performance, expected to reduce laundering, preserving the functional performance of the garment [2].	- Do not provide oil repellency [113], [8]. - Weaving techniques result in non-stretching textiles. These may not provide the comfort required by the different applications [130], [131].
	Phasing out PFAS by re-evaluating functional requirements	[QE]	- Phase out all applications where alternatives are available or where the functionality of PFAS is not needed [117], [int].	N/A
Reduce	Increasing the useful life of textile products – waste prevention	[QE]	- The strategy captures value and designs out waste and pollution in the textile industry, specifically relevant for emissions in production and EoL [132].	- Does not target emissions during the use phase.
	Reduce PFAS emissions from washing – washing instructions for users	[QE]	Reduce the release of PFAS during laundering and prevents the need to replenish the water repellent treatment [113], [int].	- Focuses on the use phase exclusively

Design strategies

With such a large variety of release mechanisms and exposure channels as well as their accumulative and persistent characteristics, the strategies to deal with PFAS cannot be targeted on the basis of one scenario or product lifecycle stage in specific. Most strategies found in this case focus on elimination of the substance by substitution, with several substitutes having similar effects on human health and the environment as PFAS or unknown effects on health and the environment that need further research.

Additionally, no substitutes have been found to have equal performance characteristics to PFAS. Therefore, the focus should shift away from finding a suitable PFAS substitute. Efforts should focus towards a re-evaluation of desired properties for different applications and the development of solutions that specifically target those.

Reduce strategies target specific emission scenarios neglecting other stages of the lifecycle. Additionally, their effectiveness in reducing PFAS emissions is unknown.

The role of designers

Although designers may have limited influence over the substitution of PFAS with alternative chemicals, further research and efforts could go into designing products that counteract some of the drawbacks of PFAS substitution and elimination through the re-evaluation of essential applications. These drawbacks include durability, performance issues, and lack of elasticity of the textiles.

In addition to that, designers also need a better understanding of PFAS and their potential alternatives, to be able to communicate in a transparent and effective way with suppliers. Some manufacturers were found to have internal policies that include adherence to restricted substances lists and educational programs for their development teams. Internal processes such as these are relevant for informed and safe substitution and elimination strategies.

Designers have a larger contribution space within strategies that aim to reduce the amount of PFAS emissions through the extension of the useful life of textile products, including repair, remanufacturing and business models that make clothes available to consumers through rental and leasing.

Limitations and challenges

Some of the mentioned challenges to deal with PFAS in textiles found in this study include, 1) Communication and transparency issues between PFAS and textile producers, and brands / manufacturers, 2) Lack of understanding and information about PFAS, including their classification and effects, and possible substitutes, 3) The lack of alternatives with similar performance characteristics has pushed manufacturers to continue to use PFAS for certain applications.

The elimination of PFAS and other substances of concern in textiles overall requires a collaborative approach across the supply chain since a great deal of innovation and development is needed to overcome all the presented challenges and scale up found solutions.

Several recommendations were found through literature and manufacturers reports to overcome these challenges, including 1) PFAS elimination policies and regulation, 2) Re-evaluating the essentiality of PFAS, 3) Improved transparency and communication within the supply chain through education and internal policies, 4) Availability of and further information about PFAS, their effects, classification etc., 5) Research and development of safe alternatives.

3.2. Map of found strategies - Proposal of SbD strategy categories

Table 12. Shows a summary map of all found strategies in the 5 different cases classified by the initially proposed classification, (Avoid/Eliminate, Reduce, Control/Prevent). The table shows a clear trend for *Avoid/Eliminate* as the preferred type of strategy to deal with SoC, very commonly by substitution of additives and/or materials, followed by *Control/Prevent* strategies, and last by *Reduce* strategies.

Table 12. Map of identified SbD strategies in all 5 cases, under the proposed categorization.

Type of strategy	**1) Identified SbD strategies, DEHP in cables**	**2) Identified SbD strategies, DEHP in flooring**	**3) Identified SbD strategies, microplastics from mulch films**	**4) Identified SbD strategies, HFC 134a in refrigerators**	**5) Identified SbD strategies, PFAS in textiles**
Avoid / Eliminate	Substitution of DEHP by another phthalate-based plasticizer	Substitution of DEHP by another phthalate-based plasticizer	Substitution of material by photodegradable and biodegradable mulch films	Substitution of HFC 134a as a refrigerant by natural refrigerants and hydrocarbons.	Substitute by per or poly fluorinated substances with shorter carbon chains
	Substitution of DEHP by a non-phthalate-based plasticizer	Substitution of DEHP by a non-phthalate-based plasticizer	Substitution of material by paper mulch	Substitution of HFC 134a as a blowing agent by hydrocarbons	Substitute by non-fluorine containing substances
	Substitution of material – halogen free alternatives	Substitution of material – Polymers and bio composites	Substitution of material by Biobased alternatives		Substitute by non- chemical techniques: weaving and fiber control
	Delivering function differently – Wireless charging				Phasing out PFAS by re-evaluating functional requirements
	Substitution of function/material Rigid cables				
Control / Prevent	Controlled / regulated recovery – WEEE Directive	Preventing emissions with coatings	Reduce mechanical degradation – less machine input	Hermetic cooling units	
	Prevent exposure – preventing mouthing	Controlling emissions - improving air quality	Mulch recovery systems	Leakage detection systems	
		Controlled recovery for controlled landfill and incineration	Recycling of used agricultural mulch films	Controlled collection – WEEE and Collection of refrigerants	
		Recovery and recycling of post-installation waste		Collection of blowing agents	
		Monitoring and recycling of post-consumer waste		Improving systems for extraction of refrigerants	
				Strengthening the components of the cooling system	

Reduce	Cable type harmonization to USB-C	Increasing the useful life – Guiding product selection	Reduce overall use – intermittent use and variation in crop types	Reducing the amount of refrigerant gas	Increasing the useful life of textile products – waste prevention
	Extending useful life – Repair with sleeves	Increasing the useful maintenance and repair			Prevent PFAS emissions from washing – washing instructions for users
	Extending useful life – Durable cables.				

3.3. SbD approaches in other fields and industry

This section contains the results of the exploratory investigation done to identify how SoC are dealt with in other fields, such as green chemistry, and safer chemicals initiatives. Additionally, approaches and tools used by the industry to tackle SoC in their products are also investigated.

3.3.1 Approaches in the industry

Through the research of the case studies, several approaches were identified to be applied by the industry to that support strategies to avoid/eliminate, reduce, and/or control/prevent the use of SoC in their products. These approaches consist of internal processes and policies, as well as external tools (e.g., certificates), that support the substitution or phase out of the SoC and facilitate the communication amongst development teams, manufacturers, and suppliers. The following actions have been found to be applied by companies as part of their larger, internal environmental programs:

a) Restricted Substances Lists (RSLs) and Manufacturing Restricted Substances List (MRSL)

Some companies within the case study investigation were found to use these or similar types of restricted substances lists, including the case of DEHP in cables and PFAS in synthetic textiles [133], [134], [43], [44]. RSLs and MRSLs are created by companies to avoid the use the listed substances. These lists go beyond compliance with various substance restricting regulations. They include additional substances which are currently not (yet) regulated, further supporting elimination strategies.

RSLs refer to the composition of the final product and define substances that should be completely avoided or have restricted content values. MRSLs differ from RSLs by considering the presence or use of certain substances during the manufacturing process. These lists allow companies to communicate with their suppliers and other stakeholder across the supply chain to avoid the listed substances as well as to make their own development teams aware of their potential presence.

b) Certification systems for materials and processes

Certification is an industry tool to communicate whether a process, material, or product meets a certain standard. In the case of substances of concern, certificates are used as a form of guarantee that certain substances are not present in a material or product, or that the risks that certain substances pose to the environment or human health were eliminated or below a threshold still considered acceptable.

Certificate systems aim to aid transparent communication throughout the supply chain. Examples of these certificate systems include Bluesign [135], for the management of harmful substance in textiles, as well as ensuring occupational safety, and the reduction of environmental impacts. Certificates also allow companies and brands to communicate their actions and the safe composition of their products to the public.

c) Testing processes

Some companies choose to implement internal testing processes [133], [134], as well as manufacturing sites evaluations [136], to verify suppliers are meeting the established restrictions (by regulation or by

RSLs) regarding SoC, as well as quality and functional requirements. These actions help guarantee that suppliers are implementing the restrictions established in agreement with companies.

d) Industry collaboration schemes

In some cases, different stakeholders in a certain industry organize themselves in the form of associations, to achieve a common goal. These associations allow the collaboration amongst organizations with similar goals, to share and generate knowledge (including assessment tools, videos and podcasts, blogs, research outputs, etc.). These collaborative efforts may be beneficial when dealing with substances of concern to distribute the burden of the technological, or research challenges when dealing with SoC, amongst the partners, accelerating the development of potential solutions. Examples of these include the Outdoor Industry Association [137], and the Sustainable Apparel Coalition [138].

e) Phase out / evaluation processes

Some companies were found to apply assessment methods to reevaluate the need for certain substances in a product depending on its application and the specific functional requirements. This was particularly used in the case of PFAS in textiles, where the use of PFAS is proposed exclusively for critical or essential applications [117], [129], [139].

The reevaluation of the presence of SoC and the function they fulfill, poses the opportunity to reframe substitution as a strategy. Instead of focusing on the substitution of a certain substance with substances with similar functional characteristics, which can cause regrettable substitutions, the focus now shifts into designing to fulfill a desired function, making elimination an opportunity for innovation [140].

3.3.2 Approaches in Green Chemistry, Green Engineering, and Safer Chemicals

The ways in which other fields deal with SoC was briefly investigated to identify and study their proposed frameworks and methods to find overlaps and useful resources for design practice.

a) Green Chemistry and Green Engineering

Green Chemistry is a concept aiming for the reduction and prevention of pollution through chemistry [141]. Its goal is to guide chemists and engineers in the development of chemicals and chemical processes that do not generate hazards, hazardous waste, intermediates, or byproducts [141]–[143].

The 12 Principles of Green Chemistry were created in order to provide a framework to support the design of greener chemicals, chemical processes, and products [144]. Subsequently, the 12 principles of Green Engineering were proposed, with the intention of combining science and technology for sustainable development, and guiding engineers when designing non harmful chemicals, products, processes, and systems in an industrial setting [145]. The Green Engineering principles are primarily targeted at chemical engineers [143], although its original intention was for them to be applied by a diversity of fields and disciplines [145]. These principles were also presented as a way to approach complexity, by designing in an integrated way and considering also the system in which substances are used (considering impacts throughout the whole lifecycle) [145].

Tables 13 and 14 present the 12 Principles of Green Chemistry and the 12 Principles of Green Engineering together [144], [145], [146]. The principles have been adapted and other principles have been added since their creation, but the presented version remains valid. The principles considered relevant for dealing with SoC in products are highlighted in green.

Table 13. The 12 Principles of Green Chemistry. The text marked in Italic marks direct citations of the principles. Other pieces of text provide further explanation of the principle whenever possible. Marked in green are those principles that were found relevant to deal with SoC in products.

Green Chemistry Principles	
1	*Prevention: It is better to prevent waste than to treat or clean up waste after it has been created.*
2	*Atom economy: Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.*
3	*Less hazardous chemical syntheses: Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity.*

4	*Designing safer chemicals: Chemical products should be designed to affect their desired function while minimizing their toxicity.*
5	*Safer solvents and auxiliaries: The use of auxiliary substances should be made unnecessary wherever possible and innocuous when used.*
6	*Design for energy efficiency: Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.*
7	*Use of renewable feedstocks: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.*
8	*Reduce derivatives: Unnecessary derivatization should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.*
9	*Catalysis: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.* Reagents are substances that change the velocity of a reaction. A stoichiometric reagent is consumed during the reaction, as opposed to catalytic reagents, which are not consumed in the reaction, making it possible for them to be recycled indefinitely, avoiding the generation of waste.
10	*Design for degradation: Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.*
11	*Real-time analysis for pollution prevention: Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances*
12	*Inherently safer chemistry for accident prevention: Substances and processes should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.*

Table 14. The 12 Principles of Green Engineering. The text marked in Italic marks direct citations of the principles. Other pieces of text provide further explanation of the principle whenever possible. Marked in green are those principles that were found relevant to deal with SoC in products.

Green Engineering Principles	
1	*Inherent rather than circumstantial: ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.* Although the consequences of hazardous substances can be minimized and somewhat controlled, the idea is that inherently benign substances prevent failure throughout the lifecycle.
2	*Prevention instead of treatment: It is better to prevent waste than to treat or clean up waste after it is formed.*
3	*Design for separation: Separation and purification operations should be designed to minimize energy consumption and materials use.*
4	*Maximize efficiency: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.*
5	*Output pulled versus input pushed: Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials* The intention is to minimize the amount of resources consumed to transform inputs into the desired outputs.
6	*Conserve complexity: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.* Products with high complexity are more suitable for reuse, while simpler products may be more suitable for recycling.
7	Durability rather than immortality: Targeted durability, not immortality, should be a design goal. Products that have a longer lifespan than its useful live *could* become a waste problem, resulting in persistence and accumulation. Targeted useful lifetimes and the avoidance of immortality are recommended.
8	*Meet need, minimize excess: Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.*
9	*Minimize material diversity: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.*
10	*Integrate material and energy flows: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.*

	An example of this strategy are regenerative braking systems in electric vehicles, where the heat generated by braking is captured and put back into a battery where it is stored to be used later to propel the vehicle.
11	*Design for commercial "afterlife": Products, processes, and systems should be designed for performance in a commercial "afterlife."* Functional and valuable components should be recovered for reuse to retain their value.
12	*Renewable rather than depleting: Material and energy inputs should be renewable rather than depleting.*

Recently, a new perspective towards Green Chemistry has been proposed that includes the transition from a linear to a circular chemical sector [147]. Proposing to make changes in the entire value chain, improving chemicals and their corresponding processes and products. This includes two main propositions: 1) An integrated systems framework for design and innovation. Intended to produce solutions to meet certain functions without causing unintended consequences elsewhere. 2) Changing the definition of performance, to not only focus on meeting functional requirements but including other aspects such as specific sustainability goals as requirements as well. The extension of the definition of performance requires future chemical products to fulfill specific functions while also being nondepleting (e.g., transitioning from fossil to renewable sources), nontoxic , and nonpersistent (designed to degrade) [148].

b) Safer and sustainable chemicals

The concept of safer chemicals has seen a long history and refers to different strategies applied by different disciplines, to address the concern of the harmful effects of chemicals on human health and the environment [149]. A recent example is the Chemicals Strategy for Sustainability adopted by the European Commission to transition to safe and sustainable chemicals. The strategy is meant to impulse the development of safe and sustainable chemicals and adapt existing policies to be able to meet challenges generated by hazardous substances [150].

This strategy considers, 1) Increasing the protection of health and the environment, 2) Strengthening and developing a knowledge base to support development and policy making, and 3) Encourage innovation for the development of safe and sustainable chemicals [150]. Table 15 presents a summary of the hierarchy of the strategies proposed by the safe and sustainable chemicals vision, prioritizing the use of safe chemicals and avoidance of SoC over remediation strategies.

Table 15. The toxic free hierarchy for chemicals management (part of the safe and sustainable chemicals vision), extracted from: [150]*(P.4).*

Category / Strategies	**Protect health and the environment**	**Encourage innovation**
Safe and sustainable chemicals	Use of safe chemicals, preventing human and environmental exposure and harm. Avoiding SoC in non-essential uses.	Promote the development of safe and sustainable chemicals and materials, and clean production processes and technologies. Develop tools for testing and risk assessments.
Minimize and Control	Minimize exposure of humans and environment to SoC through risk management measures and information to users.	Promote modern production processes, safe and sustainable uses, and business models. Implement IT solutions for tracking.
Eliminate and remediate	Eliminate SoC in waste and secondary raw materials. Restore human health and environment to a good quality status.	Promote safe and clean recycling solutions, chemical recycling, waste management and decontamination solutions.

3.4. Reflection on the SbD strategies and SbD approaches in other fields/industry and their relevance for designers

The investigation of the cases and approaches in other fields and industries delivered relevant information for the development of a SbD approach for designers. The cases showed that dealing with SoC can be a complex task where a number of factors should be considered, including the product-substance combination, its lifecycle, context, and stakeholders around it. Different types of SoC behave differently in a variety of products and their emissions may occur at different stages of the lifecycle through a variety of mechanisms, generating different exposure scenarios for a variety of actors.

Additionally, all the identified strategies in the investigation were found to present challenges, limitations, and in some cases, adverse consequences to their implementation. For example, in many of the analyzed strategies SoC were replaced with substances with similar (or worse) characteristics and hazards. Other strategies were found to have performance limitations or increased costs. Others were found to only be relevant to a certain stage in the lifecycle disregarding other relevant emission/exposure scenarios. To deal with these challenges, to provide effective strategies, and to avoid unintentional consequences an analytical and iterative approach is recommended.

For designers to identify relevant action points when dealing with SoC, an in depth and structured analysis is necessary. Through the investigation of the cases the following elements were identified to form a structured analysis when dealing with SoC:

- Essential information of the SoC, including type, hazards, function, and regulatory status.
- Emission/exposure scenarios per lifecycle stage. Understanding relevant context characteristics and actors and the relations between emission/exposure scenarios.
- The prioritization of emission/exposure scenarios. This is expected to facilitate the development of effective strategies. It does so by focusing on those situations that have the largest effects on human health and environmental impact.
- Detailed analysis of the product-substance combination. Identifying the presence of the SoC in the product, the release mechanisms of the SoC, the aggravating factors of these mechanisms, and the influence of the product architecture on emissions and exposure.

The assessment of the identified SbD strategies performed on each case study had the solely intention of finding their potential benefits or drawbacks, as well as uncertainties over additional potential risks. However, for means of decision making when selecting an alternative strategy a comparative assessment of alternatives and baseline is required.

The investigated approaches in the industry were found to focus on mechanisms of communication that support development teams in the sharing of information with other stakeholders and the monitoring of the presence of SoC in products. However, these were found to be limiting and lack transparency at times. The further development of tools to facilitate the acquisition of information, improve communication across stakeholders, and tools that support designers in dealing with uncertainty is necessary.

The investigation of approaches in other fields found that these propose a hierarchy for the development of strategies to deal with SoC. This hierarchy prioritizes strategies that avoid and eliminate the use of harmful substances over those that reduce or control their emissions. Although those fields focus on materials and chemicals, this hierarchy corresponds to the principles of the circular economy and can be extrapolated into design practice. By guiding designers when selecting and developing strategies to deal with SoC in products.

In order to deal with SoC and develop SbD strategies, designers require a great deal of information. Although designers may be able to obtain enough information for a first approximation through desk research and expert consultation, detailed information is necessary to further develop strategies in later stages of the development process.

4. Results: Preliminary SbD guidelines / approach

This chapter first presents the proposed SbD approach (Section 4.1) followed by an evaluation step (Section 4.2). This evaluation was performed internally by one of the researchers to reflect on the proposed design approach for dealing with SoC, to identify pitfalls, and to provide recommendations for further development of the method

4.1. Proposed approach for designers based on case study experience

An initial recommended approach for designers to deal with SoC resulted from the investigation and case studies. The approach thus considers a series of steps that mimic the structure followed to investigate each case study during this research. These steps aim to first guide the designer through a thorough analysis of the product-substance combination and its context, while considering all stages of the lifecycle. The approach uses the results of this analysis to inform the designer's decision concerning selecting or generating strategies that eliminate, reduce, or control concerning emission or exposure situations. These strategies are then assessed by the designer, guided by a set of recommendations and suggested methods, to select a suitable strategy for their case. First, the purpose of the approach is presented, followed by an overview of the proposed steps, concluding with a detailed description of each step.

Purpose of the approach

This approach intends to support the designer in dealing with SoC in products, to prevent human health and environmental risks, and fit the CE. It can be applied in early stages of the product development process when trying to avoid the use of SoC (design), or when analyzing and redesigning existing products (redesign). The scope of this approach proposes that designers can tackle SoC through the (re)design of the analyzed product, as well as consider design solutions in related products, services, or systems (e.g., designing a controlled collection system). The approach considers cases where the designer is aware of a problematic SoC in the product or new design, as well as when an initial scan to identify SoC is deemed necessary. This is a mostly qualitative approach, although some steps provide basic guidelines to include quantitative data if necessary. The approach is iterative so that designers can build on each iteration. Results from a first iteration should be treated as estimations, to guide following steps of the development process, and facilitate the communication with experts (RA and LCA) and suppliers. Designers are encouraged to repeat the use of this approach until a useful level of detail is obtained.

Overview of steps

Figure 1 provides an overview of the steps suggested for designers to analyze the product-substance combination, its context, possible SbD strategies to deal with SoC, and assess the effects of the strategies.

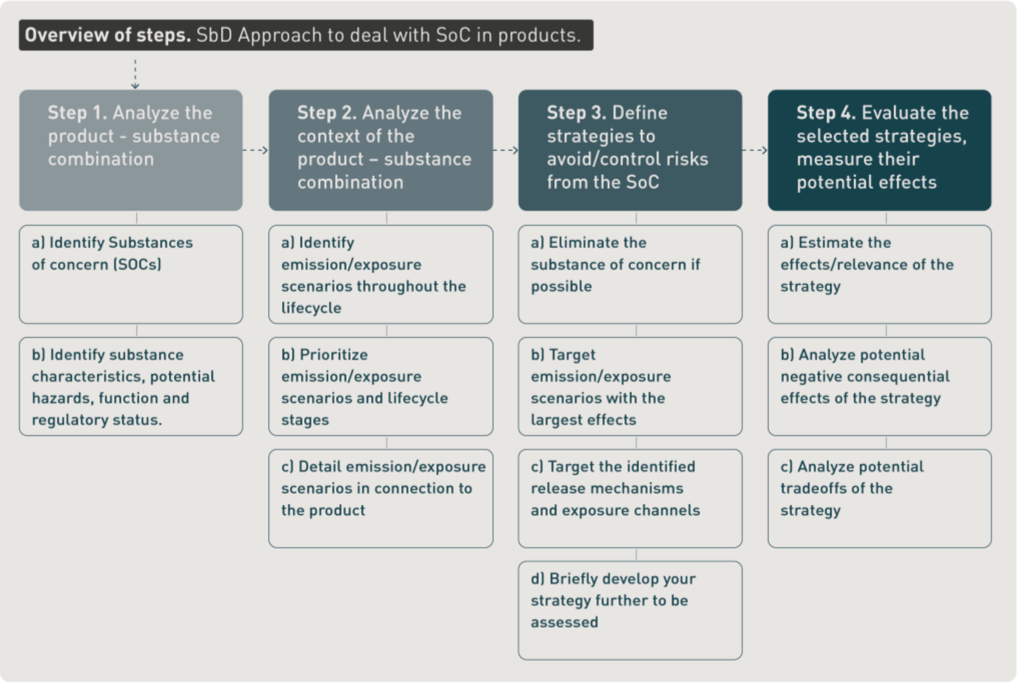


Figure 1. Overview of the stepwise SbD approach to deal with SoC

Detailed description of steps

Step 1. Analyze the product - substance combination

a) **Identify the SoC and its type (if not identified already). Table 16 provides guidance to analyze the product to identify any of the listed SoC types it contains.**

Table 16. Classification of SoC in products

Present in the product – intentionally added *(e.g., additives such as phthalates)*	**Generated by the product – byproducts generated throughout their Use/EoL** *(e.g., secondary microplastics)*	**Used or added temporarily to the product for additional functions but not intended to be present in the end product – Intermediates** *(e.g., formaldehyde added to textiles to reduce creases)*
- Obtain a full material declaration of the product and consider material compositions (i.e., content of a given material and/or substances). - If no data are available, perform testing on the material or product in question to identify the presence of a certain substance. - Review the full material declaration and screen for potential SoC using available sources (E.g., ECHA authorization lists, ECHA information about chemicals and materials, SIN list, etc.).	- Analyze the product throughout its different lifecycle stages to identify if it might generate and release SoC or harmful byproducts that were not intentionally added to its composition.	- Analyze the product throughout its production and processing stages to identify any SoC that may have been added or used but were not intended to remain in its composition for final use.

b) **Describe the substance** characteristics, potential hazards, function in the product, and regulatory status using the questions in Table 17. Designers can use the proposed sources, or other literature and/or experts to find the data.

Table 17. Questions Step 1 and possible sources

Question	**Possible sources**
1. What is the SoC? Name(s), type of substance?	- ECHA information about chemicals [151], SIN List [152], Material Wise [153].
2. What is the substance's function in the product?	- ECHA Guidance on Information Requirements and Chemical Safety Assessment, Chapter R.12, descriptor list for chemical products category and technical functions [154].
3. What kind of hazards does the substance have on human health and the environment?	- ECHA information about chemicals [151], SIN List [152], Material Wise [153], scientific literature (studies on the exposure of humans and/or organisms to the substance, studies that identify the presence of the substance in a certain environmental compartment).
4. How is the substance currently regulated? (Can be found in ECHA). Or is the substance likely to be banned or restricted in the future and therefore not advised for use? (Can be found in SIN List).	- ECHA information about chemicals [151], SIN List [152], Material Wise [153].
5. How much substance is present in the product? (If possible and available)	- Material declarations from suppliers. This information is usually displayed as ppm (parts per million) or in percentages, considering the total weight of the product.

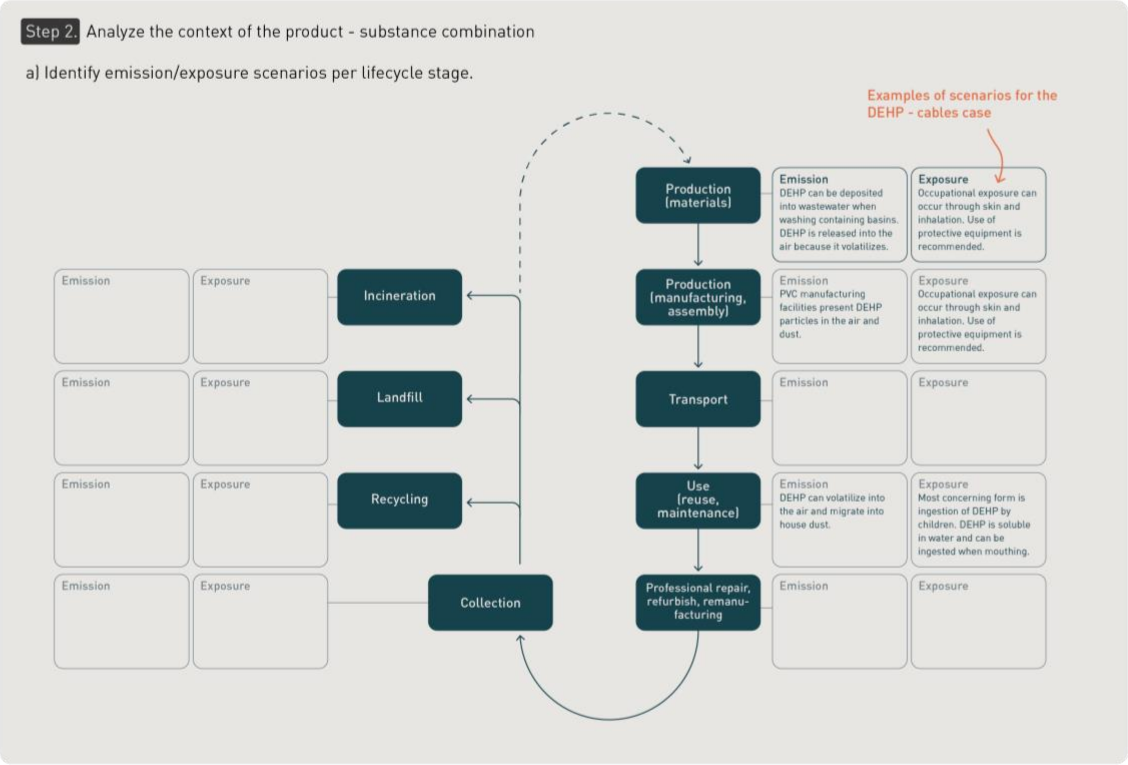
Step 2. Analyze the context of the product – substance combination

a) **Identify emission/exposure scenarios throughout the lifecycle.** Describe the emission/exposure scenarios for each stage of the lifecycle and map the findings using the diagram shown in Figure 2. Use the following questions to guide the analysis. Use literature and/or experts to find the data.

1. **Emissions**
    - i. For each stage: is the SoC released into the environment in this stage?
    - ii. How much is released? If this information is available, are these levels of release concerning? (The units and dimension in which this information is provided may vary from one product-substance combination to another depending on its physicochemical characteristics and emission mechanisms. In some cases emissions are not identified by unit or a particular product, the overall presence of a substance in a specific environmental compartment is measured and the sources of these emissions may not be clarified)
    - iii. In which compartment(s) is the SoC released? (Fresh water, marine environments, wastewater, soil, air, etc.)
    - iv. Through which processes is the SoC released? (e.g., mechanical degradation, volatilization, etc.)
    - v. Is this emission scenario already under control in any form?
    - vi. Does the SoC persist, accumulate, or mobilize, in the environment?

    Note: Substances that are released and resistant to degradation may persist for long periods in the environment, and even mobilize from one place to another. They may also accumulate in living organisms (bioaccumulation). These substances can be classified as Persistent, Bioaccumulative and Toxic (PBTs) [155]. *We suggest consulting ECHA's PBT list initially, however, not all substances may be present. These characteristics may then be noted during the analysis without exclusively following the present PBT classification.*

2. **Exposure**
    - i. Are people (e.g., workers, users) exposed to the SoC in this stage?
    - ii. Are the levels of exposure a reason for concern for human health?
    - iii. Through which channel does exposure occur? (Skin, ingestion, inhalation).
    - iv. Is this exposure scenario already under control in any form?
    - v. Are there any concerning exposure levels in other organisms in the various trophic levels (food chain levels)?
    - vi. Will the release of the substance into the environment cause indirect exposure to humans or other organisms (e.g., substances deposited in air or water can be ingested or inhaled)?



Step 2. Analyze the context of the product - substance combination

a) Identify emission/exposure scenarios per lifecycle stage.

Examples of scenarios for the DEHP - cables case

Production (materials) – Emission: DEHP can be deposited into wastewater when washing containing basins. DEHP is released into the air because it volatilizes.

Production (materials) – Exposure: Occupational exposure can occur through skin and inhalation. Use of protective equipment is recommended.

Production (manufacturing, assembly) – Emission: PVC manufacturing facilities present DEHP particles in the air and dust.

Production (manufacturing, assembly) – Exposure: Occupational exposure can occur through skin and inhalation. Use of protective equipment is recommended.

Use (reuse, maintenance) – Emission: DEHP can volatilize into the air and migrate into house dust.

Use (reuse, maintenance) – Exposure: Most concerning form is ingestion of DEHP by children. DEHP is soluble in water and can be ingested when mouthing.

Figure 2. Example template for Step 2 – a Analysis of the context of the product - substance combination

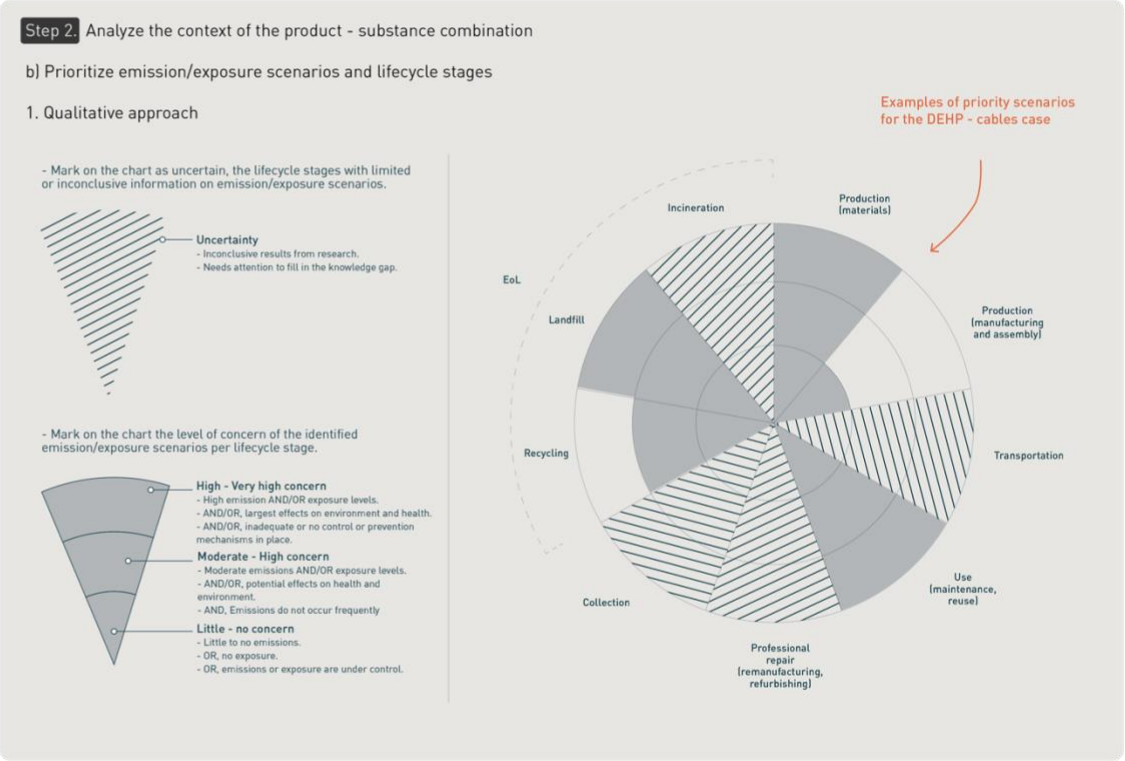
b) Prioritize emission/exposure scenarios and lifecycle stages

1. **Qualitative approach.** Compare the identified emission/exposure scenarios corresponding to each product life cycle stage and prioritize them and their corresponding lifecycle stage according to severity of their effects on human health and the environment.

   Assign a value to all the scenarios following the proposed level of concern (high, moderate, little concern) (Figure 3) and indicate uncertainty when applicable. Base the assessment on experts' opinions and the literature.

   Consider cases where the product and/or its materials and components are expected to have more than one lifecycle. Does the SoC hinder circularity?

   Note: Lifecycle stages marked with uncertainty do not rule out the possibility of concerning emissions or exposure. We recommend discussing these with an expert or initiating forms of research to identify the missing information.



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Emissions do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

Examples of priority scenarios for the DEHP - cables case

Figure 3. Example template for Step 2 - b Prioritizing emission/exposure scenarios

2. **Quantitative approach – Risk Assessment.** Ideally, if sufficient resources and data are available, a Risk Assessment (RA) can be done to estimate the effects of the SoC on human health and the environment and determine the priority risks and priority product life cycle stages. Risk Assessment requires large amounts of data; therefore we recommend involving an expert. An overview of basic concepts is provided in Figure 4 to facilitate the communication between designers and risk assessment experts.

   Three types of chemical risks are relevant through the product life cycle: ecological risk (risks to animals, plants, and microbes in the environment), human health risks (risks to workers in production and waste management sites), and public health risks (risks to the general population who are not workers in production and waste management facilities and consumers of the product). All risks are calculated as ratios of hazard (or safe levels of the SoC) and exposure (or actual levels of SoC); the smaller the exposure in actual conditions is compared to the hazard, the safer it is.

   An emission is the starting point of the occurrence of risk; an activity during the lifecycle may trigger the emission of SoC. For example, washing storage containers holding SoC may lead to emissions of SoC into wastewater. If this SoC binds to wastewater sludge that is eventually applied to farms, it may concentrate in the soil and even travel to groundwater via aquifers. Thus, depending on the SoC's physicochemical properties, fate and transformation in the environment, and environmental management systems, SoC emissions are translated into SoC concentrations in air, water and/or soil.

   Concentrations of SoC in environmental compartments may negatively affect physiological or behavioral endpoints of individual species and the functioning of ecosystems living in these compartments. In the case of human health risk, exposure may occur through the performance of an activity through a particular route i.e., inhalation, dermal, or oral. This exposure may be acute, sub-chronic (30 to 90 days), or chronic (90 days) and cause a local or systemic effect. Exposure assessment estimates the realistic concentrations to which ecological or human heath targets are exposed. Estimated environmental exposure in an ecological context is termed Predicted Environmental Concentration (PEC).

   The hazard determines the safety of the SoC using a quantitative dose response assessment, which aims to establish a relationship between physiological or behavioral response across a range of relevant SoC doses. The threshold of low or no effect levels is adjusted with multipliers that translate experimental measurement to realistic context (e.g., laboratory to field, animal to human). Hazard estimation yields a Derived No Effect Level (DNEL) in the case of a threshold for human health effects. In the case of ecological targets, the Predicted No Effect Concentration (PNEC) corresponding to a single sensitive species or the whole ecosystem is calculated.

   Risk is assessed by comparing exposure to hazard in the case of risk quotient, or vice versa in the case of margin of exposure. Risk characterization for Ecological Risk Assessment involves the comparison of PEC and PNEC; for Human Health Risk Assessment, exposure, and Derived No Effect Level (DNEL), and for Public Health Risk Assessment PEC is compared to DNEL.

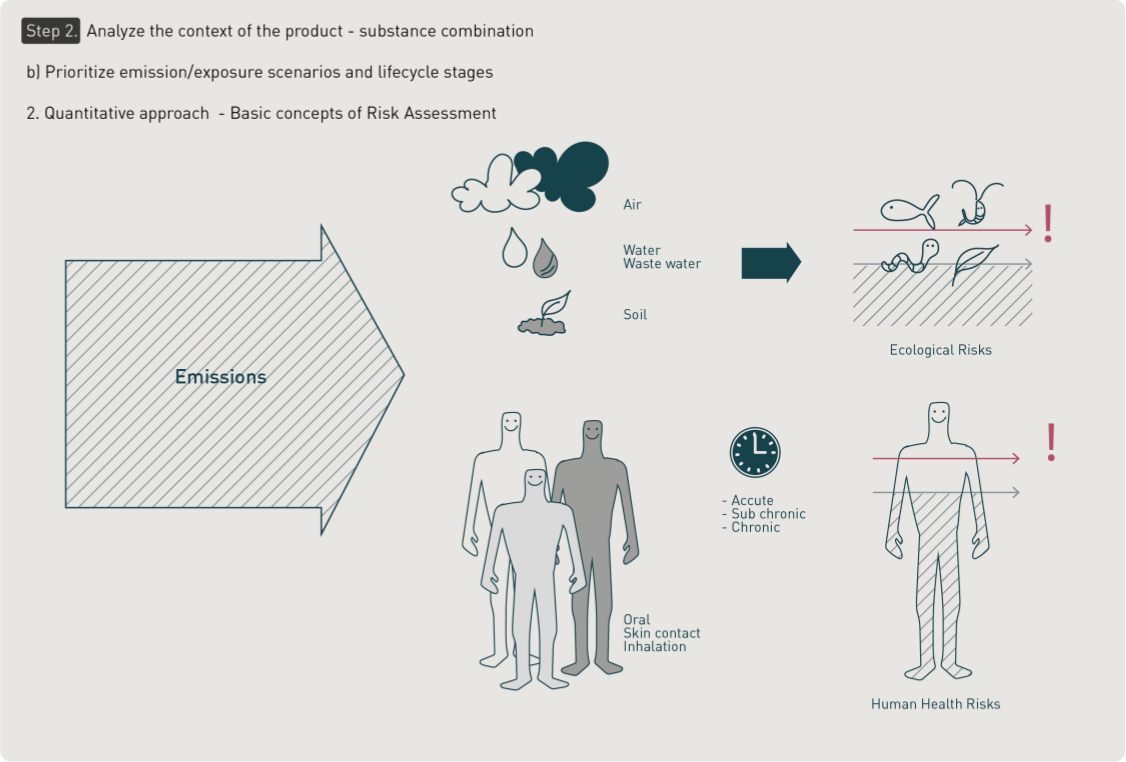


Figure 4. Relevant elements to analyze and prioritize emission/exposure scenarios using risk assessment

c) **Detail emission/exposure scenarios in connection to the product.** This step provides guidelines to connect the findings from the emission/exposure scenarios to the design of the product as a prelude to strategy selection, and detailing. Steps C1, C2, and C3 below provide guidance and examples to identify all relevant information. Figure 5 shows examples of how to illustrate the most relevant emission/exposure scenarios in relation to the product.

1. **Describe the presence of the substance in the product. Tick the boxes.**

Examples of substance presence in the product (several may apply):

☐ Part of the composition of a material
☐ Single material
☐ Composite material
☐ Separable component (non-destructive disassembly is possible)
☐ Non separable component (destructive disassembly is necessary)
☐ Contained/encapsulated
☐ Coated

2. **Identify the release mechanisms of the substance and the input that causes and/or aggravates the mechanism. Tick the boxes.**

Examples of mechanisms of release (several may apply): *ECHA's Guidance on Information Requirements and Chem Safety Assessment, Chapter R.12, can be used as a reference to describe mechanisms of release* [154].

☐ Volatilization
☐ Migration
☐ Leaching
☐ Leakage
☐ Mechanical degradation
☐ UV degradation

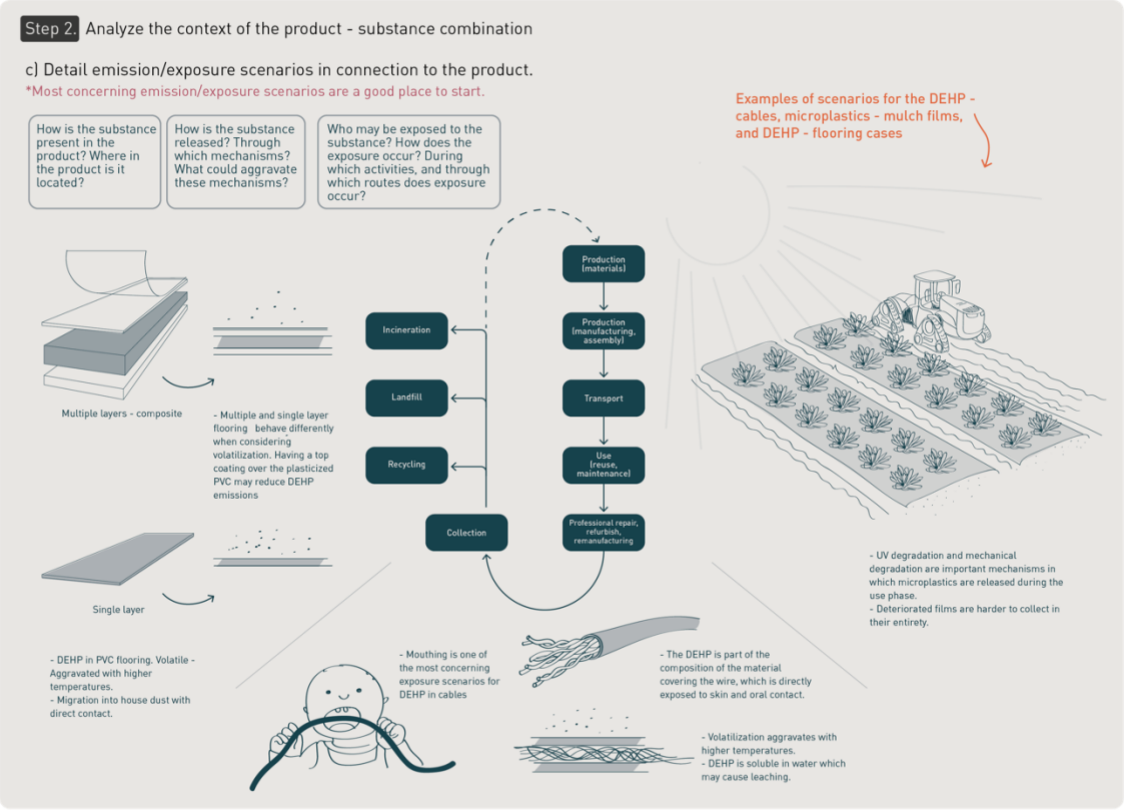
Examples of inputs that may cause or aggravate mechanisms of release (several may apply):

☐ High temperatures
☐ Humidity
☐ Mechanical input (e.g., use, machinery)
☐ User care (e.g., accidental breakage)

3. **Identify exposure channels. Tick the boxes.**

Exposure channels (several may apply):

☐ Ingestion ☐ Inhalation ☐ Skin contact



Step 2. Analyze the context of the product - substance combination

c) Detail emission/exposure scenarios in connection to the product.

*Most concerning emission/exposure scenarios are a good place to start.

How is the substance present in the product? Where in the product is it located?

How is the substance released? Through which mechanisms? What could aggravate these mechanisms?

Who may be exposed to the substance? How does the exposure occur? During which activities, and through which routes does exposure occur?

Examples of scenarios for the DEHP - cables, microplastics - mulch films, and DEHP - flooring cases

- Multiple and single layer flooring behave differently when considering volatilization. Having a top coating over the plasticized PVC may reduce DEHP emissions

- DEHP in PVC flooring. Volatile - Aggravated with higher temperatures.
- Migration into house dust with direct contact.

- Mouthing is one of the most concerning exposure scenarios for DEHP in cables

- The DEHP is part of the composition of the material covering the wire, which is directly exposed to skin and oral contact.

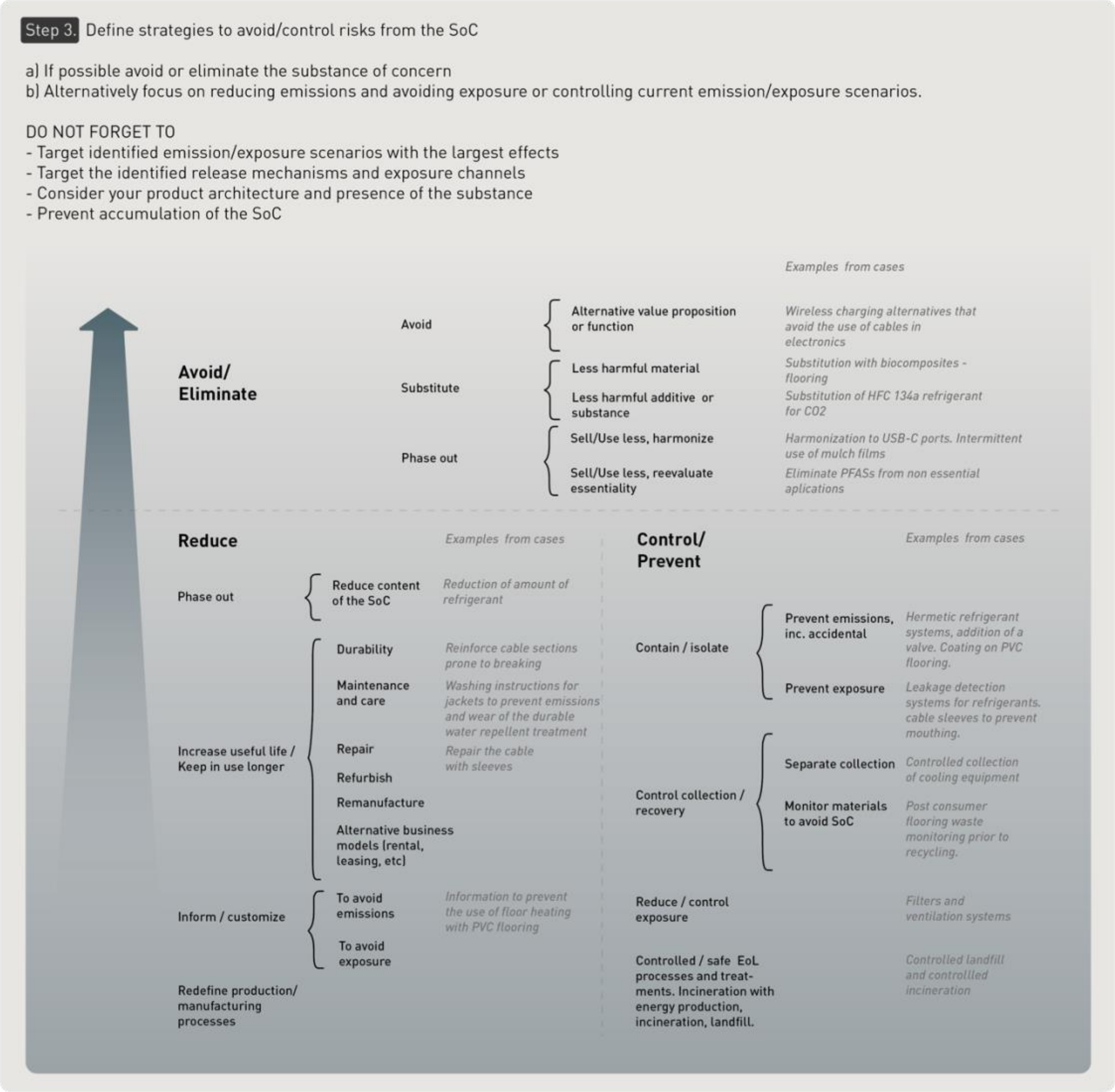
- Volatilization aggravates with higher temperatures.
- DEHP is soluble in water which may cause leaching.

- UV degradation and mechanical degradation are important mechanisms in which microplastics are released during the use phase.
- Deteriorated films are harder to collect in their entirety.

Figure 5. Example template of Step 2 - c with detailed emission/exposure scenarios

Step 3. Define strategies to Avoid/Eliminate, Reduce, and/or Control/Prevent the SoC. Select and/or generate possible strategies to target the findings from steps 1-2. **<u>First consider avoiding or eliminating the substance</u>** through the strategies provided by the list (Figure 6). If that is not possible for your case, explore Reduce and Control/Prevent strategies.

a) Avoid / eliminate the substance of concern if possible
b) Target emission/exposure scenarios with the largest effects
c) Target the identified release mechanisms and exposure channels
d) Briefly develop your strategy for assessment purposes



Step 3. Define strategies to avoid/control risks from the SoC

a) If possible avoid or eliminate the substance of concern
b) Alternatively focus on reducing emissions and avoiding exposure or controlling current emission/exposure scenarios.

DO NOT FORGET TO
- Target identified emission/exposure scenarios with the largest effects
- Target the identified release mechanisms and exposure channels
- Consider your product architecture and presence of the substance
- Prevent accumulation of the SoC

Avoid/ Eliminate

		Examples from cases
Avoid	Alternative value proposition or function	*Wireless charging alternatives that avoid the use of cables in electronics*
Substitute	Less harmful material	*Substitution with biocomposites - flooring*
	Less harmful additive or substance	*Substitution of HFC 134a refrigerant for CO2*
Phase out	Sell/Use less, harmonize	*Harmonization to USB-C ports. Intermittent use of mulch films*
	Sell/Use less, reevaluate essentiality	*Eliminate PFASs from non essential aplications*

Reduce

		Examples from cases
Phase out	Reduce content of the SoC	*Reduction of amount of refrigerant*
Increase useful life / Keep in use longer	Durability	*Reinforce cable sections prone to breaking*
	Maintenance and care	*Washing instructions for jackets to prevent emissions and wear of the durable water repellent treatment*
	Repair	*Repair the cable with sleeves*
	Refurbish	
	Remanufacture	
	Alternative business models (rental, leasing, etc)	
Inform / customize	To avoid emissions	*Information to prevent the use of floor heating with PVC flooring*
	To avoid exposure	
Redefine production/ manufacturing processes		

Control/ Prevent

		Examples from cases
Contain / isolate	Prevent emissions, inc. accidental	*Hermetic refrigerant systems, addition of a valve. Coating on PVC flooring.*
	Prevent exposure	*Leakage detection systems for refrigerants. cable sleeves to prevent mouthing.*
Control collection / recovery	Separate collection	*Controlled collection of cooling equipment*
	Monitor materials to avoid SoC	*Post consumer flooring waste monitoring prior to recycling.*
Reduce / control exposure		*Filters and ventilation systems*
Controlled / safe EoL processes and treatments. Incineration with energy production, incineration, landfill.		*Controlled landfill and controllled incineration*

Figure 6. Examples of possible SbD strategies to deal with SoC

Step 4. Evaluate the selected strategies, determine/estimate their potential effects.

a) Estimate the effects of the strategy on emissions and/or exposure for the prioritized lifecycle stages and emission/exposure scenarios. Use the results of Step 2 - B1 and B2 (prioritization of scenarios) mapped in Figure 3 as a base. Assign a value to the proposed level of concern (high, moderate, little relevance. Plot the level of concern, and all following steps on top of the prioritization results (Figure 7). Base the assessment of the selected strategies on expert opinion and the literature.

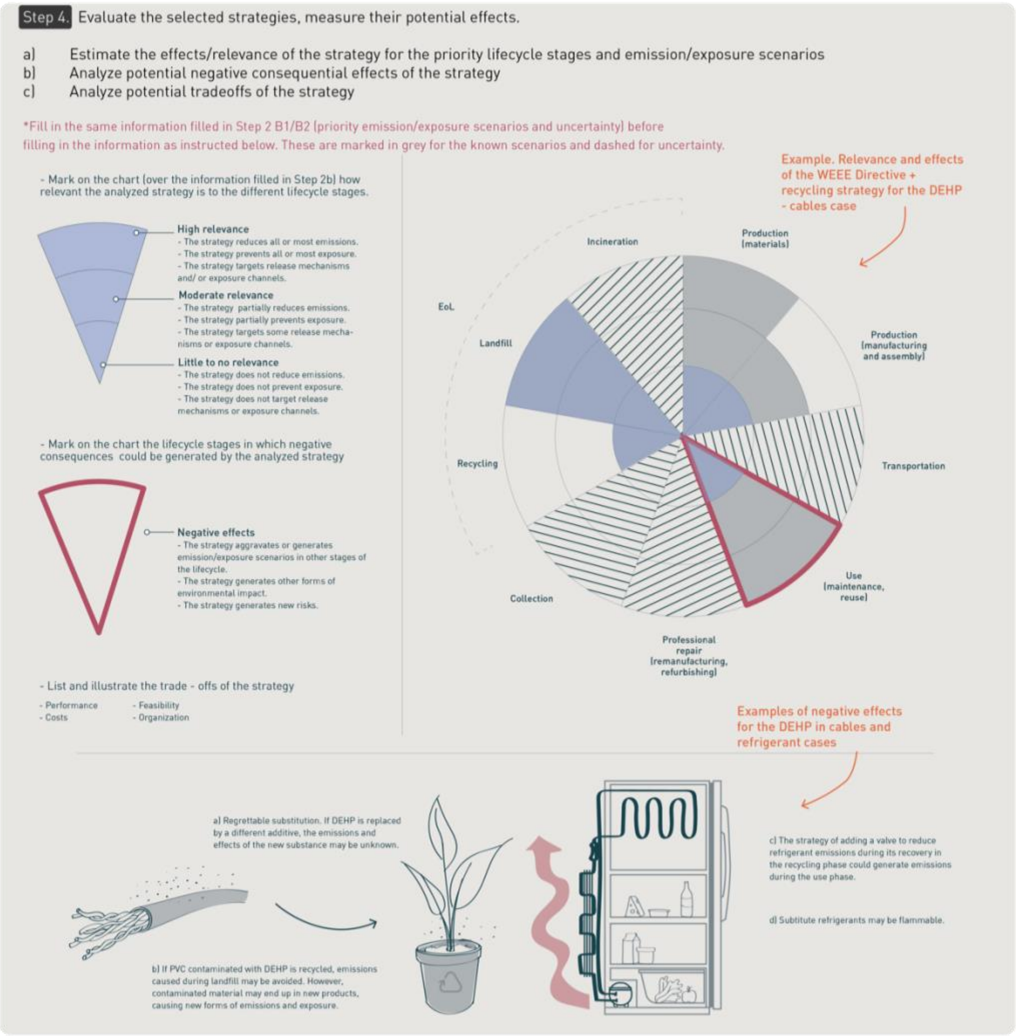
1. Does the strategy reduce/eliminate emissions into the environment?
2. Does the strategy reduce/eliminate exposure?

b) Analyze potential negative effects of the strategy. Mark the product life cycle stage where the strategy has or may have negative effects (Figure 7).

1. Analyze if it aggravates emissions/exposure in other lifecycle stages. Also consider cases where the product and/or its materials and components are expected to have more than one lifecycle. Does the strategy enable or hinder circularity?
2. Analyze if the strategy generates other environmental effects.
3. Analyze if the strategy generates new risks for human health or the environment.

c) Analyze potential tradeoffs of the strategy. These will need discussion and research for the further development and implementation of the selected strategy.

1. Product performance
2. Costs
3. Feasibility
4. Organization (e.g., internal company issues, etc.)



Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.

High relevance
- The strategy reduces all or most emissions.
- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
- The strategy partially reduces emissions.
- The strategy partially prevents exposure.
- The strategy targets some release mechanisms or exposure channels.

Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy

Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy
- Performance
- Costs
- Feasibility
- Organization

Example. Relevance and effects of the WEEE Directive + recycling strategy for the DEHP - cables case

Examples of negative effects for the DEHP in cables and refrigerant cases

a) Regrettable substitution. If DEHP is replaced by a different additive, the emissions and effects of the new substance may be unknown.

b) If PVC contaminated with DEHP is recycled, emissions caused during landfill may be avoided. However, contaminated material may end up in new products, causing new forms of emissions and exposure.

c) The strategy of adding a valve to reduce refrigerant emissions during its recovery in the recycling phase could generate emissions during the use phase.

d) Subtitute refrigerants may be flammable.

Figure 7. Example template that assesses the relevance and possible negative effects of the WEEE Directive (controlled recovery and recycling of charging cables). The evaluation results, in blue and red, are added to the filled template of Step 2 (Figure 3).

4.2. Evaluation of the approach - SbD strategies of additional cases

An internal evaluation of the approach was done by the main researcher of this project, following the steps indicated in the fillable templates (Appendix G). The aim of this evaluation is to 1) Identify any problems with the proposed workflow, 2) Obtain an estimate of the amount of time/effort necessary to complete the steps, and 3) Identify challenges designers may encounter when filling up the necessary data for the analysis and performing the assessment steps.

This section describes the results of the internal evaluation of the SbD approach (Section 4.1). The evaluation was performed using 3 additional case studies:

1) Microplastic release from synthetic textiles
2) PUR foam in sleep and respiratory care devices
3) PFAS in food packaging

The case of microplastic release from synthetic textiles is presented here in its entirety to show the process followed, and the results obtained from the application of the approach. Appendix F contains the results of the three additional cases.

4.2.1 Microplastics release from synthetic textiles

Step 1. Analyze the product - substance combination

a) Identify the SoC and its type (if not identified already).

Table 18. Answers Step 1a

Present in the product – intentionally added	Generated by the product – byproducts generated throughout their Use/EoL	Used or added temporarily to the product for additional functions but not intended to be present in the end-product – intermediates
	Microplastics released from synthetic textiles originate from the abrasion of the textile, which causes the unintentional release of small plastic particles or fibers directly into the environment [156].	

b) Describe the substance. Answers to the questions in Step 1b are shown in Table 19.

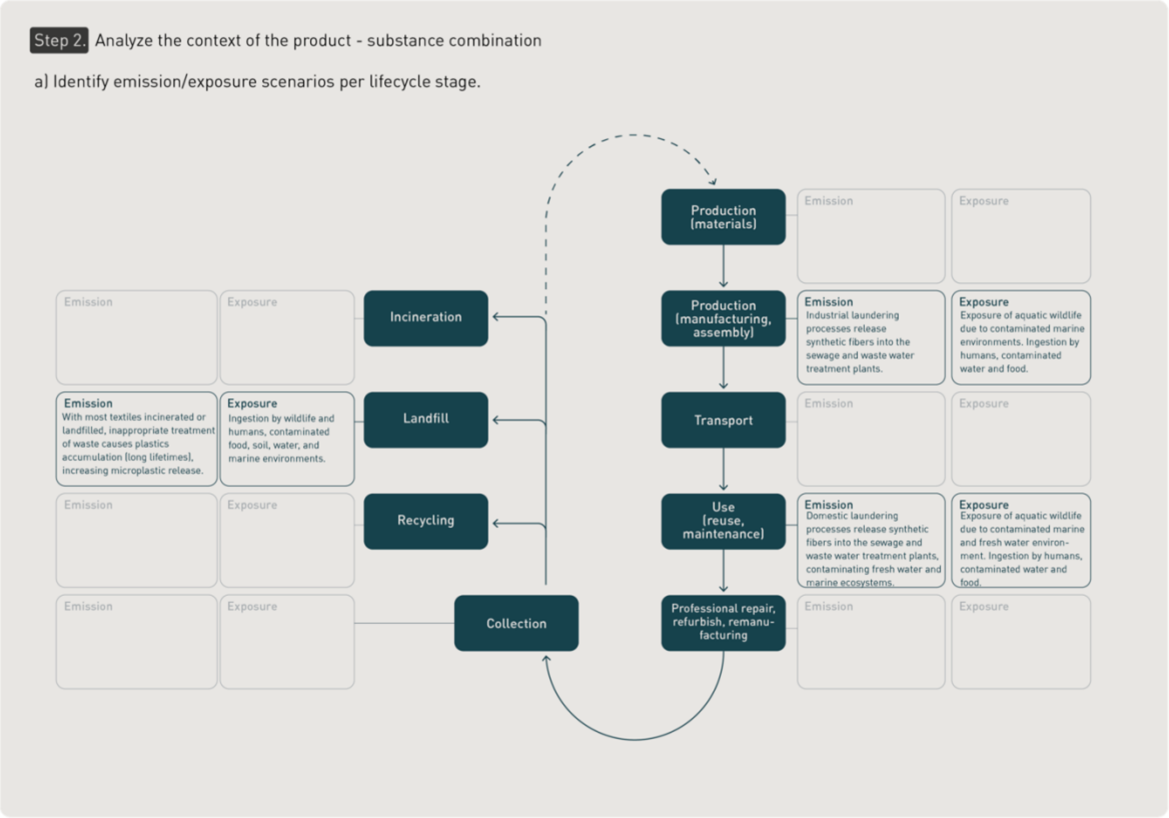
Table 19. Answers Step 1b

Question	
1. What is the SoC? Name(s), type of substance?	Microplastics are defined as small plastic particles of less than 5mm in diameter, released into the environment from plastic products [73], [74]. In the case of synthetic textiles, microplastics are usually referred to as fibers due to their elongated form [157]. Synthetic textiles are those of petrochemical origin with most common being, polyester, polyolefin (PE and PP), polyamide (nylon), and acrylic [157], [158], [159].
2. What is the function of the substance in the product?	Synthetic fibers constitute around 60% of the world's total textile production [159]. These are considered to have several advantages over natural fibers (cotton, wool, etc.), such as increased strength and durability, resistance to insects and chemicals, ease to dry, no shrinking, and lower costs. Additionally, synthetic fibers can be further chemically modified to add functions to them such as abrasion resistance, and water and stain repellency [159].
3. What kind of hazards does it have on health and the environment?	Microplastics are ubiquitous contaminants, increasingly present in the environment. Due to their resistance to degradation, they can remain for long periods of time in the environment [69], [73]. Microfibers are ingested by aquatic and terrestrial organisms, entering the food chain [160]. Additionally, they may be carriers of harmful additives (if present) and adhered pollutants and pathogens, having different effects in the environment and health [73], [157]. In wildlife, they have been found to cause feeding and reproductive disruptions as well as metabolic disturbances [69], [73]. Some of the studied health

	impacts include respiratory problems, cardiovascular diseases, and obesity [73].
4. How is the substance currently regulated/banned?	No specific regulations in relation to the emission of microplastics from textiles was identified.
5. How much substance is in the product? (If possible and available)	N/A. The SoC (microplastics) is inherently bound to the composition of the material, as it is the plastic itself that breaks down into smaller particles.

Step 2. Analyze the context of the product - substance combination

a) **Identify emission/exposure scenarios throughout the lifecycle.** Figure 8 includes the identified emission/exposure scenarios for the case.


Step 2. Analyze the context of the product - substance combination

a) Identify emission/exposure scenarios per lifecycle stage.

Production (manufacturing, assembly) – **Emission** Industrial laundering processes release synthetic fibers into the sewage and waste water treatment plants. **Exposure** Exposure of aquatic wildlife due to contaminated marine environments. Ingestion by humans, contaminated water and food.

Use (reuse, maintenance) – **Emission** Domestic laundering processes release synthetic fibers into the sewage and waste water treatment plants, contaminating fresh water and marine ecosystems. **Exposure** Exposure of aquatic wildlife due to contaminated marine and fresh water environment. Ingestion by humans, contaminated water and food.

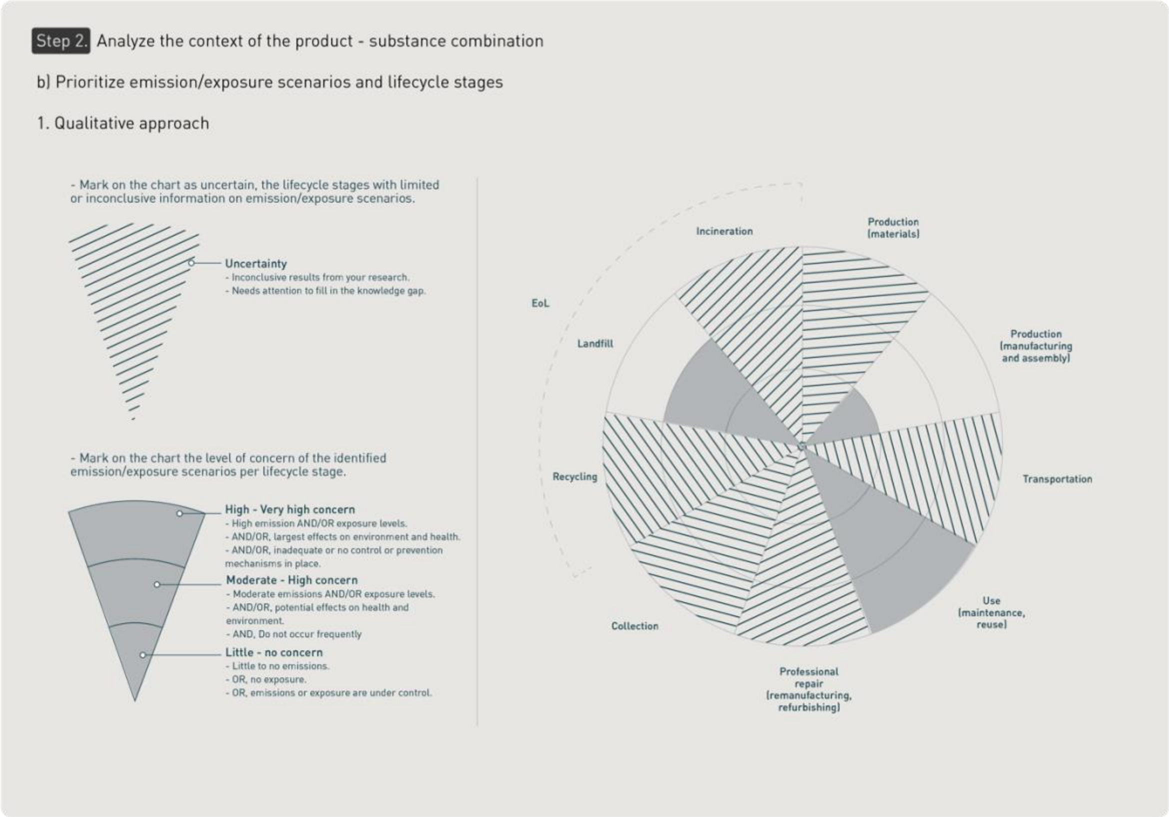
Landfill – **Emission** With most textiles incinerated or landfilled, inappropriate treatment of waste causes plastics accumulation (long lifetimes), increasing microplastic release. **Exposure** Ingestion by wildlife and humans, contaminated food, soil, water, and marine environments.

Figure 8. Answers to Step 2a, Identification of emission/exposure scenarios

Information was found regarding emission/exposure scenarios of the manufacturing, use and landfill stages, no further information on the remaining product life cycles stages could be found in this evaluation [156], [157], [160], [161], [162].

b) Prioritize emission/exposure scenarios and lifecycle stages

1. **Qualitative approach.** Figure 9 shows the qualitative evaluation of the emission/exposure scenarios of the case.



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from your research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

Figure 9. Most concerning emission/exposure scenarios

Explanation: Synthetic microplastic fibers are the most abundant form of microplastics found int the environment [160]. The most concerning emission scenario according to literature is the domestic laundering of synthetic textiles, with a typical 5 kg wash load of polyester textiles emitting more than 6,000,000 microfibers [156], [160], [162]. Synthetic fibers (microplastics) are released directly into the sewage during washing, due to their size, microplastics pass through filters in washing machines and waste water treatment plants, which cause them to be released into fresh water and marine ecosystems [156], [157], [160], [161], [162]. Washing activities during industrial processes could also generate microplastic releases into the sewage [160]. 73% of the global textile material flows is landfilled or incinerated in EoL [132], with two thirds of the textiles put on the market in the EU ending up as residual waste [163]. The landfilling of textiles as an EoL route could attribute to the accumulation and further generation of microplastics, into ground water or into the soil when the residual sludge is used as fertilizer [164], [165]. Step 2b.2 was not used (quantitative approach, RA) due to the lack of data and time restrictions for this evaluation. A lot of uncertainty was found throughout this case (marked as dashed in Figure 9) this could be due to the time restrictions.

c) **Detail emission/exposure scenarios in connection to the product.** The substance presence, the mechanisms of release, and the exposure channels identified for this case are showed in the ticked boxes. Figure 10 shows a detailed description of the priority emission/exposure scenarios.

1. **Describe the presence of the substance in the product. Tick the boxes.**

Examples of substance presence in the product (several may apply):

- ■ Part of the composition of a material
- ■ Single material (in some cases)
- ■ Composite material (in some cases)
- ☐ Separable component (non-destructive disassembly is possible)
- ☐ Non separable component (destructive disassembly is necessary)
- ☐ Contained/encapsulated
- ☐ Coated

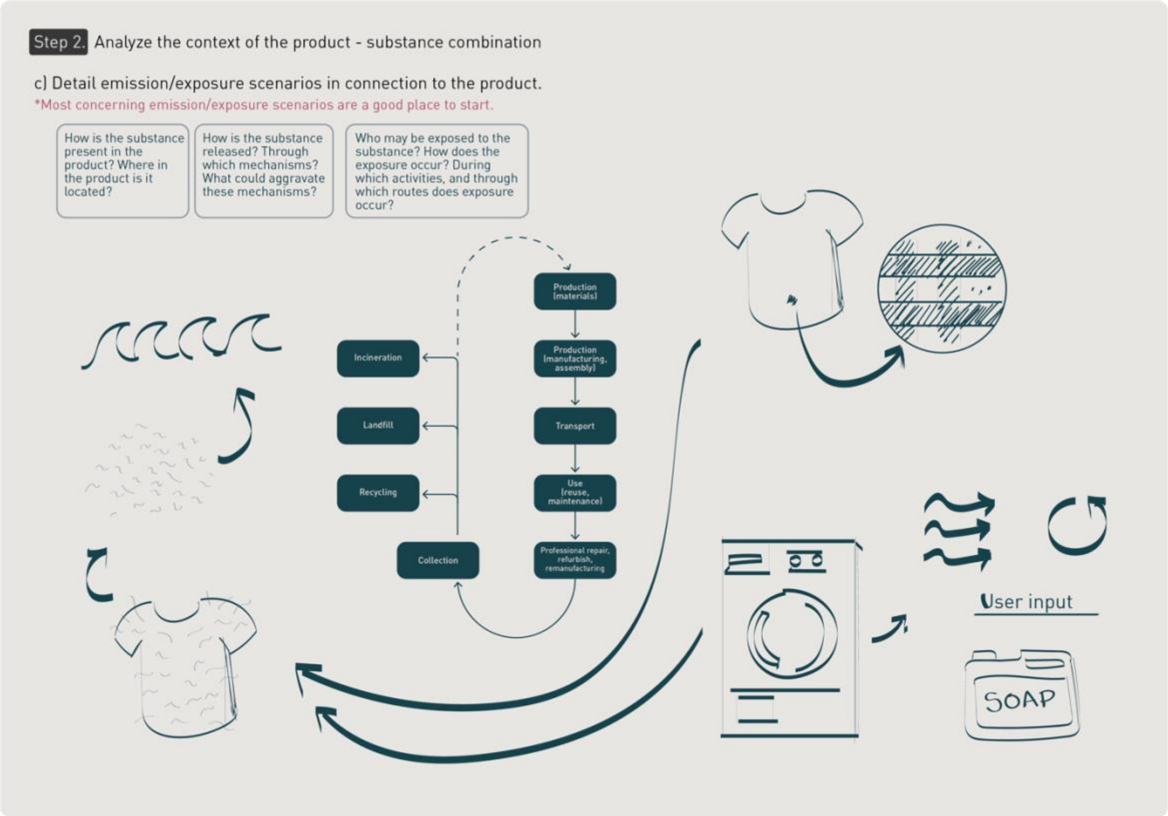
2. **Identify the release mechanisms of the substance and the input that causes and/or aggravates the mechanism. Tick the boxes.**

Examples of mechanisms of release:	Examples of inputs that may cause or aggravate mechanisms of release
☐ Volatilization ☐ Migration ☐ Leaching ☐ Leakage ■ Mechanical degradation ☐ UV degradation	■ High water temperatures ■ Mechanical input (E.g., type of machine, rotations per minute, amount of water) ■ User care (E.g., cycle selection and use of cleaning products) ■ Chemical input (detergents and others)

3. **Identify exposure channels. Tick the boxes.**

Exposure channels:

- ■ Ingestion
- ☐ Inhalation
- ☐ Skin contact



Step 2. Analyze the context of the product - substance combination

c) Detail emission/exposure scenarios in connection to the product.

*Most concerning emission/exposure scenarios are a good place to start.

How is the substance present in the product? Where in the product is it located?

How is the substance released? Through which mechanisms? What could aggravate these mechanisms?

Who may be exposed to the substance? How does the exposure occur? During which activities, and through which routes does exposure occur?

Figure 10. Detailed emission/exposure scenarios

Explanation: The release of synthetic fibers (microplastics) occurs mostly during the use phase through washing activities. The cleaning of textiles involves a combination of physical (mechanical input of the washing machine, water flow) and chemical inputs (detergents, bleach, etc.) to release dirt from the textile structure. These inputs progressively damage the textile and weaken the fibers, causing fiber release [157].

Different studies have identified a number of factors that influence the release of synthetic fibers:

- Fabric type, structure of the textile, type of yarn (staple fibers release more than filament yarns), density, thickness, finishings and treatments, and materials [157]. Woven polyester higher release than knitted polyester [162], [160].
- Aging, the older the garment is the more fibers it tends to release [160].
- Higher water temperature is also associated with an increase in fiber release because it progressively damages the structure of the textile [157], [162].
- Type of washing machine and cycle:
  - Axis position – top loader machines can release 430% more fibers than a front loader [157].
  - Central agitator could lead to more mechanical input, generating more friction and increasing the release of microplastics [157].
  - Rotations per minute, higher cycle duration and water consumption, can also generate more friction and microplastic release [157].
  - Type of filter (pore size) [157].

Inconclusive:

- Type of detergent, powder detergent increases microplastic release, while the use of softeners could decrease it. The quantity of these products used during laundry could also influence microplastic release [162], [157].
- High water hardness could influence the increase of microplastic release [162].

Step 3. Define strategies to Avoid/Eliminate, Reduce, and/or Control/Prevent the SoC. Due to time restrictions, this step was not considered as a selection or development point for a SbD strategy. Instead, the identified existing, historical, and possible SbD strategies for the case are listed and classified (as previously proposed) in Table 20.

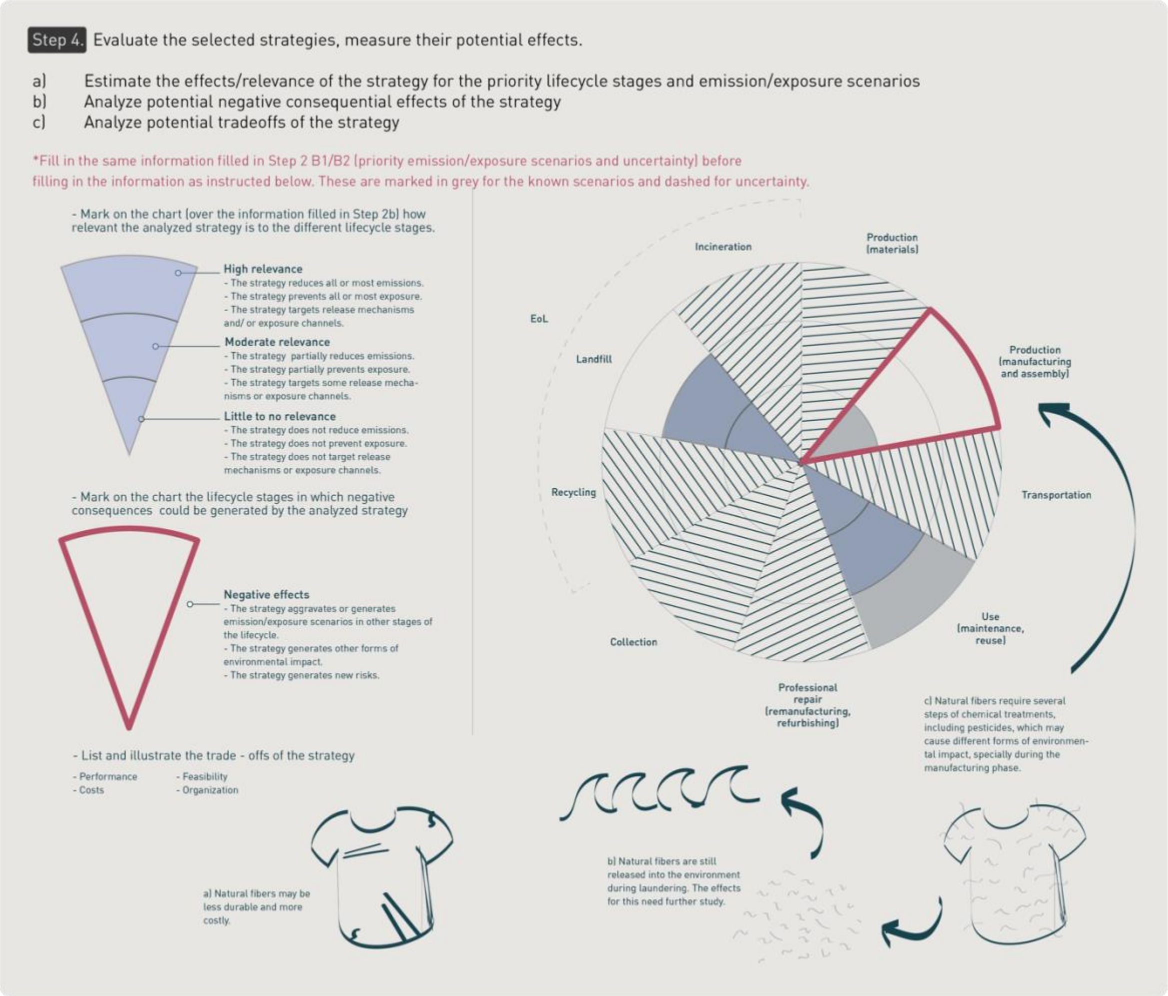
The case of microplastic release from synthetic textiles considers possible solutions at different levels and components. Including the design of the washing machine, the design of the textile or garment, user behavior, and possibly the design of cleaning products that support the reduction of friction and microplastic release as a consequence.

Table 20. Identified SbD strategies in the case.

Type of strategy	**Strategy**	**Description and possible benefits / drawbacks**
Avoid / Eliminate	**Substitution with natural fibers (wool, cotton, etc.)** [160], [166], [167]**.**	Although natural fibers may be of less concern during the use and EoL phases, these usually have higher environmental impacts in comparison to synthetic textiles during the production phase. Most concerns from natural fibers are due to the presence of a variety of chemicals used for their treatment, including pesticides, moth proofing agents and anti-shrinking agents, all of which have toxicity concerns and can enter aquatic ecosystems throughout the product life cycle. Further information about benefits and possible unintended consequences of substitution is necessary.

Reduce	**Designing textiles to reduce the shedding of fiber. E.g., types of knitting and weaving, material combinations - Blends of natural and synthetic fibers (e.g., cotton – polyester blend)** [156]**,** [161]**.**	The type of fabric and its structure were found to influence the release of fibers. These could be further studied and specifically designed to reduce fiber shedding. Blends where found to shed less fibers in comparison to fully synthetic textiles when washed. However, this does not eliminate concerns completely.
	Washing less. Addition of treatments that inhibit the growth of bacteria (E.g., silver). [168]**,** [169]**.**	There is controversy over benefits and drawbacks. Existing concerns include toxicity and sewage treatment issues. Discussed benefits include, reduced environmental impact through reduced washing, reduced use of detergents, increased durability, and decreases in consumption, amongst others.
	Informing consumer behavior to reduce microplastic release – laundering guidance and washing machine purchase [157]**.**	A number of the influencing factors to microplastic release during laundering activities are directly dependent of user behavior. Further research is necessary to identify the best washing practices to avoid microplastic release from synthetic textiles. Additionally, consumers can be provided with more information about washing machine types (e.g., front loader vs top loader) and their influence in fiber release.
Control / Prevent	**Washing machine design – addition of filtering devices** [156]**.**	The addition of filtration devices to washing machines could prevent microplastics entering the water sewage. Further study is necessary.
	External filters [170]**,** [171]**.**	External filtration devices are currently available in the form of bags and plugs for washing machine outlet connections. These have a limited amount of loads and only retain a percentage of the released microplastics.

Step 4. Evaluate the selected strategies, determine/estimate their potential effects. Due to time restrictions, only one of the identified strategies in the case is selected for the evaluation: the substitution of synthetic fibers for natural fibers such as wool or cotton. Figure 11 shows the results of the evaluation, depicting the relevance of the strategy, potential negative effects in other lifecycle stages, and a list of potential tradeoffs. The selected strategy to be assessed is the substitution of synthetic fibers for natural fibers such as wool or cotton.



Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.

High relevance
- The strategy reduces all or most emissions.
- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
- The strategy partially reduces emissions.
- The strategy partially prevents exposure.
- The strategy targets some release mechanisms or exposure channels.

Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy

Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy

- Performance
- Costs
- Feasibility
- Organization

a) Natural fibers may be less durable and more costly.

b) Natural fibers are still released into the environment during laundering. The effects for this need further study.

c) Natural fibers require several steps of chemical treatments, including pesticides, which may cause different forms of environmental impact, specially during the manufacturing phase.

Figure 11. Results of the strategy assessment

The substitution of synthetic textiles for natural fibers such as wool or cotton may be considered partially relevant for the concerns of the use phase. This is due to the fact that although these fibers are expected to degrade faster in natural environments, large amounts of them are released from domestic and industrial laundering [160], [166]. The effects of this requires further research to estimate possible hazards to human health and the environment, since many of these fibers are treated with a variety of chemicals, some of which are considered toxic [166], [167]. The chemical treatment of natural fibers can include the use of pesticides, and other agents used to improve their performance, this is specially concerning during the production phase, indicated in red in Figure 11 [166].

4.3. Findings from the evaluation – insights for further development of the approach

The evaluation described in 4.2 was performed to reflect on the proposed design approach for dealing with SoC, to identify pitfalls, and to provide recommendations for further development of the method. The evaluation centered on reviewing 1) The process proposed for the analysis of the product-substance combination and its context, 2) The steps proposed for the identification of action points, and 3) The proposed qualitative assessment of strategies.

The information obtained on the cases for the evaluation was sourced through desk research. In all cases it was possible to obtain general information on the substance, understand its function, and identify emission/exposure scenarios specific to the product-substance combination (steps 1 and 2 of the approach). However, information on all lifecycle stages and information to support the assessment of strategies and measure their potential effects was limited. Additionally, due to time constrains no consultation with experts was done although recommended by the approach. The level of detail and precision of the obtained results was found to be strongly dependent on information availability and its specificity to the case. It was, however, possible to obtain enough information to support the estimation of relevant points of attention in a short period of time (8 hours were used per case), including desk research. This could indicate that by using the current approach designers are able to obtain a basic understanding of the product-substance combination, prioritize key lifecycle stages and risks, and estimate potential effects of selected strategies.

The qualitative assessment of emission/exposure scenarios and the qualitative assessment of the SbD strategies, allow designers to identify knowledge gaps and estimate the scope of their strategies. The use of this qualitative approach is recommended for early stages of the development process to guide material selection and choose appropriate SbD strategies. At the moment, the approach does not provide the means for a comparison of strategies to identify the most suitable one but provides analytical tools that allow the designer to identify existing uncertainty for further research.

The level of certainty obtained from the approach overall will depend on the quality and availability of data, both quantitative and qualitative information. It is recommended to run several iterations of the approach in order to increment the level of detail in the results as the development process advances. The use of quantitative tools such as LCA and RA, which require more time and information, and a more detailed design embodiment, can follow when detailed information is available to further develop and/or test strategies. These were not applied during the evaluation.

The evaluation also showed that the current approach appears to be targeted at redesign exercises, making it unclear to what extent it is applicable in design assignments that do not start from an existing product or design. Further work is needed to restructure the steps and give specific recommendations for both design and redesign assignments. Additionally, further research and recommendations should be developed for the application of RA and LCA in screening exercises that provide designers with more reliable and specific quantitative estimations.

Due to time constraints, the development of strategies and the application of the proposed prioritization could not be evaluated. The recommendation is to run an evaluation of the complete approach together with other designers as part of a formal design assignment to obtain insights for the improvement of the SbD approach.

5. Discussion – Conclusion

The findings for each of this study's research questions are discussed in this section as follows.

- Section 5.1 discusses RQ 1: *How and why are SoC being used in products? What is known about their effects throughout the lifecycle of products and on the circular economy?*
- Section 5.2 discusses RQ 2: *How can the risks and hazards posed by SoC in products be eliminated or managed through design, considering the entire lifecycle of the product and when a product (or parts of it) goes through consecutive lifecycles (manufacturing, use, reuse, recycling, remanufacturing, etc.)?* Section 5.2 also discusses RQ 3: *How can tradeoffs between sustainability, safety, performance, and cost be balanced when dealing with SoC in products?*

- Section 5.3 discusses the insights gained and possible limitations of applying RA and LCA when dealing with SoC in products.
- Finally, section 5.4 concludes this report and provides recommendations for further work.

5.1. SoC in products

This investigation found that SoC can be added to, and/or generated by a large variety of products including amongst others, electronics, flooring, textiles, personal health appliances, food packaging, agricultural films. SoC are present in these products in a wide variety of forms for example as additives to materials, coatings, laminated composites, manufacturing treatments, and many more. SoC typically fulfill a given function in products with the exception of those generated unintentionally such as microplastics which originate from the degradation of the material itself. In certain applications, the functions SoC fulfill have been found not always to be essential, such as in PFAS in food packaging and some applications of PFAS in textiles. It remains unclear why these substances continue to be applied in these cases, but more studies question the essentiality of the use of SoC in certain applications.

SoC have a variety of detrimental effects on human health ranging from carcinogenic effects to endocrine disruption and respiratory symptoms. Equally concerning, SoC are released through a variety of mechanisms into different compartments in the environment where they accumulate and remain for long periods of time, having different effects on exposed wildlife and organisms.

The results of the investigations in this report show that SoC can be released into the environment throughout all stages of the lifecycle of a given product, causing a variety of exposure scenarios. Some of these situations were found to be more concerning than others, depending on the emission levels and behavior of the SoC once released.

This indicates that a prerequisite for designers to deal with SoC in products is an understanding of all the aspects discussed in the studies. A comprehensive investigation is necessary for every product-substance combination to be able to identify opportunities for actions that permit hazard prevention and/or risk management in product design.

5.2. Dealing with SoC in products - Found strategies and the role of designers

In the case investigations, several strategies for dealing with SoC were identified, classified (avoid/eliminate, reduce, control/prevent) and assessed. The assessment showed that most strategies have some form of drawback, be it a limitation, new or similar risk, or a tradeoff. This investigation made it possible to establish the role designers can play in the development of strategies and in dealing with identified drawbacks.

Avoid and Elimination strategies

a) **Substitution.** The case investigations identified elimination through substitution as a recurrent strategy to deal with SoC. However, substitution was found to be associated with one or more drawbacks including: uncertainty over the effects of the new substance, similar or new risks, alternative forms of environmental impact, and tradeoffs such as loss of performance and increased costs. This calls for forms of alternatives assessment that consider the toxicological, technical, environmental, and economic aspects to be able to identify suitable substitutions. Yet, there may be cases where no alternative may be superior in all aspects.

   Arguably, the role of designers in selecting substances for substitution is limited by the required expertise in chemistry and material science. However, designers cannot only apply substitution decisions, they also can play an important role in dealing with drawbacks. An example of this is reinforcing sections of components made with new additives or materials that caused a loss in durability, as in the case of DEHP in cables.

b) **Other forms of avoid/elimination.** The investigation found that elimination strategies are not limited to substitution; they can include other forms of elimination such as the development of alternative value propositions and different ways of fulfilling a function. Examples of this are wireless charging technologies and the modification of textile weaving patterns to repel water without chemical treatments. These can be met by designers as their expertise includes several forms of user research and iterative design processes to fulfill identified requirements and functions.

Phasing out strategies were also noted as forms of reducing or eliminating the use of SoC. This is yet another area suitable for design practice, where designers can analyze products through a reevaluation of performance and essentiality. An example of this is the elimination of PFAS in synthetic textiles for non-critical applications (medical textiles vs leisure clothing).

Reduce strategies

During the investigation, a number of strategies classified as reduce were found to be of value for designers. These strategies either reduce the overall content of the SoC in the product or reduce SoC emissions or exposure to it. An example of the first is the reduction of the quantity of refrigerant, where components in the refrigerator cooling system had to be adapted to compensate for this reduction while guaranteeing performance.

Strategies to extend the useful life of products (as well as materials and components) were also reported to be useful in reducing the accumulation of SoC, specifically at EoL. These strategies are relevant for designers and include design for repair, and refurbishment amongst others.

Prevent/Control strategies.

These types of strategies have proven valuable to prevent emissions and exposure when an SoC remains in use in a product. The application of these strategies can be stimulated by regulation. An example is the use of refrigerants where strategies were not only focused on preventing ozone depletion, but on developing alternative refrigerants with a lower GWP and low flammability. The regulation targets the design of several elements involved in the lifecycle of the refrigerator to prevent refrigerant emissions, including the device itself (hermetic refrigerant system), its manufacturing (controlled environments), transport (hermetic systems and leakage control), and recycling (controlled collection of the refrigerant).

Other forms of prevention and control of emissions or exposure can also be directly related to the product's design. An example is the use of DEHP in flooring products, where the presence of an additional layer on composite PVC floors considerably reduces DEHP emissions into dust and air.

Several strategies meant to control the recovery and the recycling of products were also listed under the Prevent/Control category. An example is the improvement of collection systems for agricultural mulch films to prevent users either from leaving the films behind or incinerating them on site. Other examples include the recovery of flooring products and the controlled recovery of refrigerants.

The example of refrigerants shows that control strategies may be effective in almost completely eliminating emissions of and/or exposure to the SoC. However, to achieve this effect, Control/Prevent strategies must be thorough and present throughout a product's lifecycle which may limit its feasibility for all product-substance combinations.

Dealing with tradeoffs and drawbacks

Strategies to deal with SoC are all associated with a number of tradeoffs and drawbacks. These include loss of performance, increased costs, consequential risks, or environmental impacts. Additionally, some strategies may be limited by technology (e.g., no comparable substitute to PFAS), while some may be easier to implement than others (e.g., large investments in adapted manufacturing sites).

To deal with tradeoffs, designers must consider their strategies' scope and measure their potential effects throughout the lifecycle of the product (Step 4 of the SbD approach). Additionally, designers should consider developing and implementing multiple strategies to deal with SoC in products to mitigate any drawbacks or tradeoffs. For example (Figure 12), in the case of refrigerants, alternatives without ozone depletion and no toxicity were found to be highly flammable, addressing concerning emission scenarios but causing potential risks of explosion in the use phase. There may be no single alternative refrigerant that fulfills all three characteristics. In this case, the substitution of the SoC as a sole strategy is insufficient and refrigerator components should be adapted to prevent risks of fire or explosion. Strategies to mitigate detrimental effects could then be considered at a component, product, and/or context level to provide a complete solution.

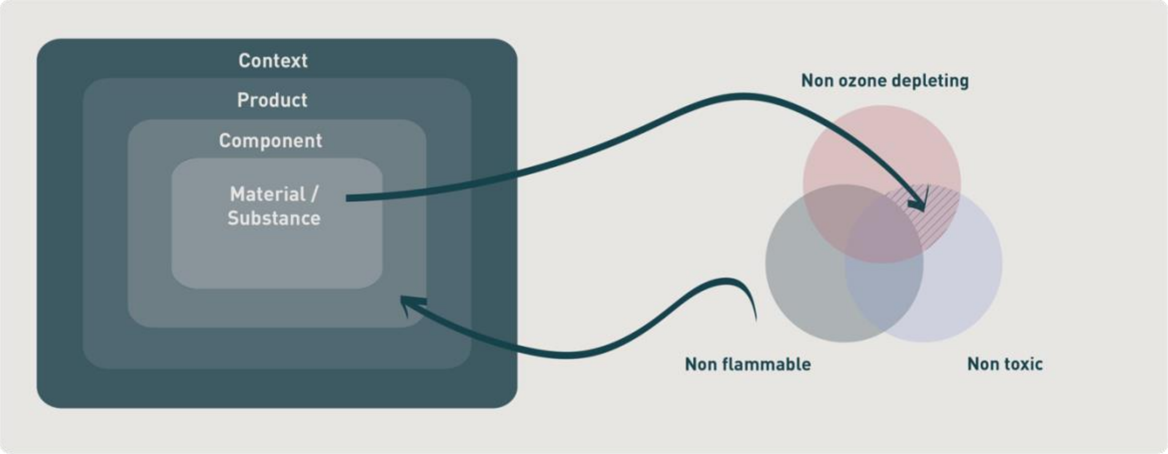


Figure 12. Dealing with tradeoffs by combining SbD strategies

5.3. Learnings from the use of RA and LCA in the prioritization of emission/exposure scenarios and the assessment of SbD strategies

The case studies confirmed that, in principle, screening LCA and RA can be used to support the design of safer products. Publicly available information can be used to compare the functional risks and environmental impacts of alternative product compositions or alternative products. However, the case studies revealed several gaps that hinder the application of these methods.

There is a large data gap in the information on product composition and chemical emissions for both RA and LCA. Information sharing mechanisms in the value chain (e.g., through mechanisms like material passports) are essential. Carbon dioxide emissions are the only ones to have been well characterized at an industrial scale. For all other chemicals, industrial scale-up estimation techniques are currently under development. Approaches like process simulation, engineering process calculations, molecular structure-based models, stoichiometric approaches, and proxies are all being used to estimate missing data [172], and designers need to collaborate with RA/LCA experts to explore these methods.
Additional limitations of RA are:

- The risks of 70% of chemicals have not yet been fully characterized [173], which makes the prioritization of SoC risks and its alternatives challenging. Predictive toxicology approaches (grouping, read across, toxicological screening) address this to an extent, but they too are resource and expertise intensive to develop and apply [174] .
- For some persistent and mobile SoC that occur in many products (e.g., plasticizer), a cumulative risk assessment of SoC emitted from all product sources may be more realistic than considering a single product.
- The knowledge and data gaps regarding the risks of novel contaminants.

Additional limitations of LCA are:

- The human toxicity and ecotoxicity impact characterization factors for many SoC have not been developed.
- LCA at relevant functional unit are important for evaluating SbD strategies. Recent tools (e.g., CLICC, IDEMAT) quantify lifecycle impacts per kg, but to explore impacts for a certain functional performance, a more specific functional unit is needed. For example, while the functional unit of an area of mulch film can indicate the impact of the material, formulating the functional unit as a specific crop yield for a season allows the incorporation of the product performance dimension.
- Even commercial LCA databases lack information on relatively well understood SoC (e.g., plasticizers) if they constitute a small part of the product composition.

- The SoC of emerging contaminants (e.g., microplastics, nanoforms) are an even greater challenge in terms of data availability.
- Commercial Life Cycle Inventories are sparsely populated for activities in the use phase; more information is available for production and end of life phase.

The case studies demonstrated that even given some substantial limitations, activities contributing to the key risks and impacts of SoC can be indicated by screening analysis.

Overall data limitations

While conceptually useful, the application of RA and LCA to product design has knowledge and data gaps. The scope of this current project is a conceptual study of SbD strategies and their evaluation by RA/LCA. A real case of product design with tight collaboration between designers and RA/LCA experts and the possibility to generate data would allow a better realization of SbD.

However, if an SbD strategy is to be implemented widely in product design practice, the availability of data, information, and tools to implement RA and LCA must be addressed. Furthermore, information and tools should be collated and presented from the designer's perspective. Some future efforts in this direction include:

- Collating and organizing databases with ecological, human health, and public health risks through lifecycle of SoC.
- Developing emissions estimation tools based on artificial intelligence.
- Developing and/or collating alternatives assessment of key SoC including risks, impacts and functional criteria.
- Developing methodologies like grouping and read across to estimate "proxy" characterization factors in LCA.
- Developing better expert and user elicitation processes to address data gaps and to develop a broader set of functional requirements.

5.4. Conclusions and recommendations for further work

The main goal of this project was to provide preliminary guidelines for designers to mitigate or manage the risks of SoC in products to make them safe and fit for the circular economy. To achieve this goal, five cases of product-SoC combinations were investigated, as well as approaches in other fields. The results were then used to develop the SbD approach which was evaluated by one of the researchers to identify points for further development and improvement.

This investigation identified three types of SbD strategies to deal with SoC in products: Avoid/Eliminate, Reduce, and Control/Prevent. Designers were found to play an important role in the design of safe and safer products on each one of these strategy groups. Examples include:

- Dealing with drawbacks of SbD strategies such as the substitution of materials and chemicals (e.g., by compensating for a loss of performance by reinforcing certain component section).
- The development of alternative value and function propositions to avoid the use of a particular substance (e.g., providing alternatives ways to charge electronics to avoid the use of cables).
- The prevention of emissions or exposure to a substance through specific characteristics of the product (e.g., hermetic systems that prevent the emission and exposure to refrigerants in cooling products)
- The reduction of accumulation of SoC at EoL through the extension of the useful life of products (e.g., design for durability and design for repair).

The study shows that to create safe products, the scope of the SbD strategy to be applied varies. Additionally, all strategies have been found to have some form of drawback or tradeoff. Strategies that avoid the use of SoC as well as elimination strategies may result in safe products as long as no other unintended consequences are generated. Although Avoid/Eliminate strategies should be prioritized, they may not always be feasible, or sufficient information to guarantee their safety may not be yet available (e.g., in the case of substitution). Meanwhile, strategies to reduce the use and/or emissions of SoC may contribute to making a product safer but not necessarily safe. Similarly, strategies to control/prevent emissions and exposure to SoC may be relevant when elimination or avoidance are not possible, but the degree of safety they provide depends on how effective the control measures are throughout the product lifecycle. This indicates that for designers to identify relevant action points when dealing with SoC and provide effective strategies to develop safe products, an in depth and structured analysis of the product lifecycle and related SoC is necessary, as well as a comprehensive assessment of the proposed strategies to measure their effects and prevent unintended consequences.

This investigation resulted in the development of the SbD approach, The approach includes a set of recommended steps and guidelines to deal with SoC that designers can apply in the early stages of the development phase. It provides guidance for a comprehensive and structured analysis of the product-SoC combination. The qualitative analysis tools successfully highlight action points for designers to focus on when developing strategies. A hierarchical approach nudges designers into prioritizing Avoid/Eliminate strategies over Reduce and Control/Prevent strategies. Lastly, the approach provides designers with an assessment tool to measure the potential effects of their SbD strategies.

Currently, both the strategy assessment tool and the product-substance combination analysis tool are limited to qualitative estimations and therefore only serve as an approximation. Although this supports designers when dealing with uncertainty, a more detailed and quantitative approach would yield a more reliable assessment, necessary at later steps of the development process. This would allow designers to systematically compare and select strategies and further develop those that do not generate unintended consequences and best target the SoC and safety.

The widespread use of Safe by Design in design practice was found to critically depend on the collaboration between product designers and other stakeholders in the supply chain, the development of comprehensive, organized databases, and the development of analytical tools catering to the needs of product designers.

This project involved a close collaboration between design researchers and Risk Assessment and Life Cycle Assessment experts. While data limitations afforded preliminary evaluations of substance-produce combinations and Safe by Design strategies throughout this research, in depth regular discussions deepened the understanding of product safety issues and the role of the involved disciplines. This suggests that although the right data for safety and sustainability evaluations is not easy to find, resourcefulness in finding approximations and openness to other disciplinary perspectives can often yield substantial results that inform the development of solutions to deal with hazardous substances in products.

Last, throughout the project, a number of points were identified to further develop the SbD approach and support designers in dealing with SoC, these include:

- Testing and further development of the SbD approach in collaboration with designers and RA and LCA experts with product design cases in practice.
- Improving the screening LCA and RA methods to more easily applicable for designers in collaboration with LCA and RA experts. This to improve and facilitate the assessment of relevant emission/exposure scenarios and SbD strategies to measure their effectiveness and prevent unintended consequences.
- Improving data availability for designers dealing with SoC. Develop comprehensive databases and tools to support the analysis of substances, the estimation of emissions and exposure for RA, and tools to communicate and collaborate with stakeholders across the value chain.
- Restructuring the SbD approach to be applicable in both design and redesign assignments.

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Appendix A – Extensive description of Case 1

This appendix presents the complete investigation of Case 1 – DEHP in charging cables. A summary of this case is provided in Chapter 3.1.1 of the report. It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 3.1.1 of the report. This was done with the purpose of having the complete documentation of each one of the cases, and to present the structure followed to investigate them.

Case 1 - DEHP charging cables

A.1 Introduction

The consumption of portable electronic devices in Europe reached approximately 420 million in 2020, including mobile phones and other devices [1]. Phones and laptops are commonly provided together with a new charger and charging cable. Charging cables are also sold separately as spare parts in case of breakage. As technology advances, different generations of charging ports and technologies become available. Due to this, cables my become obsolete and may not be used to charge newer devices, although their estimated useful life is if at least 10, and up to 30 years [2]. Additionally, companies like Apple, equip their devices with non-standardized ports which can drive users to purchase new cables that are compatible with their current devices. All of this contributes to an increased number of disposed cables. Phone chargers, considering both the adapter and the cable, are responsible for between 11,000 - 13,000 tones (0.3%) of the total annual waste of electrical and electronic equipment (WEEE) collected in Europe [1], [3].

In the case of charging cables, chemicals are added to their plastic mantle composition to make them flexible, insulating and heat resistant. Some of these additives have been classified as substances of concern due to their potential to harm the environment and human health. An example of this is DEHP (Bis(2-ethylhexyl)), a phthalate that was commonly used in cable coatings as a plasticizer before being banned in the EU in all EEE products prior to 2021.

This case study analyses the presence of DEHP in charging cables of mobile phones and portable devices to understand its function, potential hazards, and emissions throughout the life cycle. Additionally, strategies implemented by manufacturers and policy makers to eliminate/control its use have been studied and assessed to identify their benefits and drawbacks.

A.2 What is the substance?

Identifier: Bis(2-ethylhexyl) phthalate (DEHP) **EC No.:** 204-211-0 **CAS No.:** 117-81-7

DEHP, also known as Bis(2-ethylhexyl) is a Phthalate, which is a group of synthetic chemicals that is used to increase the flexibility and workability of plastics, for which they can also be called plasticizers [4], [5]. Polyvinylchloride (PVC) is the polymer for which most plasticizers are used, accounting for 64% of all plasticizers in Europe [6]. DEHP is most commonly used as a plasticizer for vinyl and flexible PVC production used for different applications, including flooring, films, toys, food packaging, packaging and cables [4].

A.3 How is the substance currently regulated? In which applications?

DEHP is restricted under RoHS (restriction of the use of certain hazardous substances in electrical and electronic equipment). The maximum level by weight specified by RoHS Annex II for Bis(2-Ethylhexyl) phthalate (DEHP) is < 1000 ppm (0.1%). This restriction does not apply to cables or spare parts of EEE (electrical and electronic equipment), for repair, reuse, updating of functionalities or upgrading of capacity, placed in the market before 22 July 2019 and on medical devices placed in the market before 22 July 2021 [7], [8].

DEHP is also part of the Candidate List for Substances of Very High Concern (SVHC) from the European Chemicals Agency (ECHA). It is regulated by the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) Regulation, under Annex XVII, entry 51. *Shall not be placed on the market after 7 July 2020 in articles, individually or in any combination of the phthalates listed in column 1 of this entry, in a concentration equal to or greater than 0,1 % by weight of the plasticized material in the article* [9], [10].

In 2016 the EC authorized the use of DEHP plasticizer for recycled soft PVC [11], to be able to mobilize recycled PVC material that could otherwise not be used due to the contamination of phthalates.

Additionally, DEHP is listed in the banned substances list from Cradle to Cradle [12].

The RoHS regulation marks a maximum concentration of 0.1%. At this concentration the function of the additive is lost. The regulation then focuses on eliminating the presence of the substance, forcing manufacturers to find alternatives.

To decrease the waste generation from chargers the EC has proposed a new policy [13] that not only harmonizes the charging port of several electronic devices to USB C, but also proposes to unbundle the sale of a charger from the device. This last can apply to the adapter only or to both the adapter and the cable. Although the cable is considered to have a smaller environmental impact in comparison to the phone and the adapter, the combination could have strong environmental benefits, reducing cable production and avoiding unnecessary charger purchases [3] [14]. Although these new policies do not regulate DEHP specifically, they have and indirect effect in the reduction of DEHP (or other phthalate) emissions.

A.4 What is the function of the substance in the product?

PVC is commonly used to produce cable mantle to provide electrical insulation to the copper wire. PVC is inherently rigid, to make it flexible a plasticizer is required as part of its formulation. Flexible PVC is commonly preferred by manufacturers due to its low cost and ease to process. DEHP has been found to have the following functions in cable coatings [15], [16], [17]:

- The plasticizer decreases the glass transition temperature of the polymer to maintain its elastic properties. This provides flexibility at low temperatures.
- Depending on its concentration, the plasticizer can attribute to the quality and durability of the cable coating.
- Protection against high temperatures. Indoor wires are usually under continuous use and must undergo temperatures of up to 60 degrees Celsius. Plasticizers used in PVC at high temperatures require a low volatility.

DEHP is used in different concentrations and mixtures depending on the application of the cable mantle [18]. According to the ECHA [19], DEHP can be found in soft PVC in concentrations of 2 – 35 %.

A.5 Substance presence and release classification. (Using the proposed classification)

- **How is the substance present in the material?**

DEHP is added to PVC as a plasticizer. It is mixed at a molecular scale with the polymer, it is therefore not possible to separate it from the product through mechanical procedures.

- **How is the material present in the product?**

The plasticized PVC forms a mantle of about 0.5 mm thick around the metal wire. The mantle is produced by extruding the molten polymer formulation (including plasticizers and other additives) through a metal die.

- **How is the substance released into the environment? Through which mechanisms? Are these mechanisms aggravated by any other input?**

DEHP is not attached to the molecules of the polymer, due to this it is possible for it to be released from the material into the environment throughout the lifecycle of the products that contain it [20], through a number of mechanisms discussed below.

DEHP and phthalate-based plasticizers are considered volatile organic compound (VOCs). VOCs are organic chemical compounds that evaporate under normal indoor atmospheric conditions due to their composition [21]. **Volatilization** is defined as the transition of a liquid chemical into a vapor, which escapes into the atmosphere[22].

DEHP is soluble in water which increases the possibilities for leaching. **Leaching** can be defined as the loss of a compound from a material or carrier into a liquid (solvents, water, saliva), which could result in the contamination of groundwater, surface water, and saliva [23][20].

DEHP can also be transferred from a material into another. **Migration** happens when materials that are in direct contact with other medium become a source of chemicals to the material they are in touch with [24].

The compatibility of a plasticizer with a polymer can also affect the volatilization, migration and/or leaching rate of the phthalate [15], this is important to consider in the selection of plasticizers in general to reduce the release of the substance from the product.

A.6 What are the possible hazards to health and the environment?

- Health

Exposure to DEHP in humans can cause endocrine disruption, deformities in the reproductive system, increased risk of premature birth, cancer risk [20], [25]–[27].

- Environment

Phthalates are considered ubiquitous environmental contaminants, which means they can be found almost anywhere in the environment, air, soil, and water. For this reason, humans, birds, fish, mammals and soil organisms are all exposed to the effects of DEHP [26] [27].

According to different reports [27] [20], DEHP is bio accumulative, but it is not considered a PBT (persistent and bio accumulative) or a vPvB (very persistent and very bio accumulative) substance.

A.7 How and in which stage of the life cycle of the product do emissions of the substance occur? How much of the substance is emitted? And how does exposure occur?

The following paragraphs describe the release of DEHP from cables in the different stages of the lifecycle as well as the different exposure routes to provide enough context to designers of the different elements involved in the release pathways of the substance.

- Production

Emissions: The extraction and manufacturing phases generate emissions to both air and wastewater (and eventually water bodies). DEHP can be released directly into sewage when containers where DEHP was deposited are cleaned [20]. Indoor PVC manufacturing facilities also present DEHP in air particles and dust [20], and also as condensate as the extrusion machines cool down. DEHP is a liquid at room temperature, increased temperatures may cause volatilization. Additionally, DEHP may be released when devices containing it are heated or in contact with water or other media [27].

Exposure: Occupational exposure can happen during the formulation of polymer compounds, the production of DEHP, processing and manufacturing of products containing DEHP, and industrial use of products containing DEHP. Workers can absorb DEHP by different routes, with skin absorption and inhalation being the most relevant, for which DEHP manufacturers recommend the use of protection equipment when manipulating the substance [25] [27]. Human health risk endpoints are systemic, and include testicular toxicity, reproductive toxicity and endocrine disruption.

The emissions to wastewater and air can cause indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [20].

- Use

Emissions: In indoor environments DEHP can volatilize into the air from plastic products. This is especially true for PVC construction materials and surfaces but, most studies on the presence of DEHP in indoor environments also consider cables in their calculations [27][15].

It has been studied that exposure to higher temperatures can contribute to the release of DEHP from products[27][20]. Another possibility for release is mechanical wear, but this has not been studied extensively [27][20]. It has been studied that the presence of DEHP in indoor environments is more substantial in dust particles than in air, highlighting the importance of cleaning floors and surfaces to reduce DEHP levels [15][28].

Exposure: Users could be exposed to DEHP from cables during the use phase through inhalation of dust, skin contact and ingestion [15] [20] [28]. The latter is specifically concerning for children who could chew on the cable. Plasticizers are soluble in water and other media, in this case saliva [20].

- **EoL– Recycling**

Emissions: According to the interviewed experts and considering that the wire constitutes most of weight of the cable; cable waste is mostly interesting for the recovery of metals due to the high value of copper and aluminum. The metal recovery occurs through the shredding and separation of the plastics. The plastic fraction can contain PVC and a mix of other polymers, which can be further separated to later be recycled. However, due to the presence of DEHP and other plasticizers, the plastic fraction is most commonly sent to incineration or landfilling [29].

Recycled materials can contain toxic substances including phthalates if not regulated or monitored. In 2016 the EC authorized the use of DEHP plasticizer for recycled soft PVC [11] as an exemption, further information about the effects of this could not be found during this study.

Exposure: Contaminated recycled materials can end up being used in other products and applications where the emissions and exposure to DEHP continue to occur and its presence is unknown. As an example, contaminated recycled materials could go into the manufacturing of toys, where DEHP has been found to leach and enter the system through saliva [30].

Occupational exposure for recycling facility workers could occur through skin contact and inhalation.

- **EoL – Landfill**

Emissions: Although data on waste management of PVC in the EU is incomplete, studies suggest landfilling and incineration have been the most common ways to manage PVC waste [29] [31][32].

DEHP is soluble in water which increases the possibilities for leaching. Leaching and evaporation (over the long term) of DEHP in landfills could result in the contamination of air, groundwater and surface water [23][20].

Exposure: The emissions to waste water and air can cause indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [20]. Occupational exposure for workers in landfills through skin contact and inhalation.

- **EoL – Incineration**

Emissions: Although data on waste management of PVC in the EU is incomplete, studies suggest landfilling and incineration have been the most common ways to manage PVC waste [29] [31][32]. Recovered PVC from the recycling of cables typically ends up in the incinerator due to the presence of phthalates an other contaminants [29].

DEHP itself breaks down to carbon dioxide and water on incineration [27]. However, the incineration of PVC in general is not recommended, due to the generation of dioxins, the generation of hydrochloric acid (HCl) in the flue gas and, the generation of solid waste containing heavy metals [29][32].

Exposure: Incineration does not produce risks from DEHP.

A.8 Prioritizing risk hotspots due to DEHP used in charger cable through the life cycle

- **Human Health risks of charger cables through their lifecycle**

LC Stage	**Sub-classification**	**Exposure route**	**Toxicity Endpoint**	**Risk Characterization Method**	**Indirect exposure**	**Risk Characterization**
Production	Production of DEHP	Inhalation	Testicular, Developmental	Margin of safety	Washing drums sends 0.01% DEHP into wastewater	**9**
		Dermal	Testicular, Developmental	Margin of safety		**10**
		Combined	Testicular, Developmental	Margin of safety		**5**
	Extrusion	Inhalation, Dermal	Testicular, Developmental	Margin of safety	0.1% emissions into air, condensation on hot machinery	**5**
		Combined	Testicular, Developmental	Margin of safety		**2**
Use	Handling by children (mouthing)	Oral (children)	Testicular	Margin of safety	0.01%/ year emissions into air for products of small surface area contact	**24**
	Interiors	oral + inhalation + dermal (children)	Testicular	Margin of safety		**21**
EOL	Landfill	Remaining DEHP leaches out into soil. Possible Bioaccumulation in humans from eating mammals eating soil dwelling organisms				

Table A1 Relevant Human Health Risk Values for DEHP along the Life cycle. From [33][2][34]
The first column shows the lifecycle stage, and sub-classification (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The exposure route (column 3) mentions how human beings are exposed to SoC (inhalation, dermal or oral exposure). The toxicity endpoint (column 4) mentions the organ systems that are affected. The Risk Characterization method (column 5) mentions whether Risk Quotient or Margin of Safety is used. Indirect Exposure (column 6) mentions emissions to the environment during the activity. Risk characterization (column 7) mentions the risk value color coded according to the heat map presented in Section 2.2.3.

It can be seen that DEHP poses testicular and/or development toxicity in the production and use phases. The highest risks are in the production phase. While the literature indicates that personal protection equipment and engineering controls can effectively control occupational exposure, indirect exposure from DEHP has been a source of concern. In the use phase, while the cable itself has relatively low emissions, there is the possibility of having inhalation, oral or dermal exposure as seen in the proxies of toys and car interiors. There can also be exposure in the end of life phase from leaching landfills and bioaccumulation in the food chain.

- **Ecological risks for Charger cables through the Life Cycle**

LC Stage	Activity	Environmental Compartment	Risk Characterization
Production	Resin production	Sediment	0.07
		Atmosphere	No risk
		Soil	0.005
		Secondary poisoning aquatic (fish eating invertebrates)	0.53
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.45
	Extrusion	Sediment	0.1
		Soil	0.02
		Secondary poisoning aquatic (fish eating invertebrates)	0.24
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.043
Use	N/A		
EOL	Incineration	Sediment	0.06
		Secondary poisoning aquatic(fish eating invertebrates)	0.15
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.01
	Municipal STP	Sediment	0.3
		Soil	0.001
		Secondary poisoning aquatic (fish eating invertebrates)	0.53
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.3
	Landfill	Local freshwater	**16.1**
		Secondary poisoning (small mammals eating worms)	**8.63**
		Secondary poisoning (large mammals eating worms)	**43.2**

Table A2 Relevant Ecological Risk Values for DEHP along the Life cycle. From [33]

Table A2 is organized as follows. The first column shows the lifecycle stage, and activity (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The environmental compartment (column 3) mentions the environmental compartment where the SoC ends up. Risk characterization (column 4) mentions the risk value color coded according to the heat map presented in Section 2.2.3.

Ecological risks in the production phase are quite low. Incineration and Municipal Sewage Treatment Plants also have acceptable risks, and landfill is the most concerning end of life scenario. Secondary poisoning of larger mammals eating worms (and thus also bioaccumulation in human beings) is the scenario with the highest risks, followed by local freshwater contamination. Better solutions for recycling cables are needed, as it constitues the least harmful end of life option.

A.9 What are existing, historical, and possible strategies to deal with DEHP?

This section presents and discusses different strategies identified in literature to reduce, control, and or eliminate the use of DEHP in cables. It provides further information on each strategy, when possible, to determine benefits and drawbacks, as well as unforeseen consequences or uncertainty.

- **Eliminate – Substitute the additive**

This strategy consists of substituting the DEHP with an alternative substance that provides similar technical characteristics. This strategy maintains the use of PVC. The change from using DEHP to using alternative substances could result in alternative environmental and health impacts. These should be studied further before deciding for substitution.

A. **Substitution with alternative phthalate plasticizers.** Phthalates in general have been linked to some form of hazard to the environment and health [4], [5]. However, not all phthalate-based plasticizers are listed as SoC nor regulated. Manufacturers choose to use these as replacement options for DEHP to maintain the quality, functional characteristics, and cost of their products [17]. Below are some examples of phthalate-based plasticizer identified to be common alternatives to DEHP in the cable industry.
   DINP and DIDP. Both were found to be the most common current alternative to DEHP in cables [17]. The Dutch cable manufacturer interviewed for this study, mentioned DINP is the most common replacement for DEHP. It provides similar characteristics and properties and maintains the low costs associated with flexible PVC [35]. DINP related hazards are unclear and under research, specifically for carcinogenic and endocrine and reproductive disrupting characteristics. A Risk Assessment report from the EC in 2003 only highlights the need to protect infants (who could be at risk depending on the concentration) from DINP [36]. DINP is regulated by REACH through Annex XVII with a maximum concentration of 0.1% in children's products [10].

B. **Substitution with alternative non-phthalate plasticizers.** This alternative eliminates the potential risks from phthalate plasticizers. However, according to the interviewed Dutch cable manufacturer these substances can considerably elevate the prices of flexible PVC. The interviewee also mentioned that these new substances may need to be studied further to rule out similar or additional environmental and health risks. The substances below are phthalate free plasticizer alternatives found through Chemsec SIN List, listed to provide a brief overview of available options and further information about their potential benefits and drawbacks.
   DEHT. Offered as a phthalate free plasticizer. According to the supplier and a screening in the ECHA database there are no known hazards from the exposure to this substance. The safety sheet provided by the manufacturer recommends the use of safety equipment for workers in contact with the substance [37]. No further information of the functional characteristics, safety, and cost of this substance is provided.
   Dioctyl adipate. Offered as a phthalate free plasticizer. Cannot be found in the ECHA database but the safety sheet provided by the manufacturer warns of effects on animals and recommends the use of safety equipment for workers in contact with the substance [38]. No further information of the functional characteristics, safety, and cost of this substance is provided.
   Alternative Biobased plasticizers. This alternative eliminates the potential risks from phthalate plasticizers. However, according to the interviewed Dutch cable manufacturer these substances can considerably elevate the prices of flexible PVC and have not been studied sufficiently to identify potential health and environmental risks. An example of a potential biobased DEHP alternative is COMGHA. The castor oil-based plasticizer is reported to require minimum changes in PVC formulations and investments in new equipment. Additionally, it has been studied to have a good performance in cable applications in households. It is more commonly used in toys and other applications [17]. There is insufficient information regarding the cost differences of the substance in comparison to DEHP. Although its environmental impact is lower in comparison to DEHP, its increased use as a replacement for phthalates could result in the displacement of land for food production [17] [20]. Its production is also recommended to be done in a controlled and protected environment to prevent the exposure to human sensitizer proteins [17].

- Eliminate – Substitute the material

Material alternatives to plasticized PVC in cables are commonly identified as halogen free alternatives. Chlorine, present in PVC, is a halogen, a group of non-conducting substances that are commonly used as insulators. Examples of these alternatives include plasticizer free elastomers such as polyethylene and polypropylene, polyurethane, polystyrene, and rubber.

Studies comparing the environmental impact of plasticized PVC to that of halogen free alternatives indicate that although they have a more energy intensive production, they are a better alternative to flexible PVC. This is because throughout their lifecycle they do not pose a health risk, do not produce any other fumes or dioxins and do not present other risks during landfill, recycling or incineration [39]. However, these materials may not have the necessary or equivalent performance requirements to those of flexible PVC. Additionally, they can be more difficult to process and can be more expensive than PVC [39] [40].

- **Eliminate – Substitution of function / material – Rigid cables**

The interviewed Dutch cable manufacturer mentioned "cables are a commodity product" specifically referring to their characteristic flexibility. Which facilitates installation in the case of house wiring and allows for people to move around while connected to a power source in the case of mobile devices. If cables were rigid the presence of plasticizers would not be an issue, but perhaps cables would not adapt to the context as we are currently used to.

No rigid forms of cables in consumer products were found in this study. A radio frequency coaxial rigid connector, used for high power applications inside electronics such as TV's, is shown in Figure A1 to illustrate an analogue to a rigid cable. The connector, made of copper, uses folds to solve the lack of flexibility. The possibility of having rigid or semi-rigid cables for charging applications could be further explored as a design strategy to eliminate the use of DEHP.

Figure A1. Coaxial copper rigid connector. Retrieved on March 2022, from: https://www.elspecgroup.de/products/semi-rigid/standard-cable

- **Control/prevent – Controlled recovery of Electrical and electronic equipment**

The WEEE Directive of the EC [41], has as an objective the collection and proper disposal of electronic devices, not only to recover the resources from those products but to avoid the release of hazardous substances from discarded devices that are not managed properly and avoid landfilling. This is achieved through an extended producer responsibility scheme. The case of cables, however, is not specified. Even if cables are properly collected and recycled, phthalates may remain and be present in the output recycled materials. Due to this, the applications of these materials could be limited. The presence of restricted substances in PVC waste streams is highlighted as one of the main limitations for its recycling, and a reason for the plastic fraction of cables to be incinerated or landfilled [29].

The volunteer initiative Vinyl plus in the EU reported the recycling 728,828 tones of PVC waste in 2020 from which about 100,00 tones was collected from cables [31]. However, there is no mention of possible contamination from restricted substances, specifically DEHP, or the possible applications of the recycled material.

- **Reduce - Increasing the useful life of charging cables**

EoL was identified as the stage of most concern in the lifecycle, during the prioritization of emission/exposure scenarios, due to possible accumulation of DEHP in the environment and possible indirect exposure. The reduction of emissions of DEHP or other phthalates during the EoL phase, especially landfilling, could be achieved by increasing the useful lifetime of charging cables. This could reduce the overall number of disposed cables.

The expected useful lifetime of cables in electronics is of at least 10 years and up to 30 years [2]. However, cables in electronics, such as lamps, fridges or coffee makers remain static and are rarely transported. While phones and laptops are movable and transportable, which means their cables must comply with this characteristic. The use and transportation of charging cables may result in an increase of wear and tear, decreasing their useful lifetime. Figures A2 to A4 show examples of how the cables break close to the attachment to the rigid connector. Which could be attributed to the strain on the material produced by the folding angles the cable acquires during use and transportation, Figures A5 and A6.

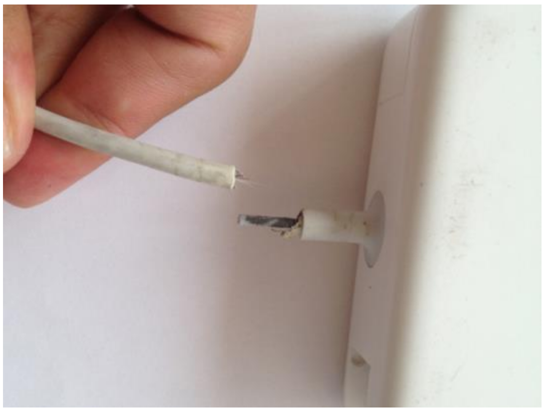


Figure A2. Broken laptop charger. Retrieved on March 2022, from:
https://www.ifixit.com/Guide/How+to+Repair+an+Apple+AC+Adapter+Broken+Cable/20434

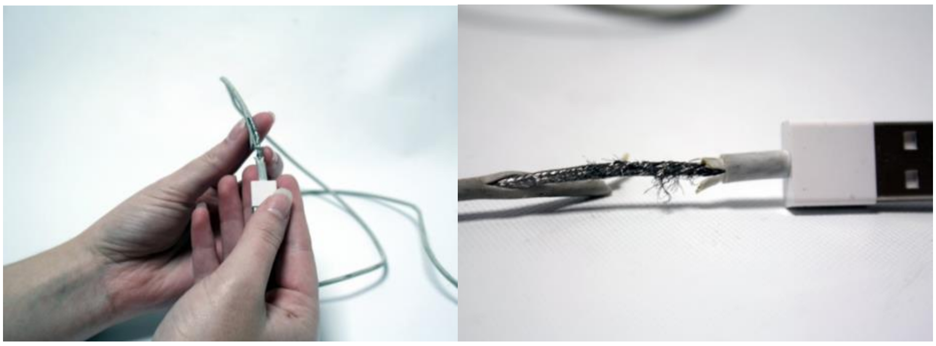


Figure A3 and A4. Broken phone chargers. Retrieved on March 2022, from:
https://www.ifixit.com/Guide/How+to+Repair+a+Frayed+Apple+Lightning+Charger/73220

Figure A5 and A6. Folding points during use and transportation. Own photographs.

Several strategies have been identified to increase the overall useful life of charging cables of portable devices:

A. **Preventive design. Protectors and reinforcement**. The strategy consists of reinforcing the breaking points of the charging cables. Either by design (Figure A7) or by providing additional supporting elements, Figure A8.

Figure A7. Reinforced ends of charging cables. Retrieved on May 2022, from: https://www.ubuy.co.de/en/product/335MCGA-heavy-duty

Figure A8. Reinforcing accessory for cables. Retrieved on March 2022, from: https://www.bol.com/nl/nl/p/astilla-kabelbeschermers-voor-alle-opladers-kabels

B. **Regulation – Cable type harmonization.** To decrease the waste generation from chargers the EC has proposed a new policy [13] that not only harmonizes the charging port of several electronic devices to USB C, but also proposes to unbundle the sale of a charger from the device. This last can apply to the adapter only or to both the adapter and the cable. Although the cable is considered to have a smaller environmental impact in comparison to the phone and the adapter, the combination could have strong environmental benefits, reducing cable production and avoiding unnecessary charger purchases [1], [3], [14]. A reduction in the number of disposed cables could also account for a reduction in phthalate plasticizer emissions.

C. **Repair with sleeves.** An alternative to reduce the number of disposed cables is to increase the options to repair charging cables. An existing solution is the use of plastic sleeves to patch broken sections of the plastic sleeve of the cable, Figure A9.

Figure A9. Sleeve to repair cables. Retrieved on March 2022, from:
https://www.bol.com/nl/nl/p/kabel-beschermer

- **Eliminate - Delivering function differently – Wireless charging**

An alternative that comes to mind to substitute charging cables is wireless charging. Although this strategy could be a way of delivering the function of charging differently and potentially eliminating the need for flexible PVC and plasticizers, wireless chargers today fail to eliminate the use of cables. Wireless chargers include a cable that connects the power outlet adapter to a charging port where the phone can be placed, Figure A10.

Figure A10. Wireless charger. Retrieved on March 2022, from:
https://www.pcmag.com/picks/the-best-apple-wireless-chargers

- **Control/Prevent – Preventing mouthing from children**

Sleeves to prevent mouthing from children are available in different forms, including textiles, flexible sleeves and plastic covers with cuts that make them flexible Figure A11. Some of the material compositions of these alternatives are unknown, so it is unclear if these contain harmful substances that children should be protected from as well.

Figure A11. Cable protection sleeve. Retrieved on September 2022, from:
https://webshop.multimeubel.nl/multi-meubel-aktie-cable-eater

A.10 Evaluation of the application of screening LCA and RA to assess SbD strategies (existing/historical alternatives)

For the baseline scenario, a functional unit of 1 meter of phone charger wire was selected. To model the production phase impacts, Ecoinvent was searched with keywords “cable’ and “PVC”. The activity chosen as a proxy for the phone charging cable was for the screening LCA was “printer cable, without plugs”. ***The composition of the printer cable did not contain DEHP or any other plasticizer, and thus the impact of the plasticizer in the context of the cable could not be explored.*** The CLIC database provided some production environmental impacts of DEHP per kilogram (Table A4), of which climate change and cumulative energy have the greatest magnitude.

The printer cable impacts (without DEHP) were also explored to get an idea of the relative impacts.
Recipe midpoint categories for climate change (GWP 20), fossil depletion (FDP), freshwater ecotoxicity (FETP100), human toxicity (HTP100), metal depletion (MDP), agricultural land occupation (ALOP) and urban land occupation (ULOP) were selected. This indicates that metal use and carbon emissions should be controlled to improve the sustainability profile of the phone charger wire. The contribution analysis showed that 21.7% of the total impact came from the PVC.

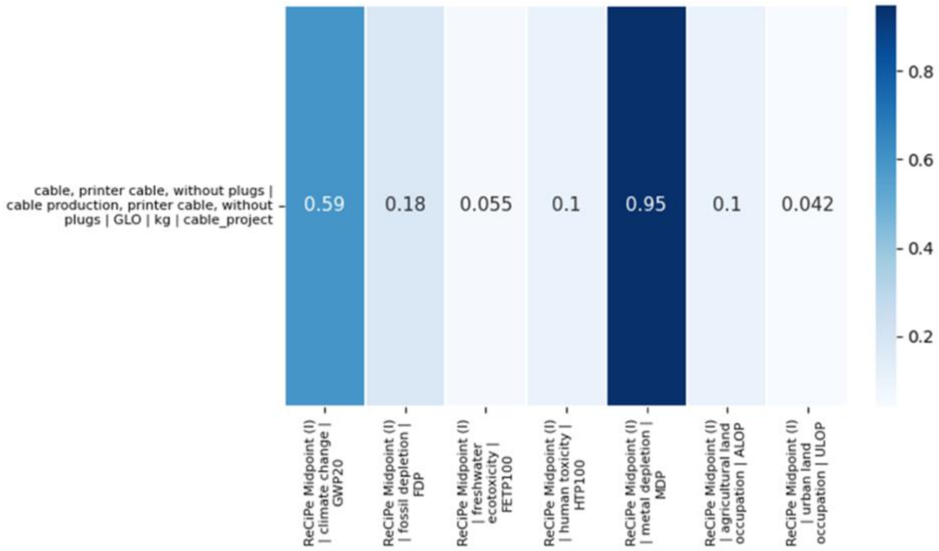


Figure A12. Baseline Scenario for Phone Charger Cable. Impacts expressed in Points.
The screening analysis indicated that metal depletion and climate change were the hotspots in the production phase.

The relative impact of human toxicity and freshwater ecotoxicity were among the lower impacts (though it must be noted that additives like plasticizer are not included in this analysis). Toxicity impacts arise mainly from the refining of copper used in the wire.

- **Assessment of strategies**

A. Substitution of the additive (phthalate and non-phthalate)- Predictive RA approaches

On providing the CAS number of DEHP, the Similarity tool provided the following chemicals (CAS numbers) that are likely to exhibit reproductive toxicity or endocrine disruption as DEHP does.

Substitutions to be avoided

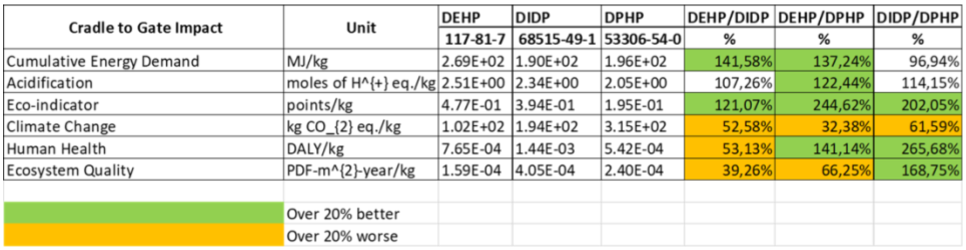
CAS numbers of chemicals likely to be reproductive toxins	CAS numbers of chemicals likely to be endocrine disruptors
68515-42-4, 84-75-3, 71888-89-6, 27554-26-3, 84-61-7, 131-18-0, 776297-69-9, 71850-09-4, 84-74-2, 605-50-5, 84777-06-0, 68515-50-4, 84-69-5, 85-68-7	84-61-7, 84-74-2, 84-69-5, 85-68-7

Table A3. ZZS Similarity Tool results for DEHP

The similarity tool indicated the following phthalates: 84-61-7 (dicyclohexyl phthalate), 84-75-3 (dihexyl phthalate), 85-68-7 (benzyl butyl phthalate), 84-69-5 (DIBP, diisobutyl phthalate), 84-74-2 (DBP, dibutyl phthalate), 605-50-5 (diisopentylphthalate), 71850-09-4 (diisohexyl phthalate), 776297-69-9 (N-pentyl-isopentylphthalate), 131-18-0 (di-n-pentyl phthalate) and 27554-26-3 (diisooctyl phthalate).These phthalates can be avoided as a substitution strategy.

B. Substitution of additive with alternative phthalate-based plasticizers - LCA

Some production (cradle to gate) impacts of plasticizers DEHP, DIDP and DINP were available in the CLICC database and are presented and compared. The functional unit is 1 kg of plasticizer. DPHP appears to have the most desirable environmental profile of the plasticizers considered.



Cradle to Gate Impact	Unit	DEHP	DIDP	DPHP	DEHP/DIDP	DEHP/DPHP	DIDP/DPHP
		117-81-7	68515-49-1	53306-54-0	%	%	%
Cumulative Energy Demand	MJ/kg	2.69E+02	1.90E+02	1.96E+02	141,58%	137,24%	96,94%
Acidification	moles of H^{+} eq./kg	2.51E+00	2.34E+00	2.05E+00	107,26%	122,44%	114,15%
Eco-indicator	points/kg	4.77E-01	3.94E-01	1.95E-01	121,07%	244,62%	202,05%
Climate Change	kg CO_{2} eq./kg	1.02E+02	1.94E+02	3.15E+02	52,58%	32,38%	61,59%
Human Health	DALY/kg	7.65E-04	1.44E-03	5.42E-04	53,13%	141,14%	265,68%
Ecosystem Quality	PDF-m^{2}-year/kg	1.59E-04	4.05E-04	2.40E-04	39,26%	66,25%	168,75%
🟩	Over 20% better						
🟧	Over 20% worse						

Table A4. Comparative evaluation of environmental impact of DEHP, DIDP and DPHP per unit mass
The data is extracted from the CLICC tool. DPHP seems to be the plasticizer with the least environmental impacts.

C. Increasing useful life of cables – Repair with cable jackets (LCA)

1 meter cable weighs about 7 grams and contains 2.1 gram (~30%) plasticizer by weight. The maximum emission from the cable in the first year is 210 micrograms of DEHP, and 0.01% of the remaining amount of DEHP is emitted every year. Over a 15 year lifetime, 8.4 mg of DEHP is emitted from the cable.
To model the impact of using jackets to extend the life of the charger cables, the activity extrusion of plastic pipes was used. Plastic pipes are composed of polyethylene and do not contain plasticizer. It was assumed that the cable jackets comprised of a mass of 20% of the charger cable). It was found that the impact of the jackets comprises of less than 1% of the impact of the cable. Thus, repairing cables has lesser environmental impact than buying a new cable.

D. Increasing useful life – Regulation, cable type harmonization

EU has rolled out a regulation to standardize types of chargers, which will reduce the life cycle impacts of charger cables (including plasticizer emissions into the environment) considerably. Typically, chargers are kept for the life of the phone unless they are lost or broken. iPhone batteries retain 80% charge after 500 charging cycles. Assuming the phone is charged every 2 days and consumers buy another phone when battery can retain charge, phones and cables are changed about every 3 years. The possible lifetime of PVC cables is 15-20 years. Thus, by keeping the charger for the possible lifetime of the material, the lifetime impacts of PVC cables are **five times** less. It must be noted here that plasticizer loss is a complex topic dependent on several factors, the kinetics is not linear and substantial loss will lead to the performance failure of the cable [42]. However, cables are discarded much earlier than their service life, hence this strategy has scope to reduce plasticizer risks.

E. Reducing emissions through a controlled EoL - Recycling phase

To model the typical end of life/recycling phase of PVC in the Netherlands, the Eco invent activity market for waste polyvinylchloride (NL) was used. It is to be noted that the composition of this activity does not include any plasticizers. This activity includes municipal incineration, open burning, unsanitary landfill, and transportation in the typical proportions found in the Netherlands. The functional unit of 1 meter of charger cable translates to 7 grams of PVC waste. The greatest impact was climate change, human toxicity and freshwater ecotoxicity were two orders of magnitude lower.

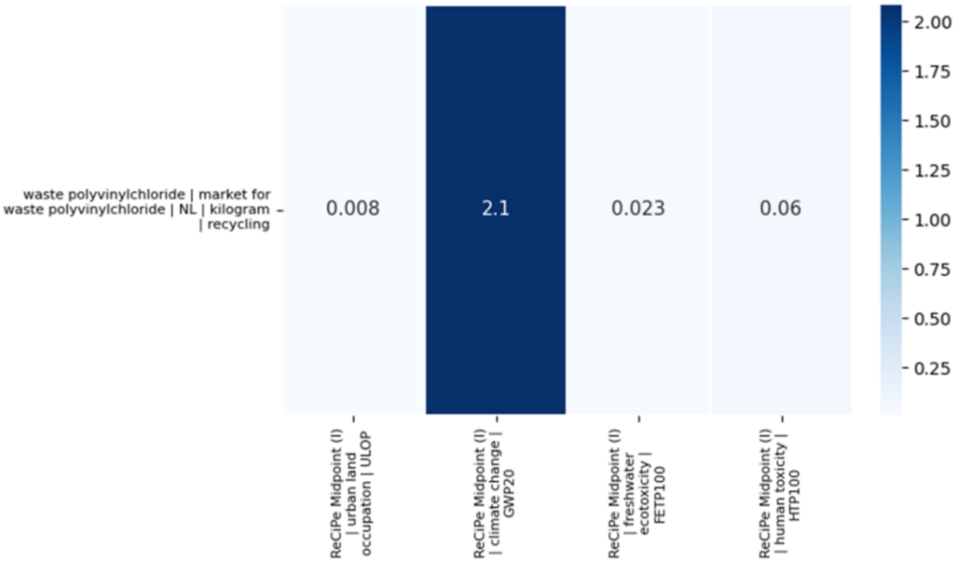


Figure A13. End of Life impacts of PVC in the Netherlands (no DEHP included) in Points Climate change is the highest impact

A.11 Conclusions – Main insights for designers

Table A5 provides a summary of the identified SbD strategies and their potential benefits and downsides according to literature and the RA, and LCA assessments when applicable.
Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with DEHP in cables				
Type of strategy	Identified SbD strategies DEHP in cables	Assessment method	Potential benefits	Potential downsides
Eliminate	Substitution of DEHP by another phthalate-based plasticizer	[QE] [LCA] [RA]	- Similar functional characteristics [int], [35]. - Similar cost [int], [35].	- Some phthalate-based plasticizers have a similar hazard profile to DEHP [RA], [36], [10]. - Unknown hazard profile for other phthalate-based plasticizers [4], [5]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [43]. - Some alternatives are currently regulated (DINP)[10]. - No clear winner, DPHP has the best environmental profile [lca].
	Substitution of DEHP by a non-phthalate-based plasticizer	[QE]	- Some types have comparable functional characteristics to DEHP [int], [35].	- Unknown effects/ hazards for health and environment [int]. - Higher cost [int]. -Potential displacement of land for food production for biobased [17] [20]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [43].

	Substitution of material – (halogen free alternatives) PE, PP, PUR, PS, Rubber	[QE]	- No known hazards to health or the environment [39].	- Increased cost [39] [40]. - Processing is energy intensive [39] [40]. - Limitations in performance [39] [40].
	Delivering function differently - Wireless charging	N/A	- *No benefits since device operates through a cable of similar dimensions as common chargers. Strategy is mentioned as a possibility for further exploration.*	
	Substitution of function/material Rigid cables (Eliminating plasticizer)	[QE]	- No DEHP present.	- Unexplored design possibility for charging cables - Functional (comfort) limitations.
Reduce	Cable type harmonization to USB -C and de-bundle the phone and charger. (By regulation)	[QE] [est]	- Increase useful life of cables, decreasing env impact [est], [1], [3], [14]. - Reduce number of disposed cables. Decreasing WEEE. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [23][20].	- Only applied to adapter. Cable under consideration [3], [15].
	Extending useful life – Repair with sleeves	[QE] [LCA]	- Increase useful life of cables, decreasing env impact [1]. - Repair sleeve has less impact than purchasing a new cable [LCA]. - Reduce number of disposed cables. Decreasing WEEE. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [23][20].	- Safety could be an issue if the repair is not done correctly.
	Extending useful life – Durable cables. Reinforce sections that are prone to breaking, improve folding and portable options.	[QE]	- Increase useful life of cables, decreasing env impact [1]. - Reduce number of disposed cables. Decreasing WEEE. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [23][20].	
Control/ Prevent	Controlled / regulated recovery - WEEE Directive	[QE] [LCA]	- Controlled disposal and recovery could facilitate recycling.	- Recycling is hindered by the presence of plasticizers other additives [29], [30]. - Recycling of cables is focused on metal recovery and not plastics [int]
	Prevent exposure – preventing mouthing by children	[QE]	- May avoid children from direct exposure to DEHP and other substances through ingestion.	- Unknown composition of sleeves and potential risks.

Table A5. Summary of identified SbD strategies for DEHP in Cables

Most relevant emission/exposure scenarios

Although the values resulting from the assessment (Section A 10) tend to minimize the effects of the plastic cover of cables in comparison to other components of the charger, in the case of DEHP emissions it is important to consider the effects of accumulation. The two lifecycle stages of most concern for this case according to the RA (Section A 8) are the use phase and EoL. The accumulation and leaching of DEHP should be avoided or controlled especially avoiding landfill, to avoid water contamination and sources of indirect exposure. In the case of recycling, the presence of DEHP remains a limitation for PVC to be safely recycled, due to contamination with additives. During the use phase, DEHP emissions to interior environments through air and dust, as well as prevention of children mouthing should be considered as points of attention.

Insights for designers and limitations

Types of strategies, scope of the strategy, benefits, and downsides

Eliminating DEHP in cables has been mostly done through substitution. Since DEHP was restricted under REACH, the industry has been forced to substitute it with other types of plasticizers and/or materials. Substitution can be challenging, especially because the effects of these substitutions regarding safety, and their effects on human health and the environment are many times uncertain. This uncertainty may lead to regrettable substitutions as shown for example, in the assessment comparing DEHP to alternative phthalates. Additionally, current substitution options for DEHP present a diversity of other challenges including performance, durability, and increased costs.

Strategies under the category of reduce, focus in this case, on the extension of the useful lifetime of cables, and thus contribute to the reduction of cable waste generation to reduce the speed of the accumulation of DEHP and other harmful substances in landfills. Although these strategies may have a positive influence in reducing DEHP emissions, it is relevant to note they do not eliminate all the risks related to the substance during other stages of the lifecycle of the product, notable the use phase.

Role of designers

Reduce strategies related to the extension of the useful life of cables may influence the design of the product. Designers have clear opportunities to apply the identified strategies for extending the useful life of cables, such as making them stronger and resistant to manipulation, making cables repairable, and avoiding incompatibility issues. The implementation of policies, such as the standardization of charging ports and unbundling of phones and chargers, facilitate designers in clear priority setting regarding strategies. Additionally, designers can also play a role in identifying these types of strategies and possible beneficial changes in the design of a product to inform policy making.

Substitution strategies need further elaboration by designers to overcome tradeoffs at the cost of durability, performance, and comfort that currently result from switching to new additives and/or materials. Equally so, designers can also further explore the possibilities of modifying the cable design to prevent exposure, e.g., mouthing from children, and volatilization during the use phase.

Limitations and challenges

Existing substitute substances and materials for DEHP and flexible PVC are showed to have a number of performance limitations. In addition to this, it is unclear how information over substances is managed and communicated across all the stakeholders through the lifecycle of a product and some substitutes appear to have limited information on their benefits, drawbacks, and potential long-term effects on the environment and health. The information on the alternatives for DEHP is sometimes unclear and/or unavailable. In the case of phones and their chargers, some manufacturers [44], [45] have installed internal policies which require their suppliers to comply to restricted substances lists and/or provide full material declarations to support substitution decisions. However, existing options for the substitution come with a large number of tradeoffs or need further development to fulfill the expected environmental, public health, cost, and performance requirements.

A.12 Limitations of the case study

The information obtained about the emission/exposure scenarios is not specific to the case study and applies to DEHP and phthalates in general. While LCA has an apparent advantage of being able to model products by virtue of inventory data on specific products (e.g., printer cable), this background LCI data is missing phthalates altogether. Very limited analysis could be performed with LCI databases and back of envelope calculations. Characterization factors may also need to be generated for SoC for toxicity impacts if missing.

DEHP is a well characterized SoC, and there was abundant information on risks for the production and end of life phases. Data on the use phase specific to cables was limited, and available information (e.g., toys, car interiors, floor dust) was provided as a proxy. It has been recommended that cumulative risk be calculated for all sources of indoor exposure to phthalates for a realistic risk estimate. A cumulative risk assessment and reduction approach to plasticizers in the indoor environment can also help tackle low hanging fruit in terms of designing out phthalates.

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Appendix B – Extensive description of Case 2

This appendix presents the complete investigation of Case 2 – DEHP in charging PVC flooring. A summary of this case is provided in Chapter 3.1.2 of the report. It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 3.1.2 of the report. This was done with the purpose of having the complete documentation of each one of the cases, and to present the structure followed to investigate them.

Case 2 - DEHP in PVC flooring

B.1 Introduction

PVC flooring belongs to a product group known as Resilient Floor Coverings. These products are specifically designed to meet different performance qualities, such as, resistance to wear, comfort, ease of maintenance and cleaning, acoustic dampening, and hygiene. Resilient floor coverings are available in a diversity of materials and forms and can be used in both residential and commercial applications [1].

Out of the 50.7Mt of plastic demand in Europe in 2019, 10% can be attributed to PVC, including mostly window frames, flooring, wallpaper, hoses, and cable coatings [2]. According to Vinyl plus [3], 7% of the annual PVC demand in Europe can be attributed to flooring.

To fulfill the different functional requirements of flooring, PVC is modified by using different additives, including plasticizers, which make PVC flexible. Up to 20% of the annual use of plasticizers in Europe can be attributed to flooring [4].

Prior to being banned by European Chemicals Agency (ECHA), DEHP (Bis(2-ethylhexyl)), a phthalate-based plasticizer, was commonly used in PVC flooring. Although some phthalate based plasticizers have been identified as hazardous or are being investigated for health and environmental hazards [5], they continue to be the most commonly used type of plasticizers used in Europe [4].

This case study analyses the presence of DEHP in PVC flooring to understand its function, potential hazards, and emissions throughout the life cycle. Additionally, strategies implemented by manufacturers and policy makers to eliminate/control its use have been studied and assessed to identify their benefits and drawbacks.

B.2 What is the substance?

Identifier: Bis(2-Ethylhexyl) phthalate (DEHP) EC No.: 204-211-0 CAS No.: 117-81-7

DEHP, also known as Bis(2-ethylhexyl) is a Phthalate, which is a group of synthetic chemicals that is used to increase the flexibility and workability of plastics, for which they can also be called plasticizers [6], [7].

Polyvinylchloride (PVC) is the polymer for which most plasticizers are used, accounting for 64% of all plasticizers in Europe [8]. DEHP is most commonly used as a plasticizer for vinyl and flexible PVC production used for different applications, including flooring, films, toys, food packaging, packaging and cables [6].

B.3 How is the substance currently regulated? In which applications?

Identifier: Bis(2-Ethylhexyl) phthalate (DEHP) **EC No.:** 204-211-0 **CAS No.:** 117-81-7

DEHP is a part of the Candidate List for Substances of Very High Concern (SVHC) from the European Chemicals Agency (ECHA). It is regulated by the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) Regulation, under Annex XVII, entry 51. *Shall not be placed on the market after 7 July 2020 in articles, individually or in any combination of the phthalates listed in column 1 of this entry, in a concentration equal to or greater than 0,1 % by weight of the plasticized material in the article* [9], [10].

Additionally, it is listed in the banned substances list from Cradle to Cradle [11].

The REACH regulation marks a maximum concentration of 0.1%. At this concentration the function of the additive is lost. The regulation then focuses on completely eliminating the presence of the substance, forcing manufacturers to find alternatives.

B.4 What is the function of the substance in the product?

PVC flooring is used in both commercial and domestic applications. PVC offers different possibilities to design the floor to meet specific requirements depending on the application. The properties listed in Table B1 can be acquired by using flexible PVC, in combination with different layers of different (e.g. printable layers, scratch resistant films and glass fiber), also known as heterogeneous flooring, or through differences in the composition and thickness of a single sheet of flexible PVC material, also known as homogeneous or single layer flooring. Different concentrations of DEHP (or other plasticizer) will also have an effect on the characteristics listed in Table B1, [1] [12] [13].

Properties	Function / Reasoning
Flexibility	The flooring should be flexible enough to be installed without cracking.
Dimensional stability	The flooring should maintain its dimensional stability even when exposed to heat to avoid deformations and separation of the floor covering.
Wear resistance	Varies from domestic, commercial, and industrial applications and the intensity of use, classified by international standards.
Stain resistance	Varies depending on the application. Provides ease of maintenance and cleaning.
Acoustic dampening	Soft flooring can absorb sounds.
Comfort	Soft flooring can provide comfort in commercial applications.

Table B1. Functional properties of DEHP in PVC flooring

PVC is inherently rigid, to make it flexible, a plasticizer is required as part of its formulation. Plasticized PVC is used by manufacturers in flooring for a number of reasons: [14] [15]

- The plasticizer (DEHP or other) decreases the glass transition temperature of the polymer to maintain its elastic properties. This provides flexibility at low temperatures.
- Depending on its concentration, the plasticizer can attribute to the quality and durability of the flooring [16].
- Flexible PVC is durable and affordable.
- Flexible PVC is easy to process over other alternatives. According to a USA film manufacturer that was interviewed for this project, PVC is preferred over other alternatives due to its capacity of easily being modified through additives to obtain different functional characteristics.

DEHP (or alternative plasticizers) are used in different concentrations and mixtures depending on the application and functional characteristics of the flooring. Some of the formulations found in this research indicate a concentration of approximately 15% to 22% of plasticizer in flooring applications [16].

B.5 Substance presence and release classification

- **How is the substance present in the material?**

DEHP is added to the PVC material as a plasticizer. It becomes part of the composition of the material, it is therefore not possible to separate it from the product through mechanical procedures.

- **How is the material present in the product?**

PVC flooring can have different configurations depending on its application. Homogeneous PVC flooring, is a single layer flooring material produced with a method called calendering, which is used to produce films and sheets by processing molten plastic through pairs of rollers [17]. Multiple-layer, or heterogeneous PVC flooring, is produced by laminating several films of PVC and other materials, such as glass fiber, wood fiber, printed layers, and polyurethane coatings. Lamination can be done with heat and or adhesives [16] [18].

- **How is the substance released int the environment? Through which mechanisms? Are these mechanisms aggravated by any other input?**

DEHP is not attached to the molecules of the polymer, due to this it is possible for it to be released from the material into the environment throughout the lifecycle of the products that contain it [19], through a number of mechanisms discussed below.

DEHP and phthalate-based plasticizers are considered Volatile Organic Compounds (VOCs), which are organic chemical compounds that evaporate under normal indoor atmospheric conditions due to their composition [20]. **Volatilization** is defined as the transition of a liquid chemical into a vapor, which escapes into the atmosphere [21]. In the case of flooring the volatilization of DEHP can increase with exposure to high temperatures [22]–[24].

DEHP is soluble in water which increases the possibilities for leaching. **Leaching** can be defined as the loss of a compound from a material or carrier into a liquid (solvents, water, saliva), which could result in the contamination of groundwater and surface water [25][19].

DEHP can also be transferred from a material into another. **Migration**, the transfer of a compound to another medium when in direct contact [26]. In the case of flooring migration of DEHP can increase with higher temperatures and higher humidity levels [24] [27].

The compatibility of a plasticizer with a polymer can also affect the volatilization, migration and/or leaching rate of the phthalate [14], this is important to consider in the selection of plasticizers in general to reduce the release of the substance from the product.

B.6 What are the possible hazards to health and the environment?

- **Health**

Exposure to DEHP in humans can cause endocrine disruption, deformities in the reproductive system, increased risk of premature birth, cancer risk [19], [28]–[30].

- **Environment**

Phthalates are considered ubiquitous environmental contaminants, which means they can be found almost anywhere in the environment, air, soil, and water. Humans, birds, fish, mammals and soil organisms are all exposed to the effects of DEHP [29] [30].
According to different reports [30] [19], DEHP is bio accumulative but it is not considered a PBT (persistent and bio accumulative) or a vPvB (very persistent and very bio accumulative) substance.

B.7 How and in which stage of the life cycle of the product do emissions of the substance occur? How much of the substance is emitted? And how does exposure occur?

In the following paragraphs the release of DEHP from PVC flooring in different stages of the lifecycle, as well as the different exposure routes are discussed.

- **Production (similar to DEHP cables)**

Emissions: The extraction and manufacturing phases generate emissions to both air and water. Industrial activities can discharge DEHP directly into the sewage. Indoor PVC manufacturing facilities also present DEHP in air particles and dust [19]. DEHP is a liquid at room temperature, increased temperatures may cause volatilization. Additionally, DEHP may be released when devices containing it are heated or in contact with water or other media [30].

Exposure: Occupational exposure can happen during the formulation of polymer compounds, the production of DEHP, processing and manufacturing of products containing DEHP, and industrial use of products containing DEHP. Workers can absorb DEHP by different routes, with skin absorption and inhalation being the most relevant, for which DEHP manufacturers recommend the use of protection equipment when manipulating the substance [28] [30].

The emissions to wastewater and air can cause indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [30] [19].

- Use

Emissions: DEHP can volatilize into the air from plastic products. The presence of DEHP has been detected in the air and dust of indoor environments with PVC flooring and/ or PVC wallpaper [14][24][30]. DEHP levels appear to be higher in dust particles than in air [24]. Emissions of DEHP from flooring are influenced by a number of factors:

Higher temperatures can contribute to an increase in the release of DEHP from products. Rooms with floor heating and areas exposed to increased temperatures due to the sun are important point of attention to the increased release of DEHP into dust and air [22]–[24]. The same studies recommend periodically cleaning (mopping) indoor spaces with PVC floorings to avoid exposure to DEHP. A controlled study in chambers to measure DEHP levels in air and dust have found that emission rates of DEHP are 100 times higher at 80°C than at 20°C [22].

Humidity has also been identified as an influencing factor in the increase of phthalate emissions into dust. This was reported for building with leakage and dampness [24]. Moreover, studies have identified an increase in DEHP emissions from materials with higher moisture content [27].

Exposure: Users could be exposed to DEHP from flooring through inhalation of indoor air and dust, skin contact and ingestion [14] [31].

- EoL – Recycling

Emissions: The use of additives, in this case DEHP, hinders the recycling possibilities of flexible PVC. Even though PVC is highly recyclable, PVC waste is often incinerated or sent to landfill [32]. Phthalates remain in the composition of PVC after recycling, which could risk reintroducing contaminated materials into the market. Countries count with limited resources to analyze PVC waste to identify the presence of phthalates. For this reason PVC waste from construction is recommended to be collected separately and incinerated in specialized incineration plants [32].

In 2016 the EC authorized the use of DEHP plasticizer for recycled soft PVC [33] as an exemption, further information about the effects of this could not be found during this study.

Exposure: Contaminated recycled materials can end up being used in other products and applications where the emissions and exposure to DEHP continue to occur. As an example, contaminated recycled materials could go into the manufacturing of toys, where DEHP has been found to leach and enter the system through saliva [34].

Occupational exposure for recycling facility workers could occur through skin contact and inhalation.

The volunteer initiative Vinyl plus in the EU has achieved the recycling 728,828 tones of PVC waste in 2020 from which about 200,00 tones was collected from Flexible PVC & films (including roofing and waterproofing membranes, flooring, coated fabrics, flexible and rigid films), but there is no mention of the presence of additives and safety measures [35] .

- EoL – Landfill

Emissions: Although data on waste management of PVC in the EU is incomplete, studies suggest landfilling and incineration have been the most common ways to manage PVC waste [32] [35][36]. DEHP is soluble in water which increases the possibilities for leaching. Leaching and evaporation (over the long term) of DEHP in landfills could result in the contamination of air, groundwater and surface water [25][19].

Exposure: The emissions to waste water and air can cause indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [30][19].Occupational exposure for workers in landfills through skin contact and inhalation.

- EoL – Incineration

Emissions: Although data on waste management of PVC in the EU is incomplete, studies suggest landfilling and incineration have been the most common ways to manage PVC waste [32] [35][36]. Recovered PVC from the recycling of cables typically ends up in the incinerator due to the presence of phthalates an other contaminants [32].

DEHP itself breaks down to carbon dioxide and water on incineration [30]. However, the incineration of PVC in general is not recommended, due to the generation of dioxins, the generation of hydrochloric acid (HCl) in the flue gas and, the generation of solid waste containing heavy metals [32][36].

Exposure: Indirect exposure through water and food is caused by the release of DEHP in the environment through water, air, soil [30] [19].Occupational exposure for workers through skin contact and inhalation.

B.8 Prioritizing risk hotspots due to DEHP used in charger cable through the life cycle

Human health risks of PVC floors through the life cycle (Table B2) indicates several risks, the most important being extrusion of tiles and exposure to children via floor dust. While occupational exposure can be addressed through risk management measures, exposure in the use phase is concerning. Floors have a large surface area and dust presents a media that emitted plasticizer can anchor to and cause exposure, and they are also amenable to be addressed through design strategies.

- Human Health risks of PVC floors through their lifecycle

LC Stage	Sub-classification	Exposure route	Endpoint	Risk Characterization Method	Indirect exposure	Risk Characterization
Production	Production of DEHP	Inhalation	Testicular, Developmental	Margin of safety	Washing drums sends 0.01% DEHP into wastewater	**9**
		Dermal	Testicular, Developmental	Margin of safety		**10**
		Combined	Testicular, Developmental	Margin of safety		**5**
	Extrusion	Inhalation, Dermal	Testicular, Developmental	Margin of safety	0.05% emissions into air, condensation on hot machinery	**5**
		Combined	Testicular, Developmental	Margin of safety		**2**
Use	Children touching flooring and licking hands	Oral (children)	Testicular	Margin of safety	0.01%/ year emissions into air for products of small surface area contact	**24**
	Interiors	oral + inhalation + dermal (children)	Testicular	Margin of safety		**21**
	Indoor dust on PVC floor tiles	Dust ingestion by toddlers, USA	Above reference dose for chronic oral exposure	Risk Quotient		1,775
		Dust ingestion by infants, USA	Above reference dose for chronic oral exposure	Risk Quotient		1,775
		Dust ingestion by children, USA	Above reference dose for chronic oral exposure	Risk Quotient		1,185

EOL	Landfill	Remaining DEHP leaches out into soil. Possible Bioaccumulation in humans from eating mammals eating soil dwelling organisms

Table B2. Human Health Risk for DEHP along the Life cycle. From [37][38] [39][40]*The first column shows the lifecycle stage, and sub-classification (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The exposure route (column 3) mentions how human beings are exposed to SoC (inhalation, dermal or oral exposure). The toxicity endpoint (column 4) mentions the organ systems that are affected. The Risk Characterization method (column 5) mentions whether Risk Quotient or Margin of Safety is used. Indirect Exposure (column 6) mentions emissions to the environment during the activity. Risk characterization (column 7) mentions the risk value color coded according to the heat map presented in Section 2.2.3.*

Prioritization of ecological risks (Table B3) pinpoints towards risks from landfills, where DEHP may leach and contaminate the adjacent soil and cause contamination of closely located local freshwater and secondary poisoning of mammals eating worms living in contaminated soil.

- Ecological risks for PVC floors through the Life Cycle

LC Stage	Activity	Compartment	Risk Characterization
Production	Resin production	Sediment	0.07
		Atmosphere	No risk
		Soil	0.005
		Secondary poisoning aquatic (fish eating invertebrates)	0.53
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.45
	Calendering	Sediment	0.08
		Soil	0.02
		Secondary poisoning aquatic (mammal eating fish)	0.23
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.031
Use	N/A		
EOL	Incineration	Sediment	0.06
		Secondary poisoning aquatic(fish eating invertebrates)	0.15
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.01
	Municipal STP	Sediment	0.3
		Soil	0.001
		Secondary poisoning aquatic (fish eating invertebrates)	0.53
		Secondary poisoning Terrestrial (mammals eating earthworm)	0.3
	Landfill	Local freshwater	16.1
		Secondary poisoning (small mammals eating worms)	8.63
		Secondary poisoning (large mammals eating worms)	43.2

Table B3. Relevant Ecological Risk Values for DEHP along the Life cycle. From [37] [41]

Table B3 is organized as follows. The first column shows the lifecycle stage, and activity (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The environmental compartment (column 3) mentions the environmental compartment where the SoC ends up. Risk characterization (column 4) mentions the risk value color coded according to the heat map presented in Section 2.2.3.

B.9 What are existing strategies to deal with DEHP?

This section presents and discusses different strategies identified in literature to reduce, control, and or eliminate the use of DEHP in flooring products. It provides further information on each strategy, when possible, to determine benefits and drawbacks, as well as unforeseen consequences or uncertainty.

- Eliminate – Substitute the additive

This strategy consists of substituting the DEHP with an alternative substance that provides similar technical characteristics. This strategy maintains the use of plasticized PVC. The change from using DEHP to using alternative substances could result in alternative environmental and health impacts. These should be studied further before deciding for substitution.

A. **Substitution with alternative phthalate plasticizers.** Phthalates in general have been linked to some form of hazard to the environment and health [6], [7]. However, not all phthalate-based plasticizers are listed as SoC nor regulated. Manufacturers choose to use these as replacement options for DEHP to maintain the quality, functional characteristics, and cost of their products [42], [43].
    a. **DINP and DIDP.** These phthalates have been used as an alternative for DEHP in PVC flooring, however, DINP related hazards are unclear and under research, specifically for carcinogenic and endocrine and reproductive disrupting characteristics [44]. DINP is regulated by REACH through Annex XVII, entry 52 with a maximum concentration of 0.1% in children’s products [10].

A. **Alternative Non-phthalate plasticizers.**
    a. **DINCH.** A non-phthalate plasticizer, used as a common DEHP alternative in PVC flooring products [43], [45], [46]. DINCH has been identified to have similar mechanical properties in comparison to DEHP and DINP [43], however, its processing is more energy intensive and costly [43]. DINCH has not been found to have hazardous effects on human health [47], [48]. There is little information over its ecological risks, some studies have found it to have toxic effects on aquatic life [49].

- Eliminate – Substitute the material

Alternatives to PVC flooring include a variety of flexible materials, such as PET and polyurethane, and bio composites such as linoleum, rubber and cork [1]. Additional alternatives include wooden floors.
Studies comparing the environmental impact of plasticized PVC to that of halogen free alternatives (e.g., PET and polyurethane) indicate that although they have a more energy intensive production, they are a better alternative to flexible PVC , because throughout their lifecycle they do not pose a health risk, do not produce any other fumes or dioxins and do not present other risks during landfill, recycling or incineration [50].
When comparing Vinyl flooring to Linoleum rubber and parquet (wooden floor), an LCA study could not recommend a better or worse flooring material in terms of environmental impact [51], although PVC was found to have the largest impact in chemical waste depending on the additives present in it. A second LCA study found solid wood flooring to be preferable over Linoleum and PVC [52].
It is important to note that these different materials have differences in performance and costs. Further and more detailed information over these differences is necessary to select a suitable substitute depending on the application.

- Control – preventing emissions/exposure during the use phase use phase

A. **Coatings and layered materials.** A study found that the migration of phthalates is also influenced by the structure of the PVC flooring material. UV coatings and layered floorings (without phthalates on the top layer) presented lower emission rates of DEHP in indoor environments [22]. Dust in direct contact with plasticized PVC presented higher amounts of phthalates [24].
B. **Improving indoor air quality.** Studies recommend combining ventilation systems and particle filtration systems in order to control and reduce the exposure to phthalates in indoor environments. Ventilation systems alone are not sufficient [24]. Additionally, studies recommend cleaning flooring surfaces periodically to avoid the accumulation of DEHP contaminated dust [14], [24], [30].

- **Reduce - increasing the useful life of flooring materials**

A. **Product selection based on requirements.** LCA studies have identified the useful lifetime of flooring to have the most influence over its environmental performance [51][52]. In addition to this, it can be assumed that a longer lifetime could represent a reduction of flooring material waste and a reduction in the accumulation of DEHP emissions during the EoL phase. Resilient floor coverings are expected to last 10 – 20 years, however, early retirement is usually attributed to the choice of the wrong type of flooring for a given application or for aesthetic and not functional reasons [51]. This highlights the importance of guiding the purchase decision to meet the specific requirements, for which the EN classification is useful [13]**.**
B. **Maintenance – Repair.** An alternative to increase the useful life of PVC flooring can be maintenance and repair. No information was found regarding the availability, technicalities and effects of maintenance and repair in the lifetime of flooring products. However, an internet search provides a variety of professional services and products available for both options. When analyzing the benefits of maintenance, it is important to consider the intensity of energy and water use and their effects in the environment [51].

- **Control - Prevent emissions through a controlled EoL**

A. **Recovery and controlled landfill and incineration.** According to a study [32], several Nordic countries have different policies that classify PVC waste into non-hazardous, and hazardous (flexible PVC). PVC waste is collected and sorted to then deal with hazardous PVC waste in controlled landfills (controlling DEHP emissions) or special incineration plants that control dioxin emissions.
B. **Recycling post-installation waste.** LCA studies on resilient floor coverings recommend the recycling of PVC flooring as a preferable scenario from the environmental point of view [51]. However, the presence of additives hinders the possibilities for safe recycling [32]. To overcome this issues some companies have installed a closed loop recovery and recycling systems of post installation waste (not post- consumer) [32].
C. **Monitoring and recycling of post-consumer waste.** This study found an example of a company that has a recovery and recycling program in place for post-consumer flooring waste. The service accepts post-consumer flooring waste of specific types of floorings from their catalog. They recover the approved material and use it in the production of new flooring products [53], [54]. This type of monitoring system allows them to avoid harmful chemicals while allowing the recycling of flexible PVC materials.

B.10 Evaluation of the application of screening LCA and RA to assess SbD strategies (existing/historical alternatives)

- **Baseline scenario**

It has been mentioned in Case 1 that DEHP is not available in Ecoinvent database and only some indicative production impacts were available via the CLICC tool. In Case 2, the baseline scenario draws upon the work done by CML in EC FP7 project RISKCYCLE, where a square meter of a cushioned flooring is modelled from cradle to grave [55]. Cushioned flooring is produced by spread coating several layers on a glass fiber substrate. The foamed layers are mixtures of polyvinyl chloride, plasticizer, limestone, stabilizers, pigments, and some other additives. As emissions of DEHP were lacking, and Material Flow Analysis studies were used for emissions of DEHP during production, use and end of life. For the waste disposal four different scenarios are considered: incineration of the cushion vinyl floor covering, landfill of the cushion vinyl floor covering (no emissions), land fill of the cushion vinyl floor covering (with DEHP emissions) and material recycling of the cushion vinyl floor covering [56].

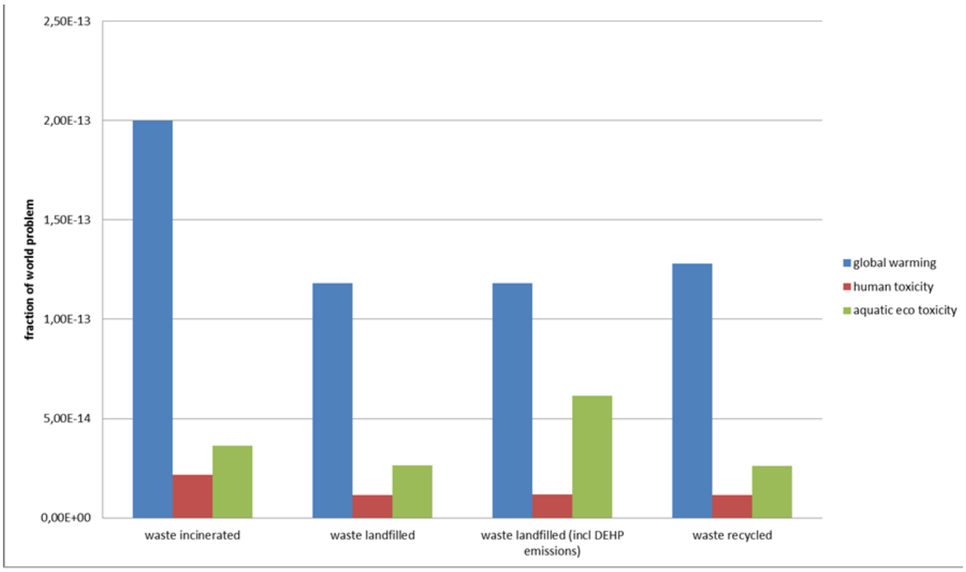


Figure B1.Normalized LCA results for PVC flooring for four waste treatment scenarios-Incineration, Landfill without DEHP emissions, Landfill with DEHP emissions and Recycling. The lifetime of the cushion vinyl floor covering is assumed to be 15 years. The maintenance of the floor during use phase is not considered. From [55]

Global warming is the biggest impact especially for incineration. Ecotoxicity impacts are next, especially for the uncontrolled landfill due to DEHP emissions. Human toxicity impacts are about the same, and not significantly caused by DEHP emissions (less than 1%).Significant contributors to aquatic ecotoxicity and human toxicity impacts are explored in Figure B2 and B3 respectively.

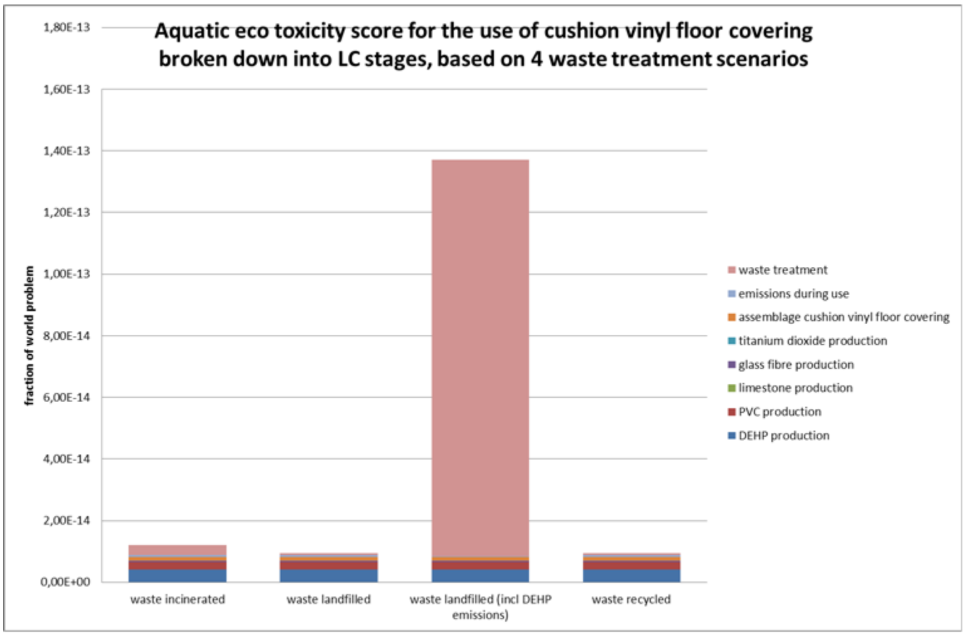


Figure B2.Contibution of Aquatic Ecotoxicity Impacts for four waste treatment scenarios-Incineration, Landfill without DEHP emissions, Landfill with DEHP emissions and Recycling. The lifetime of the cushion vinyl floor covering is assumed to be 15 years. The maintenance of the floor during use phase is not considered. From [55]

The comparison of aquatic ecotoxicity scores between the scenarios shows the importance of DEHP emissions from the (uncontrolled) landfill site. If an emission is assumed the score for aquatic ecotoxicity will increase fifteen-fold, resulting in a contribution of 56% toward ecotoxicity impacts. DEHP emissions during recycling contributes about 5% toward ecotoxicity impacts. DEHP emissions during vinyl cushion production, contributes around 10% of ecotoxicity impacts., while the impact of use phase emissions is 5%.

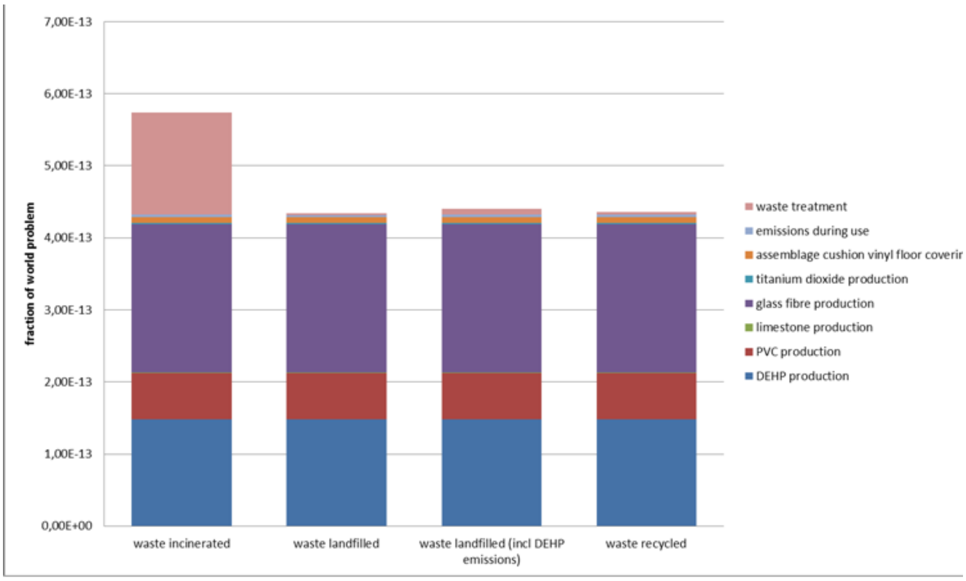
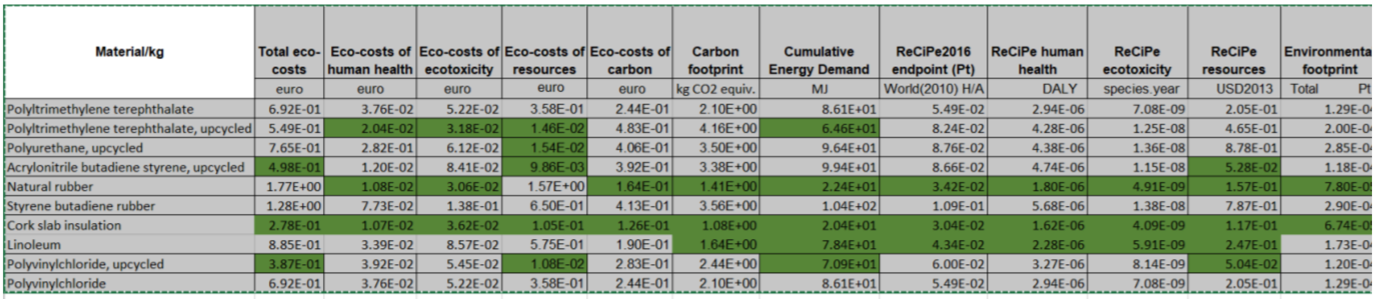


Figure B3. Contribution of Human Toxicity Impacts for four waste treatment scenarios-Incineration, Landfill without DEHP emissions, Landfill with DEHP emissions and Recycling. The lifetime of the cushion vinyl floor covering is assumed to be 15 years. The maintenance of the floor during use phase is not considered. From [55]

DEHP and glass fibre production contribute to the human toxicity impact, and incineration has by far to the highest score. During incineration, PVC will lead to toxic emissions of metals (antimony, selenium) causing human health effects. The scores for the other scenarios are more or less the same. Note that DEHP emission has a negligible contribution to the human toxicity impact category (contribution < 1%). It must be noted here that the human health risk assessment of DEHP has shown risk hotspots in the production and use phase.

- ### Assessment of strategies
- ### Eliminate – Substitute the material

In order to investigate the impact of potential flooring layers, materials (virgin or upcycled) that can be used within flooring were extracted from IDEMAT and compared to PVC. Materials doing better on an indicator than PVC are highlighted in green.



Material/kg	Total eco-costs	Eco-costs of human health	Eco-costs of ecotoxicity	Eco-costs of resources	Eco-costs of carbon	Carbon footprint	Cumulative Energy Demand	ReCiPe2016 endpoint (Pt)	ReCiPe human health	ReCiPe ecotoxicity	ReCiPe resources	Environmenta footprint
	euro	euro	euro	euro	euro	kg CO2 equiv.	MJ	World(2010) H/A	DALY	species.year	USD2013	Total Pt
Polyltrimethylene terephthalate	6.92E-01	3.76E-02	5.22E-02	3.58E-01	2.44E-01	2.10E+00	8.61E+01	5.49E-02	2.94E-06	7.08E-09	2.05E-01	1.29E-0
Polyltrimethylene terephthalate, upcycled	5.49E-01	2.04E-02	3.18E-02	1.46E-02	4.83E-01	4.16E+00	6.46E+01	8.24E-02	4.28E-06	1.25E-08	4.65E-01	2.00E-0
Polyurethane, upcycled	7.65E-01	2.82E-01	6.12E-02	1.54E-02	4.06E-01	3.50E+00	9.64E+01	8.76E-02	4.38E-06	1.36E-08	8.78E-01	2.85E-0
Acrylonitrile butadiene styrene, upcycled	4.98E-01	1.20E-02	8.41E-02	9.86E-03	3.92E-01	3.38E+00	9.94E+01	8.66E-02	4.74E-06	1.15E-08	5.28E-02	1.18E-0
Natural rubber	1.77E+00	1.08E-02	3.06E-02	1.57E+00	1.64E-01	1.41E+00	2.24E+01	3.42E-02	1.80E-06	4.91E-09	1.57E-01	7.80E-0
Styrene butadiene rubber	1.28E+00	7.73E-02	1.38E-01	6.50E-01	4.13E-01	3.56E+00	1.04E+02	1.09E-01	5.68E-06	1.38E-08	7.87E-01	2.90E-0
Cork slab insulation	2.78E-01	1.07E-02	3.62E-02	1.05E-01	1.26E-01	1.08E+00	2.04E+01	3.04E-02	1.62E-06	4.09E-09	1.17E-01	6.74E-0
Linoleum	8.85E-01	3.39E-02	8.57E-02	5.75E-01	1.90E-01	1.64E+00	7.84E+01	4.34E-02	2.28E-06	5.91E-09	2.47E-01	1.73E-0
Polyvinylchloride, upcycled	3.87E-01	3.92E-02	5.45E-02	1.08E-02	2.83E-01	2.44E+00	7.09E+01	6.00E-02	3.27E-06	8.14E-09	5.04E-02	1.20E-0
Polyvinylchloride	6.92E-01	3.76E-02	5.22E-02	3.58E-01	2.44E-01	2.10E+00	8.61E+01	5.49E-02	2.94E-06	7.08E-09	2.05E-01	1.29E-0

Table B4. Comparison of potential flooring materials based on IDEMAT 2022 database.

In the materials compared, cork slab insulation (a proxy for cork based flooring) does better than PVC on all indicators. Natural rubber does better than PVC on all indicators except total eco cost and all indicators based on resources. Taking other design criteria into account, it is a complex task to choose the best layers.
As plasticizer concentrations in indoor air tend to increase with flooring area, PVC should particularly be avoided in large facilities housing vulnerable populations[39].

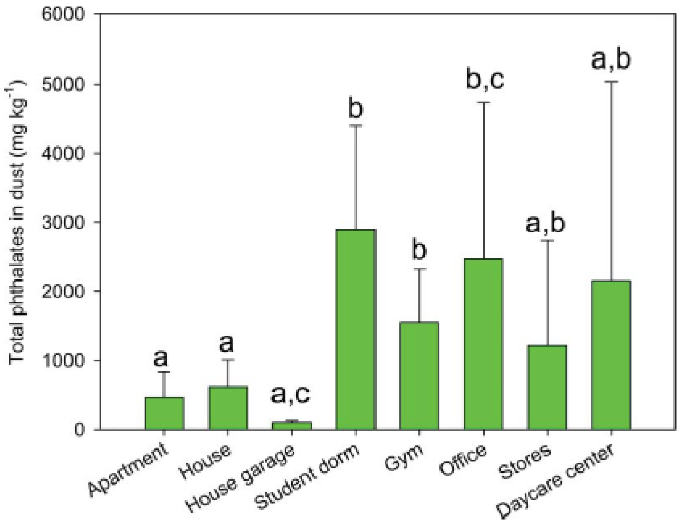


Figure B4. Phthalate concentrations in different locations. From [39]

- **Eliminate – Substitute the additive**

Substitution of the additive (phthalate and non-phthalate)- Predictive RA approaches

On providing the CAS number of DEHP, the Similarity tool provided the following chemicals (CAS numbers) that are likely to exhibit reproductive toxicity or endocrine disruption as DEHP does (Table B5).

Substitutions to be avoided

CAS numbers of chemicals likely to be reproductive toxins	CAS numbers of chemicals likely to be endocrine disruptors
68515-42-4, 84-75-3, 71888-89-6, 27554-26-3, 84-61-7, 131-18-0, 776297-69-9, 71850-09-4, 84-74-2, 605-50-5, 84777-06-0, 68515-50-4, 84-69-5, 85-68-7	84-61-7, 84-74-2, 84-69-5, 85-68-7

Table B5. ZZS Similarity Tool results for DEHP

The similarity tool indicated the following phthalates: 84-61-7 (dicyclohexyl phthalate), 84-75-3 (dihexyl phthalate), 85-68-7 (benzyl butyl phthalate), 84-69-5 (DIBP, diisobutyl phthalate), 84-74-2 (DBP, dibutyl phthalate), 605-50-5 (diisopentylphthalate), 71850-09-4 (diisohexyl phthalate), 776297-69-9 (N-pentyl-isopentylphthalate), 131-18-0 (di-n-pentyl phthalate) and 27554-26-3 (diisooctyl phthalate).These phthalates can be avoided as a substitution strategy.

- **Substitution of additive with alternative phthalate-based plasticizers - LCA**

Some production (cradle to gate) impacts of plasticizers DEHP, DIDP and DINP were available in the CLICC database and are presented and compared (Table B6). The functional unit is 1 kg of plasticizer. DPHP appears to have the most desirable environmental profile of the plasticizers considered.

Cradle to Gate Impact	Unit	DEHP	DIDP	DPHP	DEHP/DIDP	DEHP/DPHP	DIDP/DPHP
		117-81-7	68515-49-1	53306-54-0	%	%	%
Cumulative Energy Demand	MJ/kg	2.69E+02	1.90E+02	1.96E+02	141,58%	137,24%	96,94%
Acidification	moles of H^{+} eq./kg	2.51E+00	2.34E+00	2.05E+00	107,26%	122,44%	114,15%
Eco-indicator	points/kg	4.77E-01	3.94E-01	1.95E-01	121,07%	244,62%	202,05%

Climate Change	kg CO_{2} eq./kg	1.02E+02	1.94E+02	3.15E+02	52,58%	32,38%	61,59%
Human Health	DALY/kg	7.65E-04	1.44E-03	5.42E-04	53,13%	141,14%	265,68%
Ecosystem Quality	PDF-m^{2}-year/kg	1.59E-04	4.05E-04	2.40E-04	39,26%	66,25%	168,75%

🟩	Over 20% better
🟧	Over 20% worse

Table B6. Comparative evaluation of environmental impact of DEHP, DIDP and DPHP per unit mass. The data is extracted from the CLICC tool. DPHP seems to be the plasticizer with the least environmental impacts.

B.11 Conclusions – Main insights for designers

Table B7 provides a summary of the identified SbD strategies and their potential benefits and downsides according to literature and the RA, and LCA assessments when applicable.

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int].

Safe by Design strategies to deal with DEHP in PVC flooring				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential downsides
Eliminate	Substitution of DEHP by another phthalate-based plasticizer. DINP and DIDP.	[QE] [LCA] [RA]	- Similar functional characteristics [int], [43]. - Similar cost [int], [43].	- Some phthalate-based plasticizers have a similar hazard profile to DEHP [RA], [6], [44], [10]. - Unknown hazard profile for other phthalate-based plasticizers [6], [7]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [57]. - Some alternatives are currently regulated (DINP)[10]. - No clear winner, DPHP has the best environmental profile [lca].
	Substitution of DEHP by a non-phthalate-based plasticizer. DINCH.	[QE]	- Some types have comparable functional characteristics to DEHP [43].	- Unknown effects/ hazards for health and environment. DINCH does not appear to have health effects but potential effects on aquatic organisms [47], [48],[49]. - Higher cost [43]. - Lack of information and prioritization of cost and function may result in a regrettable substitution [57].
	Substitution of material - Alternative polymers and bio composites PET, PUR, linoleum, rubber, and cork.	[QE] [LCA]	- No known hazards to health or the environment [50].	- Unclear benefits and tradeoffs over environmental effects and functional performance [51], [52].

Control/ Prevent	Preventing emissions with coatings and layered materials	[QE]	- Coated flooring presented lower emission rates of DEHP in indoor environments [22] and lower migration of DEHP into dust [24].	- Only targets the use phase
	Controlling emissions by improving indoor air quality	[QE]	Ventilation systems, particle filtration systems, and cleaning flooring surfaces improve indoor air and reduce exposure to DEHP [14], [24], [30].	N/A
	Controlled recovery for controlled landfill and incineration of flooring waste	[QE]	- Avoids uncontrolled emissions from landfill and incineration [25], [19], [32].	N/A
	Recovery and recycling of post-installation flooring waste	[QE]	- Recycling can have the most env benefits for flooring materials [51]. - Avoids uncontrolled emissions from landfill and incineration [25], [19], [32].	- Recycling is hindered by the presence of plasticizers and other additives, so this strategy can only be applied to internal recycling cycles [32], [34], [int].
	Monitoring and recycling of post-consumer waste	[QE]	- Recycling can have the most env benefits for flooring materials [51]. - Monitoring of materials avoids the introduction of harmful additives. - Avoids uncontrolled emissions from landfill and incineration [25], [19], [32].	- Only possible to recycle products were it is certain that no DEHP or other harmful phthalates are present [53], [54].
Reduce	Increasing the useful life of flooring products - Product selection based on requirements.	[QE]	- Increase useful life can have a positive influence over env performance [51], [52]. - Guidance for buying decision can avoid early retirement due to failure or wrong product selection for a certain application [51]. The EN classification already in place [13]. - Reduce number of disposed floorings. Decreasing waste. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [25], [19].	- Only relevant to prevent waste and the accumulation of DEHP in landfills.
	Increasing the useful life of flooring products -	[QE]	- Increase useful life can have a positive influence over env performance [51], [52].	- Unknown effects (water and energy for maintenance) and availability of repair components [51].

	maintenance and repair.		- Reduce number of disposed floorings. Decreasing waste. Decrease of DEHP emissions in EoL (Uncontrolled landfill being of most concern) [25], [19].	

Table B7. Summary of identified SbD strategies for DEHP in PVC flooring

Most relevant emission/exposure scenarios - literature + RA

DEHP is not attached to the molecules of the polymer (PVC), making it possible for it to be released from the material into the environment throughout the lifecycle of the products that contain it [19]. This can occur through a number of mechanisms, including volatilization (transition of a liquid chemical into a vapor, which escapes into the atmosphere [21]), leaching (the loss of a compound from a material into a liquid), and migration (the transfer of a compound to another medium when in direct contact [26]).
This study found the production of the chemical and flooring, the use phase, and landfill to be the most concerning emission scenarios for DEHP in flooring. During manufacturing, industrial activities can discharge DEHP directly into the sewages as well as releasing volatilized DEHP in air particles and dust [19].
DEHP can volatilize into the air from plastic products, during the use phase, it is released into the air and dust of indoor environments with PVC flooring and/ or PVC wallpaper [14], [24], [30]. DEHP levels appear to be higher in dust particles than in air [24]. Emissions of DEHP from flooring may increase by a number of factors, including higher temperatures and humidity [22]–[24].

DEHP hinders the recycling possibilities of flexible PVC [32]. This is because phthalates remain in the composition of PVC after recycling, which could risk reintroducing contaminated materials into the market. For this reason PVC waste from construction is recommended to be collected separately and incinerated in specialized incineration plants [32]. However, even though PVC is highly recyclable, PVC waste is most commonly incinerated or sent to landfill [32], [35], [36]. Leaching and evaporation (over the long term) of DEHP in landfills could result in the contamination of air, groundwater and surface water [25][19].

Concerning exposure scenarios include 1) Occupational exposure during the production of DEHP and manufacturing of PVC flooring , where workers are exposed through skin absorption and inhalation [28] [30], 2) Indirect exposure to humans by the intake of contaminated water, food and inhalation of contaminated air [30][19], and 3) Direct exposure of users to DEHP from flooring through inhalation of indoor air and contaminated dust, skin contact and ingestion [14] [31].

Insights for designers and limitations

Types of strategies, scope of the strategy, benefits, and downsides

Like the case of DEHP in cables, substitution of the additive has been a common strategy to eliminate DEHP in PVC flooring. Uncertainty about the safety and potential effects of alternative phthalate and non-phthalate based plasticizers on human health and the environment can lead to regrettable substitutions of DEHP.

Although the cable case showed limitations to the strategy of substitution of the material, including limited performance and increased costs. The case of flooring showed several suitable material substitutions which are flexible without the need of a plasticizer, have the desired functional performance for certain applications and are currently commercialized.

Reduce strategies, such as informing product selection to avoid early retirement, and increasing the useful life of flooring through repair and maintenance, are only effective in avoiding DEHP (or other concerning phthalates) from accumulating in landfills. However, if further explored, and in combination with other strategies increasing the useful lifetime may have a positive influence over the overall environmental performance of flooring products. Control strategies appear to be limited to the development of additional products to prevent emissions or improve air quality. Additionally, those control strategies focused on the recovery and recycling of flooring materials, remain limited by the presence of DEHP.

Role of designers

Designers may have influence over the substitution of plasticizers and other chemicals in products if they are able to understand the product-substance combination, the properties, and potential effects of the SoC, and the functional requirements of the product. Additionally, designers must count with the knowledge to communicate with suppliers to either avoid regrettable substitutions or prevent emissions and exposure to limit the hazard of the substance in question.

Designers can also focus on the strategy of substitution of the material to achieve the functional, cost, and performance requirements of different applications whilst avoiding the use of PVC (and plasticizers) overall. Design can also play a role in strategies that aim to increase the useful life of flooring (Reduce strategies). By designing services that support customers in the correct purchase of a product companies could understand their customer needs better and avoid early retirement of products due to failure or inappropriate product selection. Additionally, designers can also develop systems that allow and facilitate the repair and maintenance of flooring products.

Decreasing emissions (Control/Prevent strategies) throughout the use phase was shown to be possible by the addition of top coatings or layers that avoid dust and air to be directly in touch with materials that contain DEHP. This can also be considered by designers in applications where eliminating DEHP or plasticizers overall is not possible for specific applications or functions.

Last, although designers may not have direct influence over strategies for a controlled EoL, incineration and recycling, and internal policies from manufacturers for monitoring of post-consumer waste for recycling, they may be involved in the design of the services that support those strategies (e.g., collection) or in the design of flooring products that can cope with the use of recycled materials.

Limitations and challenges

An important challenge when dealing with DEHP in flooring products is the transparent communication between chemical and polymer producers, and flooring manufacturers. Similar to the case of cables, PVC flooring manufacturers are using strict policies to communicate their requirements to their suppliers. Such as adherence to restricted substances lists and issuing material declarations.

Although studies on the environmental impact of resilient floor coverings recommend the recycling of PVC flooring as the preferable option [51], the presence of plasticizers hinders the possibilities for safe recycling. To overcome this challenge, some companies have installed a closed loop recovery and recycling systems for post installation waste (not post- consumer), making sure only known materials (without DEHP) are used. In order to make it possible for post-consumer flooring waste to be recycled, DEHP and other harmful plasticizers need to be phased out or removed through chemical recycling. Additionally, monitoring systems need to be further developed to avoid other harmful chemicals and DEHP in older discarded products that may still contain them.

B.12 Limitations of the case study

As with Case 1, there was no information about DEHP in Ecoinvent and information from a previous study was used to assess the impacts of DEHP in PVC based flooring. The impacts of non-phthalate bio based plasticizers could also not be explore due to lack of information.

Layered flooring, with alternative sequences of PVC and other materials, could not be explored due to lack of information. Information on PVC itself was used from MFA studies, there was no information on how much emissions could be reduced if PVC was in different positions in layered flooring.

While many papers talked about the importance of maintenance of flooring in the use phase, there was not enough information to explore such SbD strategies quantitatively.

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Appendix C – Extensive description of Case 3

This appendix presents the complete investigation of Case 3 – Microplastic release from agricultural mulch films. A summary of this case is provided in Chapter 3.1.3 of the report. It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 3.1.3 of the report. This was done with the purpose of having the complete documentation of each one of the cases, and to present the structure followed to investigate them.

Case 3 – Microplastics release from agricultural mulch films

C.1 Introduction

Plastic mulching is an increasingly common agricultural practice that consists of covering agricultural soils with plastic films, commonly made of polyethylene, to create a barrier to avoid water evaporation, increase the soil temperature, protect soil from pests and contaminants, and control weed growth [1]–[3]. In 2016 there were 20 million hectares using plastic mulch films around the world (with China covering approximately 90%), and Europe covering up to 427,000 hectares. The plastic mulching global market was calculated back then to be 4 million tons, and expected to grow 5.6% every year [3], [4].

Although plastic mulching is found to have many benefits on product quality, growth, and yield of crops [1], [4], it has also been found to be a major contributor of macro and microplastic release in terrestrial environments. This mainly due to its increasing and continuous use, to meet the growing global food demand, and the improper removal and disposal of the films [2], [3], [4]. Macro and microplastics generated from plastic mulch films accumulate in the soil throughout time and may have long-term negative effects in soil quality [4].

C.2 What is the substance?

Macro and microplastics have different definitions in literature, the most commonly used in publications involving agricultural mulch films are used in this document. Microplastics are defined as small plastic particles of less than 5mm in diameter, released into the environment from plastic products, while Macroplastics are defined as plastic particles of greater than 5mm diameter [5], [6].

Microplastics can also be classified as primary or secondary based on their source. Primary microplastics are purposely made small and introduced into products (e.g., microbeads in exfoliants and toothpaste). Secondary microplastics, are those resulting from the breakdown of larger plastic bodies through mechanical, chemical and/or UV degradation [5], [6]. The latter fits the case study of agricultural mulch films, which can be a source of macro and microplastics when degrading throughout their lifecycle.

C.3 How is the substance currently regulated? In which applications?

Even though they account for the largest contribution to microplastic pollution [5], there are currently no regulations in place specifically applied to secondary microplastics , nor microplastics generated by agricultural plastic mulch films. Primary microplastics have been regulated in certain areas (Canada, USA, France), with the regulations focusing on eliminating microbeads from cosmetic products [5]. There is a proposed restriction being currently revised by the ECHA to ban microplastics being intentionally added to products [7].

Although secondary microplastics are not specifically banned or controlled, some regulations focus on the reduction and management of plastic waste. Banning or controlling landfills, promoting recovery and recycling, and reducing the consumption of single use plastics are some examples of existing regulations that contribute to the reduction of microplastic pollution in Europe [5], [8], [9].

C.4 What is the function of the substance in the product?

The use of plastic mulch films has many benefits, including the reduction of development times of seeds and fruits, crop yield increase, conservation of water, reduced weed growth, increased product quality, and reduced pests and diseases; even in cold and arid areas [2], [4], [10]. This results in a less intensive use of water, and reduced use of pesticides and fertilizers [4], [10].

These benefits are possible because plastic mulch films maintain soil moisture and create a protective layer on the crop from external conditions, such as rainfall, hail, human and animal traffic, and erosion from wind and water. Films can also modify soil temperatures by absorbing, transmitting, or reflecting solar radiation [1], [4]. The optical and physical properties of the films can be modified to increase, slightly lower, or maintain soil temperatures depending on the type of crop and local climate [4].

Films are available in different colours and thicknesses and have additional compounds added to them to provide different functions, including extending their useful life and reducing UV degradation depending on the application [4], [11].

Two commonly discussed characteristics required from plastic mulch films are flexibility and resistance to tear and wear, to ease the installation and removal processes [10].

C.5 Substance presence and release classification. (Using the proposed classification)

- **How is the substance present in the material?**

The SoC (microplastics) is inherently bound to the composition of the material, as it is the plastic itself that breaks down into smaller particles that are released into the environment.

- **How is the material present in the product?**

Low density polyethylene (LDPE) and Linear low-density polyethylene (LLDPE) are commonly used to produce mulch films due to their flexibility, high impact resistance, ease of processing, low cost, and to reduce the weight of the film [1], [4], [12]. The films are produced by casting or blown film [11].

Additives are used to adjust the properties of the films, to withstand environmental conditions, modify their capacity to absorb and transfer solar radiation, to withstand mechanical degradation and increase their useful life [11]. These additives can include UV stabilizers, pigments, plasticizers, co-polymers [4], [11].

- **How is the substance released into the environment? Through which mechanisms?**

Plastic aging and degradation cause the mulch film to break into macro and microplastics [13]. Macroplastics left on the soil also eventually degrade further into microplastics if not removed from the soil [3]. Degradation of mulch films has been linked to UV exposure [13], type of material (Biodegradable, photodegradable, PE) [13], and farming activities (irrigation systems and mechanical input)[2].

C.6 What are the possible hazards to health and the environment?

Microplastics are ubiquitous contaminants, increasingly present in the environment as a result of the increased production, consumption, and low recovery of plastics. Due to their resistance to degradation, they can remain for long periods of time in the environment [3], [5]. Additionally, other pollutants are easily adhered to them and transported to different environmental compartments (water, soil, air) having different effects in the environment [5].

The effects of microplastics have been studied mostly in terrestrial and aquatic wildlife, identifying feeding and reproductive disruptions as well as metabolic disturbances [3], [5]. So far, humans have been found to be exposed to microplastics indirectly and directly through food, water, and air. Some of the studied health impacts include respiratory problems, cardiovascular diseases, and obesity [5]. Exposure to plastic particles can also have a negative impact in health if the plastic is contaminated by hazardous additives, such as plasticizers and flame retardants, or adhered pathogens [5]. Some of these plastic additives have been identified as carcinogenic and endocrine disruptors [14]. Additionally, exposure through inhalation has been related to respiratory symptoms and asthma [5]. The long-term effects of human exposure to microplastics are unclear and further research is necessary.

Environmental and health concerns specific to microplastic contamination through plastic mulches include damages to soil health, including changes in humidity, modified PH, and loss of nutrients, long term yield reduction when films are not removed and disposed, and food contamination, all of which have implications for food security [3], [10]. Additionally, literature highlights possible hazards of plastic mulch films that release harmful additives into the soil either during use, through microplastic release, or during EoL when landfilled [4], [15].

C.7 How and in which stage of the life cycle of the product do emissions of the substance occur? *How much of the substance is emitted?* And how does exposure occur?

When microplastics are identified in an environmental compartment (soil, water, air) it is challenging to identify their origin, and quantify the contributions, due to the complexity of the sources [16]. Material Flow analysis in Switzerland has identified soil as an important environmental compartment where microplastics end up (73 grams per capita as compared to 13.3 grams per capita for water), and emissions of LDPE was identified as the primary source of microplastic from agricultural films [17]. This section illustrates potential microplastic emission scenarios for agricultural mulch films throughout their lifecycle. For some lifecycle stages it is possible to provide quantitative data and closer estimations over the potential sources, while some stages only provide general information.

- Extraction and manufacturing

Emission: Although unclear for agricultural mulch film production, several studies have identified plastic residue in ecosystems near plastic processing plants, in water and terrestrial environments [5], [16]. Studies also discuss potential emissions into waste water [5], [16]. This could be evidence of microplastic release during the manufacturing phase of the plastic films. Studies also discuss the potential presence of airborne microplastics in plastic processing sites [5].

Exposure: Occupational exposure via inhalation, causing respiratory symptoms, and indirect exposure from contaminated water, air, food and soil [5], [16].

- Use

Emission: During the use phase, agricultural plastic mulch films are exposed to environmental conditions that can contribute to their deterioration and release of microplastics in the soil. The most important factor identified to affect the plastic mulch films integrity is UV degradation [13]. Plastic aging has been observed in films exposed to the environment, presenting chemical change, reduced strength, deterioration of the surface, and fragmentation [13].

A study [13] measured the amount of microplastic particles present in different samples of soil covered with 4 different plastic mulch films (Biodegradable (PBAT), Oxodegradable, White PE and black PE) exposed to UV radiation simulated in a weathering chamber. The results showed the presence of microplastics from day 28. At day 70, they measured cumulative quantities of 475, 265, 163, and 147 particles/cm2 in the biodegradable, oxodegradable, white PE mulch and black PE mulch respectively. This shows microplastics accumulate in the soil throughout the use phase, and this can be attributed to the aging and deterioration of the films, which can be used for months or even years depending on the type of crop [13].

Other studies [2], [3] found higher numbers of macroplastics and microplastics in samples from areas that continuously use plastic mulch films in comparison to those using films intermittently and doing crop rotation. Finding 97.4 kg/ha of macroplastics in areas with 6-8 years of continuous mulching and 53.7 kg/ha in areas with 30 years of intermittent mulching [2]. Macroplastics left on the soil also eventually degrade further into microplastics if not removed from the soil [3].

An additional element found to influence the amount of microplastic release from plastic mulch films is degradation from farming activities, suggesting farms with manual labour may have lower amounts of macro and microplastic release as opposed to farms with irrigation systems and high mechanical input [2].

Exposure: Indirect exposure from contaminated soil and food [5]. Additionally, literature highlights possible hazards of using plastic mulch films that could release harmful additives into the soil [4], [15].

- Recovery – Removal of the plastic mulch film

Emission: The removal and proper disposal of plastic mulch films is a labour-intensive and expensive activity. In consequence, plastic mulch films are often left on agricultural areas where they break down into smaller plastic particles over time. This has been highlighted as an issue of major concern in relation to the accumulation of microplastics in the soil in several publications [2]–[4], [10], [13]. The degradation of the film during the growing season also complicates its removal in its entirety [13]. The leftover of the film is sometimes buried and sometimes just left on the surface [1].

Some of the identified ways for people to remove the plastic mulch film include field discing, physical removal, and on-site burning [1]. The last is commonly adopted by farmers because it is the most convenient and cheap option, avoiding removal and transportation costs, as well as landfilling and incineration tipping fees [1]. On-site burning can generate air pollutants, for which it is illegal in some areas [1], [10].

Exposure: Indirect exposure from contaminated soil and food [5]. Additionally, literature highlights possible hazards of using plastic mulch films that could release harmful additives into the soil [4], [15].

- **Recycling and limitation of recycling**

Emission: Although recycling is the preferred alternative to incineration and landfill, removed plastic mulch films are not suitable for the process due to high contents of contaminants, including soil, vegetation, water, and agrochemicals, such as pesticides [1], [4], [10]. Plastics films are only accepted for recycling with less than 5% of contaminants by weight. This is easily surpassed, since mulch films can have a contamination of 40% - 50% by weight [1]. In addition to this, films that are heavily degraded by UV light may also not be suitable for recycling [1].

Although no emissions of microplastics were found to be linked to the recycling of mulch films, it is relevant to highlight that the limitations to recycling push farmers to adopt other disposal practices that may be more harmful to the environment.

Exposure: No exposure routes to microplastics were found to be linked to the recycling of mulch films.

- **EoL – Landfill**

Emission: Landfilling is used in areas where recycling and incineration facilities are not available [10]. Mulch films are not suitable for landfill due to their contamination with additives and agrochemicals, which can leach [4]. Plastics accumulate in landfills where they continue to degrade from macroplastics into microplastics. In addition to hazardous substances, microplastics concentrations (0.42 to 24.58 items/L) in landfill leachates have been found [18], [19]. The leachate could leak into the environment during landfill or during treatment processes to eliminate hazardous substance from the leachate [19].

Exposure: No exposure routes to microplastics were found to be specifically linked to the landfill of mulch films. However, if the leachate is contaminating the soil, as well as ground and surface waters we could assume it is a possible source of indirect exposure from contaminated water, food and soil [5], [16].

- **EoL – Incineration**

Emission: Limitations in space for landfill as well as the limitations for recycling due to the mulch film contamination, make incineration an alternative common practice for disposal [1], [4]. Due to their energy potential content, PE films are suitable for incineration with energy recovery but in many cases are not accepted by the incinerators due to their level of contamination with dirt, vegetation, additives, and water [4]. Although it has not been studied extensively, a study found the presence of microplastics in incinerator ashes, suggesting incineration may not be a solution to microplastic generation from plastic waste [20].

Exposure: No exposure to microplastics were found to be specifically linked to the incineration of mulch films. However, wastewater or soil contamination with microplastics will depend on the management of the ashes produced by the process of incineration.

C.8 Prioritizing emission/exposure scenarios

In order to assess the risk hotspots arising from the use of microplastics from mulch films, we searched for ecological and human health risk assessments of mulch films.

- Human Health risks of microplastics derived from mulch films through their lifecycle

The understanding of human health of microplastics is poorly understood due to lack of standardized reference materials (different sizes, shapes and coatings) as well as the need for sampling techniques in the micro and nano size range [21]. Recent studies show that microplastics from a variety of sources are ubiquitous in the environment [22] . Soil was indicated as the main environmental compartment where microplastics accumulate [17], so exposure through agriculture or groundwater is likely to be important source of indirect exposure. The chief types of microplastics in the soil were based on Low Density Polyethylene and Polyvinyl Chloride[17].

- Ecological risks for microplastics derived from mulch films through the Life Cycle

As clear data is not yet available for deterministic risk assessment of microplastics in the environment, some Probabilistic Risk Assessment (PRA) studies for ecological target have been reviewed. PRA are typically based on Material Flow Analysis studies that assess material flow of a substance through a defined economy, and how much SoC typically ends up in each compartment. Due to the nascent stage of our knowledge on microplastics, ecological risks are generic and could not be calculated for specific activities. Further, It is not always possible to place PRA results on a heat map as they are not expressed in terms of ratios.

- Ecological risks for microplastics produced from mulch films through the Life Cycle

Lifecycle Stage	Environmental Compartment	Risk
Production/Use/End of Life	Soil	1.28
	Marine	PRA: 10^{-4} but small part of the probability distribution is beyond 1
		PRA with future scenarios: 0.17% of the surface of the Mediterranean Sea and the Yellow Sea is at risk due to microplastic. Under business as usual, this fraction increases to 0.52% (2050) and 1.62% (2100).
	Freshwater	PRA: 1.3·10-6 in North America, 3.3·10-6 in Europe and 4.6·10-3 in Asia
		Toxicokinetic study: The promoted oxidative stress in zebrafish response to continent-based MPs exposure concentration with probabilities exceeding 50% ranged from 0.18–0.42-fold increase from control

Table C1. Relevant Ecological Risk Values for microplastics emitted from Mulch Films along the Life cycle. From [23][24][25][26]

Table C1 is organized as follows. The first column shows the lifecycle stage. The environmental compartment (column 2) mentions the environmental compartment where the SoC ends up. Risk characterization (column 3) mentions the risk value color coded according to the heat map presented section 2.2.3.

Soil is the chief environmental compartment that is of concern with respect to microplastics. Marine environments are of concern under conditions of high microplastics production and accumulation in the environment. For freshwater, while one study showed no risk, a mechanistic study on oxidative stress showed a significant increase in response above control [25].

C.9 What are existing strategies to deal with microplastics from mulch films?

- Eliminate - Substitute the material.

A. **Photodegradable and Biodegradable alternatives.** This strategy has been developed as a response to the challenge of recovering the mulch film after use, having a material that does not need to be picked up and is degraded by natural processes [1]. Photodegradable films degrade by chemical reactions triggered by light [1], [10]. Biodegradable films are made of materials (several film types are available, including bio based and petrochemical based plastics) that are degraded into the soil when transformed by microorganisms into carbon dioxide, water, methane and other organic compounds [1], [10]. This type of films has been studied extensively for about 20 years and present similar to better functional performance than PE films (product quality, growth, and yield of crops) [1], [10], but still present several negative effects and challenges [1], [4], [10], [13], [27], [28]:

- Photodegradable films may be less effective in areas with lower solar radiation.
- Photodegradable and biodegradable films could degrade prematurely, during growing season.
- There is concern and uncertainty regarding complete degradation and possible consequences for soil quality.
- Photodegradable and biodegradable films are both more expensive than PE films, since their production costs are higher.
- Biodegradable films were found to break down into microplastics faster that PE films.
- Big challenge for material science to follow requirements over agricultural cycles. Maintaining its properties during use and degrading at the right time and rate.

B. Paper mulch. Paper mulch was a common mulching technique in the past [10]. It can be naturally degraded unless other materials, such as PE, are added [10]. Paper mulch, however, can tear easily and its installation can be challenging, additionally, they are most expensive than PE films and have a shorter useful life due to environmental conditions [10].

C. Biobased alternatives – Agricultural waste and living mulches

Straw – This mulching technique is biodegradable and a good alternative costly recovery of PE films [10]. However, it is not suitable for all crops since it can positively or negatively influence yield [10], [29], [30]. Straw is mostly sourced from agricultural waste, so its quality and availability cannot be ensured [29], [31], [30].

Woodchips – Like straw, this alternative is biodegradable and a good alternative to PE films in terms of recovery. It has also been observed to be effective in controlling weed infestation, but not very efficient at soil water conservation [30]. It also presents availability problems, and attention must be given to the source to ensure quality [29], [30].

Living mulches – White clover and different types of grass are examples of living mulches [29]. These alternatives are still under test for their effects on soil quality, competition for nutrients, and effects on yield [29]. Some studies found that uncontrolled use of living mulch films had negative effects on yield [30].

- Reduce – Phase out / use less

A. Reduce overall use – intermittent use and variation in crop types

Studies [2], [3] have found that areas with continuous use of plastic mulch films present higher numbers of macroplastics and microplastics in comparison to those using films intermittently and doing crop rotation. The limitations of this possible strategy are unknown.

- Control – Prevent emissions by preventing degradation

A. Reduce mechanical degradation – less machine/automated input

Farms with high input of mechanical processes and irrigation systems were found to have higher amounts of macro and microplastic release in comparison to those with manual labour and less mechanical input [2]. In addition to a reduction of microplastic release, maintaining the film in good condition could benefit its recovery. The limitations of this strategy are unknow, however, it can be inferred that it may be limited to smaller agricultural areas with lower production volumes.

- Control – Prevent emissions by collecting

A. Mulch recovery systems

A possible response to the challenges of mulch film recovery after use are mulch film recovery systems. These consist of machinery pulled by tractors that retrieve the films into rollers [32], [33]. The exact recovery rate of these systems is unclear, as well as their costs and availability.

B. Recycling of plastic mulch films.

Although recycling is the preferred alternative to incineration and landfill, removed plastic mulch films are not suitable for the process due to high contents of contaminants (40% - 50% by weight), and high levels of degradation [1], [4], [10]. These study found a few examples of recycling processes available for plastic mulch films [34], [35], which include several cleaning steps. The limitations, costs and availability of these systems are unknown.

C.10 Evaluation of the application of screening LCA to assess SbD strategies (existing alternatives)

- Baseline scenario

For the baseline scenario, a functional unit of a hectare of mulch film of thickness of 25 µm was selected. To model the production phase impacts, Ecoinvent was searched with keywords "mulch' and "plastic". No relevant activity was found. The activity chosen as a proxy for the mulch film was for the screening LCA was a low density polyethylene packaging film. Relative impact categories were explored (Figure C1), though emissions of microplastics from mulch films could not be explored via screening due to lack of information. The screening analysis indicated that freshwater ecotoxicity is the chief impact, followed by global warming potential. The greatest contribution to ecotoxicity was from emissions of aluminium to air and soil.

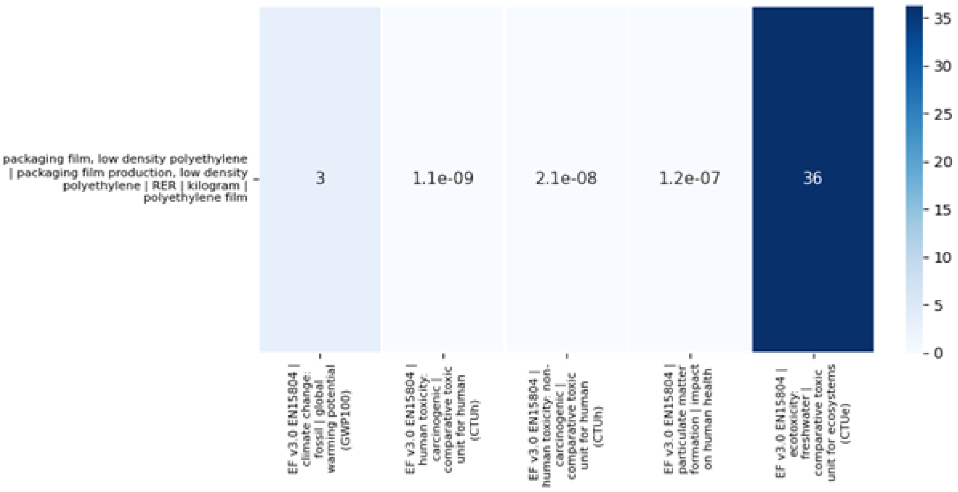

Figure C1. Baseline Scenario for One Hectare of Polyethelene Mulch film. Impacts expressed in Points

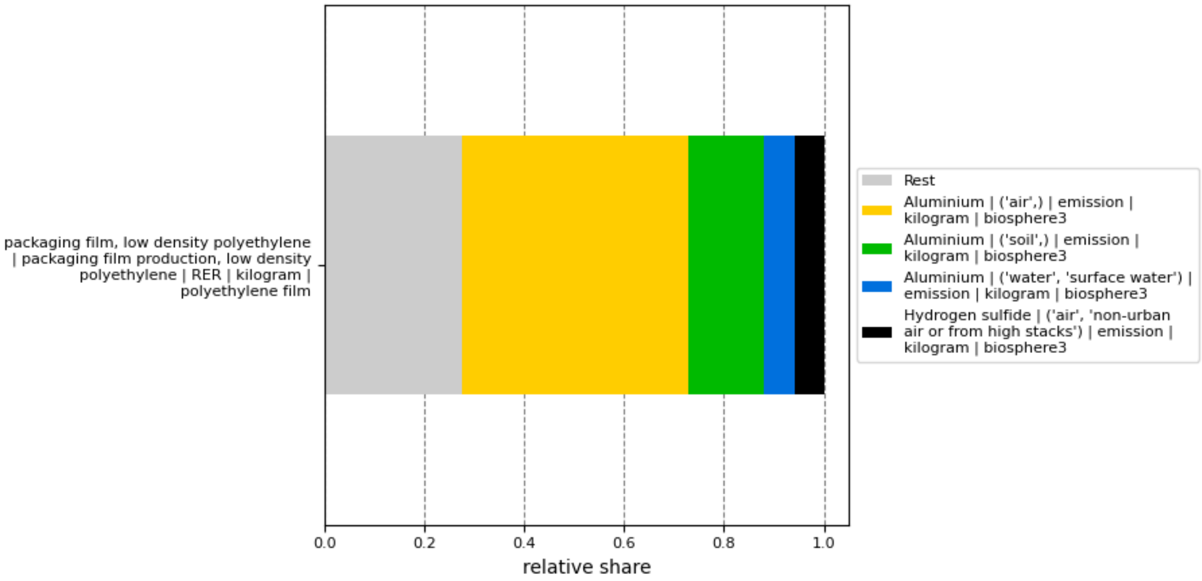

Figure C1a. Contributions to Freshwater Ecotoxocicity Impact from One Hectare of Polyethelene Mulch film. Aluminium emissions to air and soil had the greatest contribution toward freshwater ecotoxicity.

- **Assessment of strategies**
- **Eliminate - Substitute the material-Recyclable and Biodegradable alternatives**

A study compared the environmental impacts of mulching films from fossil based feedstock (virgin Low Density Polyethylene (LDPE) and recycled LDPE (R-LDPE)) with biodegradable alternatives (starch based biopolymer and Poly Lactic Acid based biopolymer) [36]. ***Microplastics emissions were not considered in this assessment.*** The functional unit is defined as “mulching 1 ha of cultivated land in Europe”. Overall, R-LDPE showed lower impact than LDPE for all impact categories except human toxicity-cancer. The starch based alternatives did better than the fossil fuel based alternatives on all categories except land use. PLA based alternative did less good; ozone depletion, climate change and acidification impacts were comparable to the other alternatives. The toxicity impact categories through the lifecycle (Figure C2) shows production as the phase with the greatest impact, and starch based mulch films as the best in terms of human toxicity whereas PLA based films as the best in terms of freshwater ecotoxicity impacts. Thus, there is no clear best alternatives, although all alternatives perform better than virgin LDPE overall.

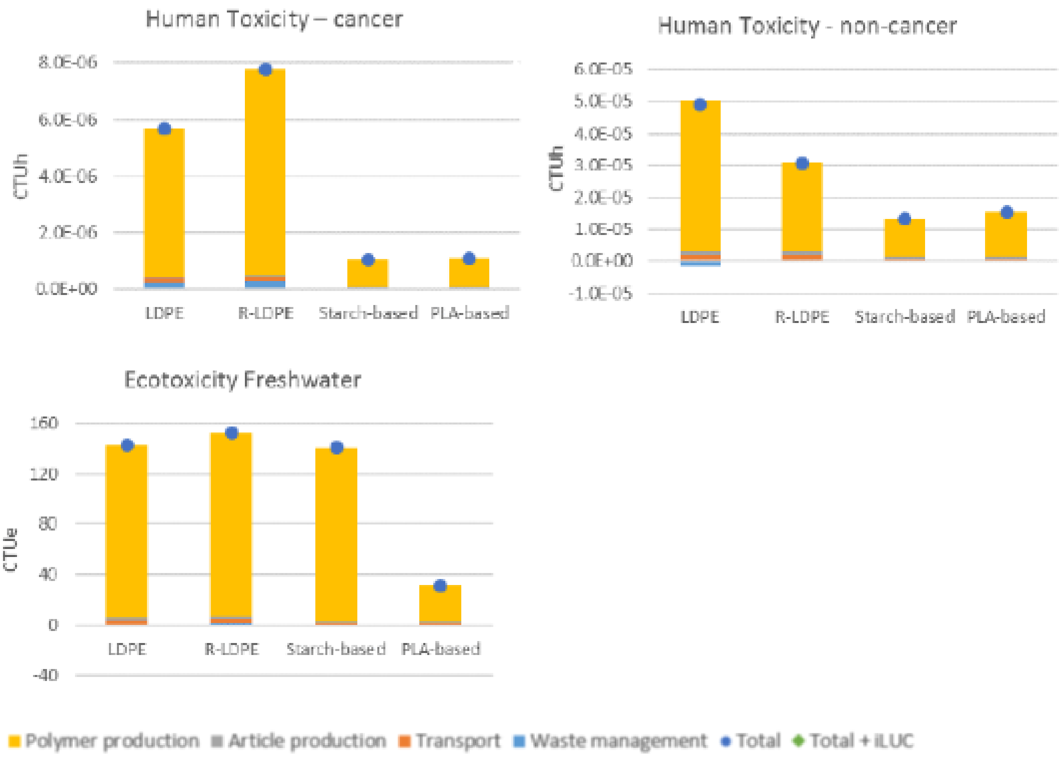

Figure C2 Comparison of environmental impacts through the Life Cycle of one hectare mulch films for the following scenarios: LDPE, recycled LDPE, starch based biopolymer and PLA based biopolymer. Impact expressed in Comparative Toxicity Units (CTU), from [36].

Eliminate - Substitute the material-Biobased alternatives – Agricultural waste and living mulches

The impact of wood chips could be explored based on an activity available in Ecoinvent. ***Microplastics emissions were not considered in this assessment.*** A bulk density of 165 kg dry matter per cubic metre loose volume of chips and a thickness of four inches was considered. As transportation is a significant element in the production of wood chips,” lorry under 7.5t, EURO 3” was chosen. It was found that the freshwater ecotoxicity of wood chips was substantially higher than polyethylene film spread on the same area.

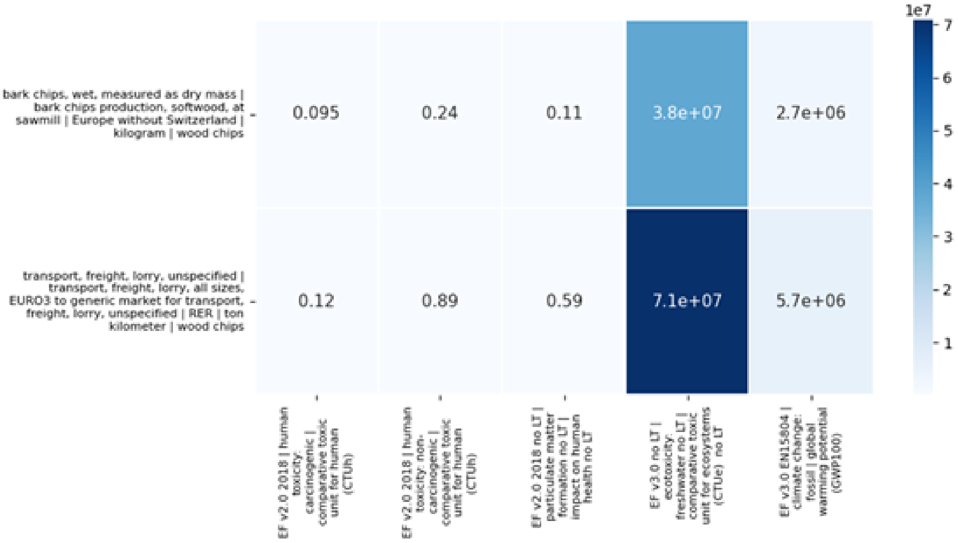

Figure C3 Environmental Impacts of wood chips spread on one hectare of land with a thickness of 4 mm. Impacts are expressed in CTU.

C.11 Conclusions – Main insights for designers

Table C2 provides a summary of the identified SbD strategies and their potential benefits and downsides according to literature and the RA, and LCA assessments when applicable.

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int]

Safe by Design strategies to deal with microplastic release from agricultural mulch films.				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential downsides
Eliminate	Substitution of material for photodegradable and biodegradable mulch films	[QE]	- Could substitute the need of collecting the film after the harvest [1], [4], [10].	- Concerns about complete degradation [1], [4], [10], [13], [27], [28], [int]. - Photodegradable films degrade prematurely [1], [10]. - Biodegradable degrade faster into microplastics than PE films [13]. - Unclear effects on crops and soil quality [27], [28], [int].
	Substitution of material for paper mulch	[QE]	- Eliminates microplastic release unless combined with PE [10].	- Lower durability [10]. - Higher costs than PE [10].
	Substitution of material for Biobased alternatives. (Straw, woodchips, living mulches)	[QE], [LCA]	- Eliminates the use of plastic mulch films and challenges related to recovery [10], [29], [30].	- Not suitable for all crops [10]. - Availability problems and quality cannot be guaranteed [29], [31], [30]. - Unclear effects on soil quality and yield [29], [30]. - Reduced efficiency over soil water conservation [30].
Control/Prevent	Reduce mechanical degradation – less machine/automated input	[QE]	- Avoids the film from breaking/degrading during use, reducing microplastic release and facilitating its collection [2].	- Unknown limitations and consequences over production.

	Mulch recovery systems	[QE]	- Collection avoids macro and microplastic emissions of leaving the film behind [2]–[4], [10], [13].	- Unknown costs and availability. - Unknown collection rates.
	Recycling of used agricultural mulch films	[QE]	- Reduction of microplastic emissions due to recovery [2]–[4], [10], [13]. - Some systems include cleaning steps to reduce contamination [34], [35].	- Challenges due to contamination with soil [1], [4], [10], [int]. - Unknown limitations, costs, and availability.
Reduce	Reduce overall use – intermittent use and variation in crop types	[QE]	- Reduces microplastic emissions. Fields with intermittent use have an important reduction compared to continuous use [2], [3] .	- Unknown limitations and consequences over production.

Table C2. Summary of identified SbD strategies for microplastic release from agricultural mulch films

Most relevant attention points - emission/exposure scenarios

This study found the use phase, uncontrolled recovery, and landfill to be the most concerning emission scenarios of microplastics from agricultural mulch films. During the use phase, agricultural plastic mulch films are exposed to environmental conditions that can contribute to their deterioration and release of microplastics in the soil, including UV degradation and mechanical degradation [13]. Microplastics were found accumulate in the soil throughout the use phase, and this can be attributed to the aging and deterioration of the films, which can be used for months or even years depending on the type of crop [13].

The removal and proper disposal of plastic mulch films is a labour-intensive and expensive activity. In consequence, plastic mulch films are often left on agricultural areas where they break down into smaller plastic particles over time. This has been highlighted as an issue of major concern in relation to the accumulation of microplastics in the soil in several publications [2]–[4], [10], [13]. The degradation of the film during the growing season also complicates its removal in its entirety [13]. The leftover of the film is sometimes buried and sometimes just left on the surface [1].

When recycling and incineration facilities are not available mulch films are deposited in landfills where plastics accumulate and continue to degrade from macroplastics into microplastics [10]. Additionally, mulch films are not suitable for landfill due to their contamination with additives and agrochemicals, which can leach into the soil and water [4]. No direct exposure routes were found for microplastics from agricultural mulch films. Indirect exposure from contaminated soil and food is highlighted as a concerning exposure scenario [5]. Additionally, literature highlights possible hazards of using plastic mulch films that contain harmful additives that could be released into the soil [4], [15].

Types of strategies, scope of the strategy, benefits, and downsides

Like the case of DEHP in cables, substitution of the additive has been a common strategy to eliminate DEHP in PVC flooring. Uncertainty about the safety and potential effects of alternative phthalate and non-phthalate based plasticizers on human health and the environment can lead to regrettable substitutions of DEHP.

Although the cable case showed limitations to the strategy of substitution of the material, including limited performance and increased costs. The case of flooring showed several suitable material substitutions which are flexible without the need of a plasticizer, have the desired functional performance for certain applications and are currently commercialized.

Reduce strategies, such as informing product selection to avoid early retirement, and increasing the useful life of flooring through repair and maintenance, are only effective in avoiding DEHP (or other concerning phthalates) from accumulating in landfills. However, if further explored, and in combination with other strategies increasing the useful lifetime may have a positive influence over the overall environmental performance of flooring products. Control strategies appear to be limited to the development of additional products to prevent emissions or improve air quality. Additionally, those control strategies focused on the recovery and recycling of flooring materials, remain limited by the presence of DEHP.

Role of designers

Designers may have influence over the substitution of plasticizers and other chemicals in products if they are able to understand the product-substance combination, the properties, and potential effects of the SoC, and the functional requirements of the product. Additionally, designers must count with the knowledge to communicate with suppliers to either avoid regrettable substitutions or prevent emissions and exposure to limit the hazard of the substance in question.

Designers can also focus on the strategy of substitution of the material to achieve the functional, cost, and performance requirements of different applications whilst avoiding the use of PVC (and plasticizers) overall. Design can also play a role in strategies that aim to increase the useful life of flooring (Reduce strategies). By designing services that support customers in the correct purchase of a product companies could understand their customer needs better and avoid early retirement of products due to failure or inappropriate product selection. Additionally, designers can also develop systems that allow and facilitate the repair and maintenance of flooring products.

Decreasing emissions (Control/Prevent strategies) throughout the use phase was shown to be possible by the addition of top coatings or layers that avoid dust and air to be directly in touch with materials that contain DEHP. This can also be considered by designers in applications where eliminating DEHP or plasticizers overall is not possible for specific applications or functions.

Last, although designers may not have direct influence over strategies for a controlled EoL, incineration and recycling, and internal policies from manufacturers for monitoring of post-consumer waste for recycling, they may be involved in the design of the services that support those strategies (e.g., collection) or in the design of flooring products that can cope with the use of recycled materials.

Limitations and challenges

An important challenge when dealing with DEHP in flooring products is the transparent communication between chemical and polymer producers, and flooring manufacturers. Similar to the case of cables, PVC flooring manufacturers are using strict policies to communicate their requirements to their suppliers. Such as adherence to restricted substances lists and issuing material declarations.

Although studies on the environmental impact of resilient floor coverings recommend the recycling of PVC flooring as the preferable option [37], the presence of plasticizers hinders the possibilities for safe recycling. To overcome this challenge, some companies have installed a closed loop recovery and recycling systems for post installation waste (not post- consumer), making sure only known materials (without DEHP) are used. In order to make it possible for post-consumer flooring waste to be recycled, DEHP and other harmful plasticizers need to be phased out or removed through chemical recycling. Additionally, monitoring systems need to be further developed to avoid other harmful chemicals and DEHP in older discarded products that may still contain them

C.12 Limitations of the case study

One substantial limitation of the case is that microplastics emissions could not be included in any way in this evaluation. The evaluation of various scenarios provides an indication of relative (bulk material) impacts, which could be potentially enhanced with microplastic emissions. With increased understanding on the degradation kinetics and accumulation in various environmental compartments of various size fractions of microplastics, the impact of microplastics produced from mulch films could be better evaluated. Understanding the human health and ecotoxicity impacts from microplastics is an urgent concern, and these studies are currently at a very nascent stage.

Further, the functionality of mulch films (e.g. yield of crops in specified climatic conditions) need to be specified as functional unit and compared with alternatives through the life cycle to assess comparative advantages in specific crop and climatic context.

C.13 References

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Appendix D – Extensive description of Case 4

This appendix presents the complete investigation of Case 4 – HFC 134a in refrigerators. A summary of this case is provided in Chapter 3.1.4 of the report. It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 3.1.4 of the report. This was done with the purpose of having the complete documentation of each one of the cases, and to present the structure followed to investigate them.

Case 4 - 1,1,1,2 Tetrafluoroethane (HFC 134a) in household refrigerators.

D.1 Introduction

In 2020, the globally generated waste of electrical and electronic equipment (WEEE) was estimated to reach 53.6Mt (Europe 12Mt) [1]. Temperature exchange equipment, the category in which refrigerators fall in according to the WEEE Directive [2], accounted for 20.14% (10.8Mt) of that total [1].

The environmental impacts of temperature exchange equipment are specifically related to the ozone-depleting substances, and substances with high global warming potential (GWP), which are used as refrigerants and blowing agents for insulating foam (e.g., Tetrafluoroethane) [3]. These may be released into the environment throughout the lifecycle of refrigerators, with end of life (EoL) being the most concerning stage [3].

Prior to the Montreal Protocol in 1987 [4], and the Regulation (EC) No 1005/2009 [5], the most used substances for refrigerants and blowing agents in cooling equipment were Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), which were identified as ozone depleting substances (ODS) [6], [7]. Through regulation, these refrigerants have been replaced for Hydrofluorocarbons (HFCs), which are not ozone depleting substances but are greenhouse gases and have a high global warming potential [6], [7]. Their high GWP make HFCs important contributors to radiative forcing, hence climate change [8],[9].

HFCs are the most used type of fluorinated gases, with HFC 134a (Tetrafluoroethane) being one of the most common in the atmosphere [7], [8]. In 2016 the Montreal Protocol was amended to reduce greenhouse gas emissions, particularly focusing on reducing the production and use of HFCs [10]. In Europe, the Regulation (EU) (No 517/2014) [11] was implemented in 2014, establishing conditions to place fluorinated gases with high GWP in the market in certain applications and quantities, as well as regulating containment, transportation, leakage, recovery, and destruction. Due to this, manufacturers have found alternatives with lower GWP in comparison to HFCs, as well as implemented measures to comply with the regulation during the production, use and EoL of refrigerators and other cooling appliances [7].

This case study analyses the presence of HFC 134a (Tetrafluoroethane) in household refrigerators to understand its function, potential hazards, and emissions throughout the life cycle. Additionally, strategies implemented by manufacturers and policy makers to eliminate/control its use have been studied and assessed to identify their benefits and drawbacks.

D.2 What is the substance?

Chemical name: 1,1,1,2, Tetrafluoroethane, also known as Norflurane [12].
Industrial designation: HFC 134a
CAS no.: 811-97-2

HFC 134a is a gas within the family of hydrofluorocarbons that can be used as a refrigerant in domestic refrigerators and air conditioning units of vehicles [13], [14]. HFC 134a is also used as a blowing agent for insulation foam in refrigerators, most commonly in Polyurethane foams [6].

D.3 How is the substance currently regulated? In which applications?

Kigali Amendment to the Montreal Protocol – The Montreal Protocol adopted in 1987, is a UN treaty that originally focused on the phase down of the consumption and production of ODS [4]. In 2016, several amendments to the Montreal Protocol were adopted to add the reduction of the consumption and emissions of HFCs, specifically those with long atmospheric lifetimes and high GWP with a targeted reduction of 90% by 2050 [4], [10].

Regulation (EU) (No 517/2014), on fluorinated greenhouse gases (F-gases, which include HFCs among others) [8], [11]. Regulates the containment, use, recovery, and destruction of F-gases.

- Containment focuses on leakage prevention. Intentional releases are prohibited, precautions and early detection for repair are indicated.
- Emissions during production transport and storage. Producers of fluorinated compounds must take action to limit emissions of fluorinated greenhouse gases during all processes dealing with F-gases.
- Recovery should be ensured for recycling, reclaim or destruction of f-gases in stationary cooling equipment. F-gases contained in foam are not considered.
- Establish certification programs to people carrying out installation, servicing, maintenance, repair, leak checks ad recovery of F-gases.
- Labelling of refrigerant equipment and F-gas containers, F-gases in foams are included.
- Conditions on the market placing and applications of F-gases. HFC 134 a is prohibited in all new vehicle air conditioning systems from 2017.
- The regulation states specific quotas to place HFCs on the market. By 2030, companies are only allowed to place 21% of their total annual quantity placed on the market from 2009 to 2012.

EU Directive 2008/68/EC, on the inland transport of dangerous goods. Regulates the terrestrial, railway and inland water transport of 1,1,1,2 Tetrafluoroethane for it to be carried out as safely as possible [15].

The WEEE Directive. Focused on preventing impacts of the generation and management of waste from electrical and electronic equipment (WEEE) [2].

- Design products to facilitate re-use, dismantling and recovery or recycling of WEEE, its components and materials.
- Separate collection of WEEE, giving priority to temperature exchange equipment containing ozone-depleting substances and fluorinated greenhouse gases. The collection should not generate costs to the end user.
- Establishment of collection rates though the ‘producer responsibility’ principle - 65 % of the average weight of EEE placed on the market in the three preceding years.
- Proper treatment of refrigerant products, including the removal and separate collection of CFC, HCFC, HFC, and HCs. Gases contained in foams and refrigeration circuits must be properly extracted and treated.

Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures. Focuses on identifying hazardous chemicals and informing about their hazards through standardized symbols [16].
The following hazard statements should be displayed for HFC 134a [17]:

- H280 - Contains gas under pressure may explode if heated.
- H370, H371 - Causes or may cause damage to organs (cardiovascular and central nervous system if inhaled, skin if dermal contact occurs).

D.4 What is the function of the substance in the product?

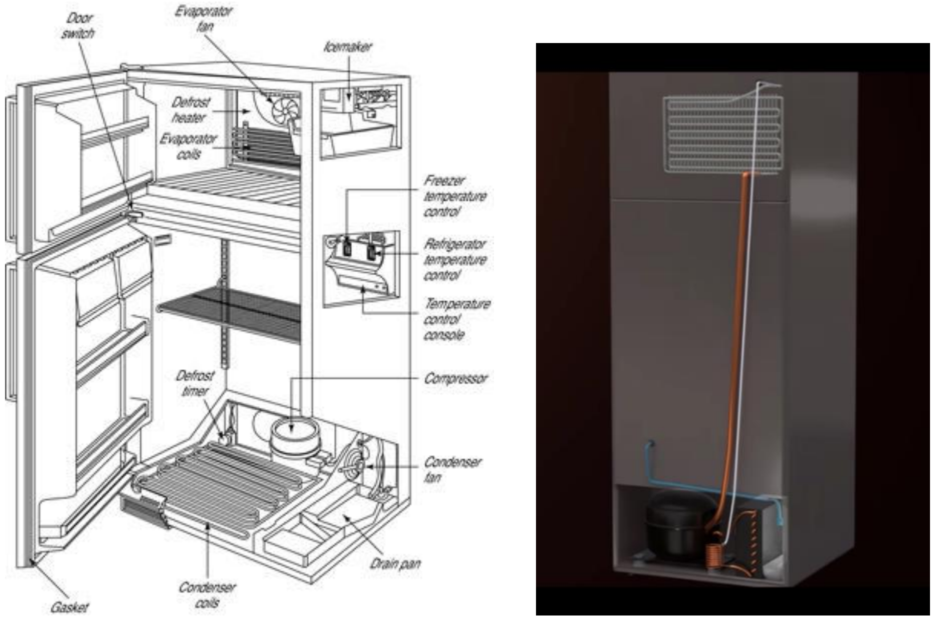
HFC 134a is a type of refrigerant, which are chemical compounds used as heat carriers in the refrigeration cycle. During the cycle, the refrigerant or heat transfer fluid, continuously changes from gas to liquid and back to gas state when going through compression and expansion processes [13]. The temperature of the fluid depends on its pressure, generating heat transfer in the system during evaporation and condensation [14].

HFC 134a is also used as a blowing agent for insulation foam in refrigerators, most commonly in Polyurethane foams, the trapped gas contributes to the insulating properties [6], [18].

D.5 Substance presence and release classification

- **How is the substance present in the product?**

HFC 134a as a refrigerant. When used as a refrigerant, HFC 134a is contained and flows through the components of the hermetically sealed cooling unit of the refrigerator [6], [18]. These components include the compressor, condenser, capillary tube, and evaporator (Figures D1 and D2).



Figures D1 and D2. Components of the cooling unit in a domestic refrigerator. Retrieved on July 1st, 2022, from: https://www.dummies.com/article/home, https://www.youtube.com/watch?

HFC 134a as a foam blowing agent. The walls and door of the refrigerator are composed by an external metal sheet layer and an internal liner made of metal or plastic. Between the two walls polyurethane foam is injected at high pressure to create the insulating layer (Figures D3 and D4). The HFC 134a remains contained within the cells of the foam [6], [18].

Figures D3 and D4. Refrigerator walls assembly for foam injection, Cut refrigerator walls where the foam can be seen. Retrieved on July 1st, 2022, from: https://www.youtube.com/watch?v, https://transparency-partnership.net/system/

- **How is the substance released in the environment? Through which mechanisms? Are these mechanisms aggravated by any other input?**

HFCs are considered volatile organic compounds, VOCs [19]. VOCs are organic chemical compounds that evaporate under normal indoor atmospheric conditions due to their composition [20]. **Volatilization** is defined as the transition of a liquid chemical into a vapor, which escapes into the atmosphere[21].

Leakage is the most discussed form of emission for HFC 134a and refrigerants in general, which can occur at different stages of the lifecycle of cooling equipment [18]. Emission scenarios are further discussed in section 7 of this chapter. Some of the identified forms of leakage include faulty or loose components in the cooling system, leakage from a broken cooling system due to lack of care when manipulating and transporting the equipment, and leakage during recycling and servicing processes.

D.6 What are the possible hazards to health and the environment?

- Health

1,1,1,2 Tetrafluoroethane is considered non-toxic and non-flammable, no significant health risks are expected from exposure [19], [22]. It has low acute toxicity but in case of spillage it is recommended to wear personal and respiratory protection because it can cause oxygen deficiencies [22]. Overexposure can cause central nervous system depression and cardiac sensitization [19]. Exposure level limits have been established at 1000 ppm [19].
According to the Classification and Labelling regulation, the following hazard statements should be displayed for HFC 134a [17]:

- H280 - Contains gas under pressure may explode if heated.
- H370, H371 - Causes or may cause damage to organs (cardiovascular and central nervous system if inhaled, skin if dermal contact occurs).

No carcinogenicity, no genotoxicity potential, no immunological or neurological effects, and no reproductive toxicity were found for exposure to HFC 134a [22]. HFC 134a is non-flammable under normal temperature and pressure conditions, but may be become flammable if these increase or in mixtures with other elements, especially oxygen [23].

- Environment

Their high GWP make HFCs important contributors to radiative forcing, which contributes to climate change [8], [9], [19]. HFC 134a has a 100yr GWP of 1360 [8], [9]. Calculated for a 100-year warming potential of a greenhouse gas relative to 1kg of CO2 (GWP of CO2 = 1) [24], [19].

Being a VOC, HFC 134a resides in the lower atmosphere when released, where it is photochemically oxidized. Its atmospheric oxidation generates degradation products, which can be transformed into trifluoroacetic acid and formic acid to which humans can be exposed via rainfall and smog [19].

D.7 How and in which stage of the life cycle of the product do emissions of the substance occur? How much of the substance is emitted? And how does exposure occur?

In the following paragraphs the release of 1,1,1,2-Tetrafluoroethane (HFC 134a) from refrigerators in different stages of the lifecycle, as well as the different exposure routes are discussed.

Emissions of this gas are mostly discussed in regard to leakages, which can vary over time and quantity, making them hard to quantify [18]. Out of the total HFC 134a emissions in the EU in 2005, it is estimated that 71% originate from refrigerant fluids and 8% from foams [18].

In general, HFC 134a is expected to be emitted into the atmosphere almost exclusively. Emissions into wastewater and water bodies are expected to volatilize. It is also not expected to accumulate in any form of organism nor to be absorbed by soil [22].

Global emissions of HFCs measured in the atmosphere in 2016 reached 0.88 (± 0.07) GtCO2-eq yr−1 in 2016, with HFC 134a being 34% [25] .

- Production

Emissions: Losses are possible while filling up the hermetic cooling unit [18]. Losses can also occur during the blowing process of insulation foams [18].No other data was found in relation to emissions of HFC 134a during the production phase.

Exposure: Occupational Exposure is normally low and not of concern [22]. In case of spillage it is recommended to wear personal and respiratory protection because it can cause oxygen deficiencies [22]. Overexposure via inhalation can cause central nervous system depression and cardiac sensitization [19]. Additional risks include possible flammability at high temperatures and high pressure [23].

- Use

Emissions:

The hermetically sealed cooling units can avoid emissions completely, but may leak if damaged or present losses when frequently serviced, or when components are of low quality [18]. Leakages of 0.3% (of the initial charge) are calculated to occur annually for domestic fridges [24]. Medium commercial applications can leak up to 11% and industrial refrigeration 8% annually [24].

Refrigerant losses can occur from leaking joints and seals, as well as damaged pipes and components, during safety relief operations, re- charging operations or other types of servicing [24], [26]. Re- charging and relief operations are done by piercing the hermetic system using piercing valves, which can be a potential source for leakage, Figures D5 and D6.

Figures D5 and D6. Man installs a piercing valve. Man re-charges refrigerant into the cooling system through the piercing valve. Retrieved on July 1st, 2022, from: https://www.youtube.com/watch?v=j

Leakage generates direct environmental impact as well as indirect environmental impact, by reducing the system operating efficiency, increasing energy consumption and CO2 emissions [24], [26].

Gases used as blowing agents for foams are typically trapped within the material, and may not be of concern for emissions during the use phase or may present releases at very slow rates [18], [27], [28]. There appears to be high uncertainty in the release rates of blowing agents from foams during the use phase.

Exposure: In case of spillage it is recommended to wear personal and respiratory protection because it can cause oxygen deficiencies [22]. Overexposure via inhalation can cause central nervous system depression and cardiac sensitization [19].

Additional risks include possible flammability at high temperatures and high pressure [23].

- EoL – Recycling

Emissions: The recycling of refrigerators is especially complex due to the presence of 1,1,1,2 Tetrafluoroethane in the refrigerant system and insulating foams (as a blowing agent) [6]. The main climate related impacts from WEEE are related to the release of ODS and gases with high GWP due to inappropriate treatment and disposal of cooling and refrigerating equipment [29]. When transported and stored refrigerators should be treated with caution to avoid any breakage of the cooling system components and avoid leakage [29].

Regulation (EU) (No 517/2014), establishes f-gases in stationary cooling equipment should be recovered and properly treated for recycling, reclaim, or destruction [8], [11]. The WEEE Directive establishes gases contained in foams and refrigeration circuits must be properly extracted and treated [2]. Refrigerators go through a pre-processing prior to their recycling, where the refrigerant system is disassembled, and the refrigerant is extracted [6]. This is done by piercing and suction, since the refrigerant system components are hermetic by regulation [11]. The refrigerant is filled into a gas cylinder to then be destroyed or recycled [29]. During the process of extraction and storage of the refrigerant, accidental breakage or faulty operations or components can cause leakage [6], [24], [18].

After the 1,1,1,2 Tetrafluoroethane is extracted from the refrigerant system, the refrigerator is then shredded. The shredding should be done in a control environment since it is possible to have emissions of Norflurane or other substances used as blowing agents in the insulation foams [6], [2]. The shredding is usually performed in steps, during the first shredding, the blowing agents are drained out in a closed atmosphere (gas tight treatment plant) and collected by filters to then be liquified and stored for destruction [29]. Nitrogen is injected to the enclosed environment to reduce the risk of explosion due to high concentrations of blowing agents [6].

Exposure: Occupational Exposure is normally low and not of concern [22]. In case of spillage it is recommended to wear personal and respiratory protection because it can cause oxygen deficiencies [22]. Overexposure via inhalation can cause central nervous system depression and cardiac sensitization [19].

- **EoL – Landfill and incineration**

Most materials obtained from cooling appliances are recycled including, in cases, the collected refrigerants and blowing agents. The collected refrigerants and blowing agents, which are not recycled are stored to then be destroyed in a high temperature reactor or at high temperature incinerators [6] , [29]. No other data on possible emissions/exposure scenarios was found for landfill and incineration.

D.8 Prioritizing risk hotspots due to HFC 134a used in charger cable through the life cycle

While HFC 134a has some risks, they are not substantial and climate change related impacts are of greater concern. Hence, they are not explored much in the literature. For risk prioritization, the exposure guidance limit concept was explored, which are occupational limits formulated for specific chemicals. Refrigerants are meant to be handled in controlled conditions during their lifecycle, so an exposure is an accidental or brief exposure. In this context, Emergency exposure guidance level (EEGL) are ceiling concentrations that will not cause irreversible harm or prevent performance of essential tasks during a rare emergency situation (e.g. using a fire extinguisher) [30]. An EEGL is acceptable only in an emergency, when some risks or some discomfort must be endured to prevent greater risks (such as fire, explosion, or massive release).
EEGLs can be matched to activities through the lifecycle to have an indication of risk (Table D1). For example, a proxy for chronic occupational exposure to the refrigerant could be the Continuous exposure guidance level (CEGL), which simulates 90 day exposure. One hour EEGL is considered in the case of infrequent leaks to which workers and consumers may be exposed. In the case of venting, given the intermittent nature of the activity, one day EEGL is considered. Prioritization of risks and use of color codes to indicate hotspots is not meaningful in this case.

- **Human Health risks of HFC 134a use in refrigerators through their lifecycle**

Lifecycle stage	Activity Subclassification	Route of exposure	Toxicity endpoint	Risk characterization method	Risk characterization (allowable exposure concentration in ppm)
Production	Filling cooling unit with HFC 134a	Inhalation	Developmental toxicity Reproductive Toxicity	EEGL (1 hour) CEGL (90 days) EEGL (1 hour) CEGL (90 days)	4000 900 8000 900
	Blowing insulation foam with HFC 134a	Inhalation	Developmental toxicity Reproductive Toxicity	EEGL (1 hour) CEGL (90 days) EEGL (1 hour) CEGL (90 days)	4000 900 8000 900
Use	Repair of cooling system	Inhalation	Developmental toxicity	EEGL (1 hour) CEGL (90 days) EEGL (1 hour)	4000 900 8000

			Reproductive Toxicity	CEGL (90 days)	900
EOL	Recycling coolant	Inhalation	Developmental toxicity	EEGL (1 hour) CEGL (90 days)	4000 900
			Reproductive Toxicity	EEGL (1 hour) CEGL (90 days)	8000 900
	Venting HFC 134a	Inhalation	Developmental toxicity	EEGL (1 hour) EEGL (24 hour) CEGL (90 days)	4000 1000 900
			Reproductive Toxicity	EEGL (1 hour) EEGL (24 hour) CEGL (90 days)	8000 5000 900
	Shredding foam containing HFC 134a		Developmental toxicity	EEGL (1 hour) CEGL (90 days)	4000 900
			Reproductive Toxicity	EEGL (1 hour) CEGL (90 days)	8000 900

Table D1. Relevant Human Health Risk Values for HFC 134a along the Life cycle. From [30]
The first column shows the lifecycle stage, and sub-classification (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The exposure route (column 3) mentions how human beings are exposed to SoC (inhalation, dermal or oral exposure). The toxicity endpoint (column 4) mentions the organ systems that are affected. The Risk Characterization method (column 5) mentions whether the type of exposure guidance value used. Risk characterization (column 6) mentions the exposure guidance value.

As expected, developmental toxicity is the most sensitive endpoint. EEGL and CEGLs are fairly high and not expected to be violated in contexts where occupational safety is followed.

- Ecological risks of HFC 134a use in refrigerators through their lifecycle

In the literature search for ecological risks of HFC 134a, only one paper was found with risk values [31]. It must be mentioned that a wide divergence was found between risk calculated from experimental values of single organisms and estimation for whole ecosystem (e.g. for terrestrial plants). The worst case values were used here for risk prioritization.

Lifecycle stage	Activity	Environmental compartment	Risk Characterization methodology	Risk Characterization
Production/Use/EOL	Accidental release	Surface Freshwater	Margin of exposure for *R. subcapitata*	124
		Marine	Margin of exposure for R. subcapitata	469
		Terrestrial plants	Margin of exposure for plants exposed to fog and rain	3
		Terrestrial vertebrates	Humans and terrestrial vertebrates exposed to surface freshwater	3,535,000

Table D2 *Relevant Ecological Risk Values for DEHP along the Life cycle. From* [31]
Table D2 is organized as follows. The first column shows the lifecycle stage, and activity (column 2) refers to the specific activity (industrial activity or exposure scenario) causing the risk. The environmental compartment (column 3) mentions the environmental compartment where the SoC ends up. Risk characterization (column 4) mentions the risk value color coded according to the heat map presented in section 2.2.3.

It appears from Table D2 that exposure to plants from fog and rain is the scenario with highest priority. Algae (*R. subcapitata*) in freshwater are above the safe Margin of Exposure, but still merits precaution.

D.9 What are existing SbD strategies to deal with 1,1,1,2-Tetrafluoroethane?

This section presents and discusses different strategies identified in literature to reduce, control, and or eliminate the use of Tetrafluoroethane. It provides further information on each strategy, when possible, to determine benefits and drawbacks, as well as unforeseen consequences or uncertainty.

Recommendations found in literature to reduce HFC134a emissions from refrigerators include, improvements in the engineering of the cooling systems to reduce leakage, reduce the gas charge size, better containment strategies/engineering, recovery at end of life, substitution for refrigerants with lower GWP, low toxicity, and no flammability [6], [18], [27], [32].

The F-gas Regulation and WEEE directive have influenced a lot of the strategies currently being implemented to deal with HFC134a. Both regulations have established norms to control, reduce and eliminate emissions from HFC 134a, and refrigerants in general, throughout the lifecycle of cooling equipment, with the WEEE directive focusing on EoI. Both have influenced the design of refrigerating equipment and their components, as well as their production and recycling processes [2], [11]. Additionally, Regulation (EU) (No 517/2014) or F-gas regulation has established a plan to limit the use and placing in the market of fluorinated gases to further reduce emissions [11].

- Eliminate – Substitution of refrigerant and blowing agent

A. Substitution of HFC 134a

Refrigerant: In the 1800's methyl ether, CO2, propane, isobutene, and gasoline, among others, were used as refrigerants in vapor compression systems. These substances are toxic and/or flammable, and they were easily leaked due to the lack of hermetic systems [32]. These early refrigerants were substituted by CFCs, which were later identified to have a high ozone depleting potential and were substituted by HCFCs which do not deplete the ozone layer but have high GWP [4], [6], [10], [32], [33]. HFCs became the new substitutes, with HFC 134a becoming the most produced fluorocarbon, until the Kigali Amendment to the Montreal Protocol, in which it was decided to phase HFCs down due to their high GWP and long atmospheric lifetime [4], [10], [32], [33].

HFCs are now being substituted by natural refrigerants such as CO2, and hydrocarbons [32]. CO2 has a GWP of 1 and zero ODP, and has recently been researched to create energy efficient cooling systems with it [33]. Hydrocarbons are currently the most suitable substitutes to HFCs, economically speaking and due to their thermodynamic properties, their low GWP and no ODP, and potential energy efficiency [32]. However, hydrocarbons have been classified as highly flammable [6], [32]. This can be challenging during the use phase, specifically for domestic applications but can be controlled by changing the charge quantity and adjusting the system design [34]. Risks of fire and explosion should also be considered in recycling plants [6].

In relation to environmental impact of different alternatives, energy efficiency plays an important role. Alternatives with lower GWP but that cause a reduction in energy efficiency in the refrigerating equipment, could account for a higher environmental impact [8]. These effects should be considered when performing LCAs to assess the different alternatives [8].

The selection of refrigerant alternatives must consider the tradeoffs between a low or zero global warming potential (GWP), zero ODP, short atmospheric lifetime, toxicity, flammability, and energy efficiency [8], [32], [35].

Blowing agent: In the 1950's, CFCs were discovered and widely used in the production of PU foams due to their thermal stability and low cost [33]. However, they were found to be ozone depleting substances so they were substituted by HFCFs [6], [32], [33]. HCFCs presented a lower ozone depleting potential but a higher GWP than CFC for which the Montreal Protocol pushed for them to be phased out [32], [33]. In response to that, HCFCs were substituted by HFCs which have no ozone depleting potential (ODP) but still high GWP which are being phased out currently as well by local regulations and the Kigali Amendment [4], [10], [32], [33].

Nowadays there are several alternatives available to the use of CFCs, HCFCs, and HFCs as blowing agents, including natural inert gases such as carbon dioxide and nitrogen, hydrocarbons (HCs) and hydrofluoroolefins (HFOs) [32], [33]. All the listed alternatives have a lower GWP and no ODP, however, they have higher costs in comparison to HFCs and require changes in the production methods [33].

Today, one of the most used blowing agents for PU foams is Cyclopentane, which has zero ODP and low GWP [29]. It is, however, flammable and can be highly explosive when mixed with oxygen [29]. This not only poses a challenge to make it safe to use during the use phase but also makes recycling challenging and demands different technology to be treated [29].

Similar to the selection of refrigerant alternatives, the selection of a substitute blowing agent must consider the tradeoffs between a low or zero global warming potential (GWP), zero ODP, toxicity and flammability, as well as costs and consequences over production and recycling processes. An example of these trade off values is shown in Table D3.

Refrigerant group:	CFCs	HCFCs	HFCs	HFOs	Natural Refrigerants (Including hydrocarbons)
Ozone depleting potential (ODP)	0.6 - 1	0.02 - 0.11	0	0	0
Global Warming Potential	4,750 – 14, 400	400 – 1800	140 – 11,700	<0 – 12	0

(GWP) (100 yrs)					
Flammable	No	No	No	Yes	Yes
Atmospheric lifetime (years)	45 - 1700	1 - 20	1 – 300	-	Few days

Table D3. Comparison table of different refrigerant groups, extracted from: [34]

- Control -Prevent emissions during the use phase

A. **Hermetic cooling units.** Cooling systems must be hermetic by regulation [11]. Studies have found a decrease in refrigerants emissions in connection with the widespread use of hermetic cooling systems in refrigerating equipment [18], [36]. The hermetically sealed cooling units can avoid emissions completely, but may leak if damaged or present losses when frequently serviced, or when components are of low quality [18].

B. **Leakage detection systems.** This study found a potential strategy to reduce emissions of refrigerants during the use phase through a system that detects and warns when leakage occurs by obtaining and analyzing data on the working status of the product [26]. This system could warn of gradual leakages from joints or seals or important losses due to damaged components. However, this system is only applied to commercial units and not domestic [26].

- Control - Preventing emissions through a controlled EoL

A. **Collection of refrigerants.** As established by the WEE directive all gases and fluids in refrigeration circuits must be properly extracted and treated [2]. This regulation has influenced the process in which refrigerators are recycled, forcing recyclers to establish a preprocess step, where the refrigerant system is disassembled, and the refrigerant is extracted and collected [6] to then be destroyed or recycled [29]. The configuration of the fridge in this step is relevant to facilitate the extraction of the refrigerant as well as the further disassembly of the cooling system.

B. **Collection of blowing agents - Controlled environments for shredding.** During recycling, refrigerators are shredded after the removal of the cooling system. By regulation [2], the shredding should be done in a control environment to avoid emissions of blowing agents in the insulation foams [6]. The shredding occurs in a gas tight environment where the blowing agents are collected in filters to then be liquified to be stored and then destroyed [29]. This process is challenging and can only be performed by specialized treatment plants since it may pose an explosion risk, requiring the addition of nitrogen to the controlled environment where the shredding takes place [6], [29].

C. **Reducing leakage - Improving systems for extraction and recharge of refrigerants.** Literature suggests an improvement in the design of the hermetic cooling systems to facilitate the extraction of refrigerant fluids during recycling and avoid leakage [6]. A designated valve for the extraction and charging of refrigerant could in theory also support the reduction of potential leakage during servicing processes in the use phase. However, these systems are hermetic by regulation [11], and manufacturers suggest installing an additional valve could increase the risks of leakage during the use phase [6]. This strategy would have to be further developed and studied before any conclusion of its success can be driven.

D. **Strengthening or protection of the cooling system.** Leakages can occur during the transportation and handling of refrigerating equipment if not done with care [6], [29] . A study suggests strengthening or protecting the components of the cooling system could prevent leakages cause by their breakage [6]. This strategy would have to be further developed and studied to weigh its benefits to prevent emissions and possible drawbacks regarding additional materials, costs, and ease of disassembly.

- Reduce – Using less refrigerant

E. **Reducing the amount of refrigerant gas.** This strategy is mentioned as a way to reduce refrigerant emissions in general as well as facilitating recycling processes [6], [18]. This reduction is limited, since the mass of the refrigerant influences the energy efficiency of the cooling appliance [6].

D.10 Evaluation of the application of screening LCA and RA to assess SbD strategies (existing/historical alternatives)

- **Baseline scenario**

For the baseline scenario, the functional unit chosen was 1 kilogram of HFC 134a. There were several activities in Ecoinvent using the search words "HFC 134a" and the whole life cycle of the refrigerant could be modelled. Production of both refrigerant (Figure D7) and blown foam (Figure D8) is considered. The use phase considers the use of a refrigeration machine (Figure D9). End of Life phase considers Incineration (Figure D10), Reclamation (Figure D11) and Venting (Figure D12). In the scenarios where toxicity impacts were one of the top two impact categories, the emissions contributing to the impact was explored.

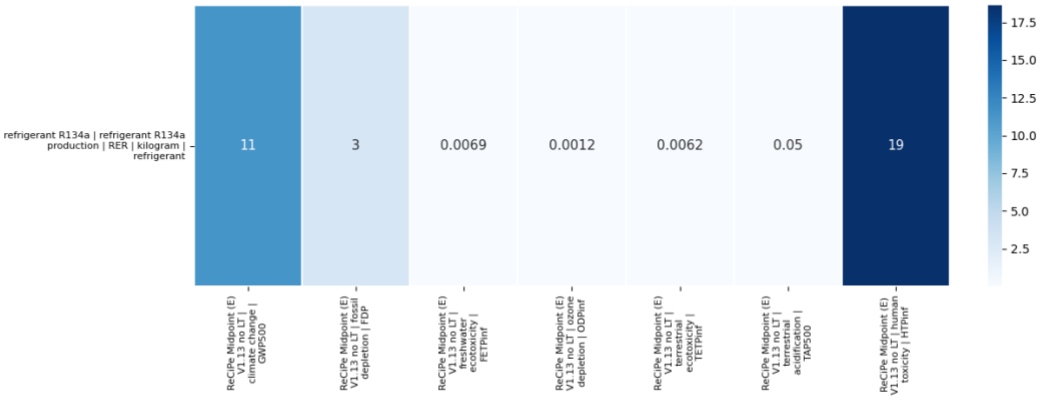


Figure D7 Screening LCA for Production of 1 kg HFC 134a. Human toxicity Impact was the highest, followed by climate change.

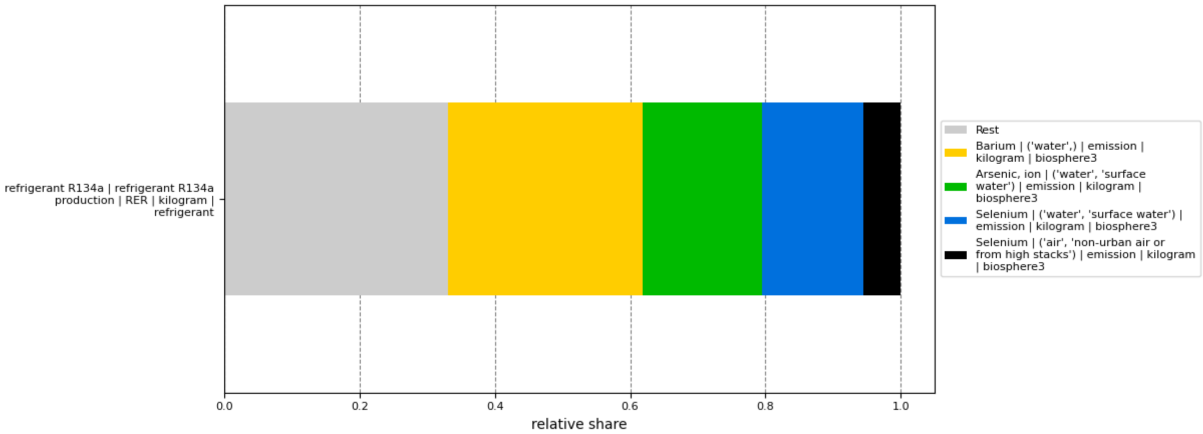


Figure D7a Contributions to Human Toxicity Impact for Production of 1 kg HFC 134a. Emissions of barium and arsenic are the two contributions to human toxicity impacts.

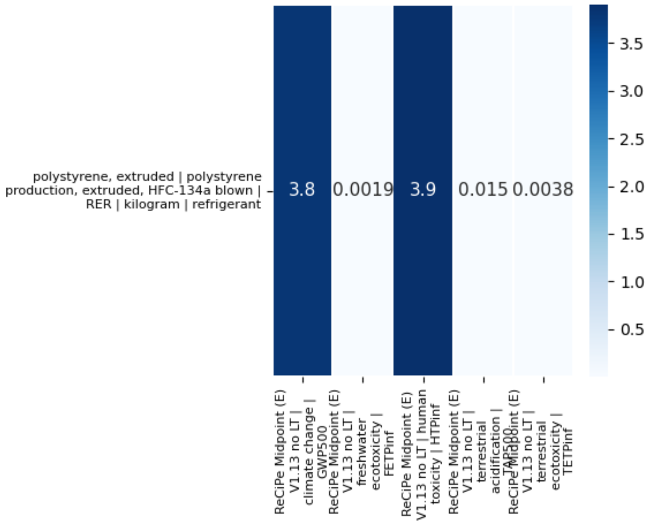


Figure D8 Screening LCA for Production of 1 kg HFC 134a blown polystyrene foam. Human toxicity Impact and climate change were the highest impacts.

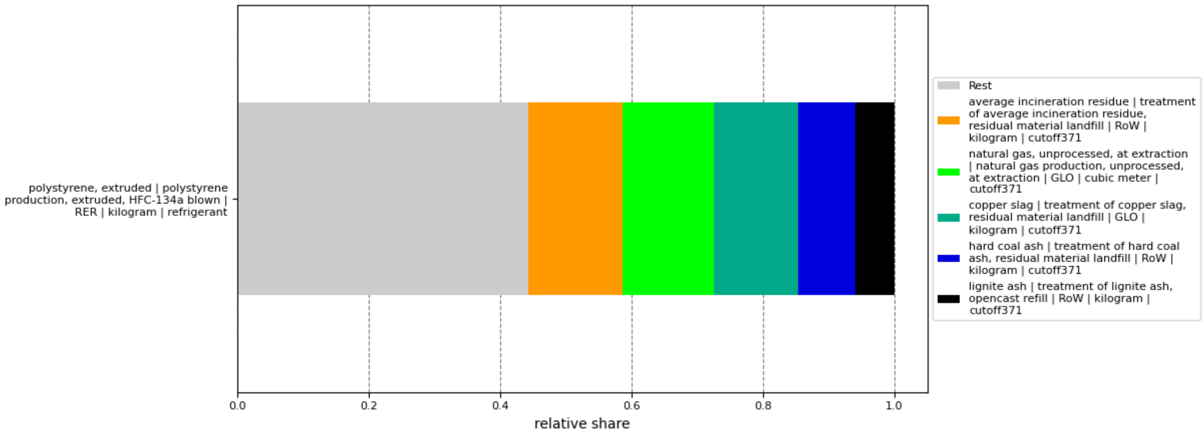


Figure D8a Contributions to Human Toxicity Impact for Production of 1 kg HFC 134a blown polystyrene foam. Incineration residue is the highest contributor to human toxicity impacts

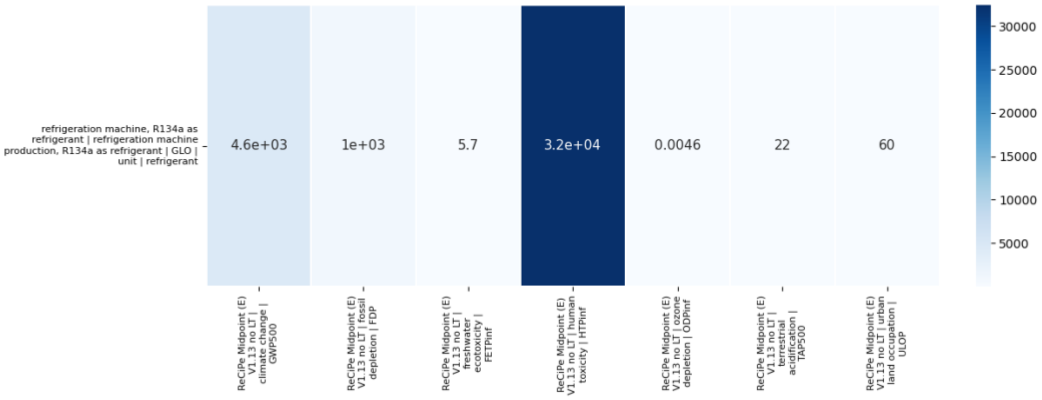


Figure D9 Screening LCA for Use of 1 kg HFC 134a as refrigerant. Human toxicity Impact was the highest, followed by climate change.

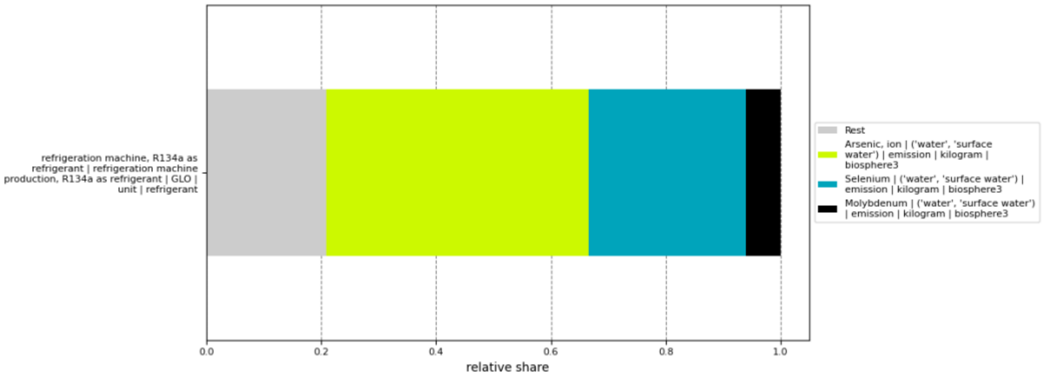


Figure D9a Contributions to Human Toxicity Impact for Use of 1 kg HFC 134a as refrigerant. Emissions of arsenic contributes most to human toxicity impacts.

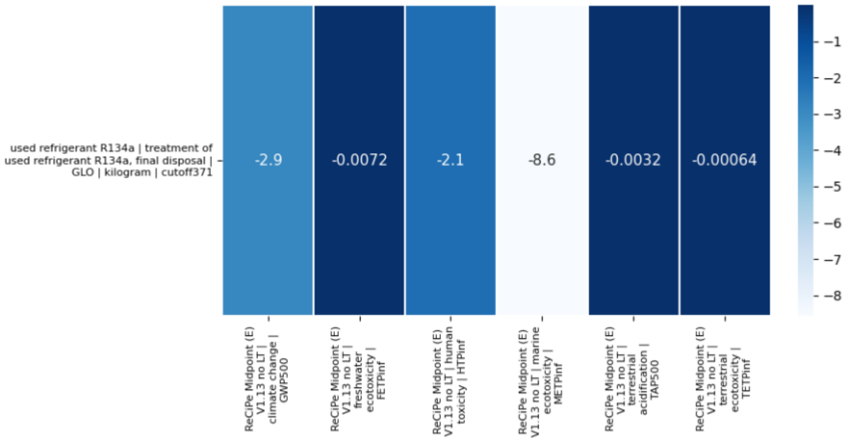


Figure D10 Screening LCA for Incineration of 1 kg HFC 134a. Climate change, Marine ecotoxicity and Human ecotoxicity are the key impacts.

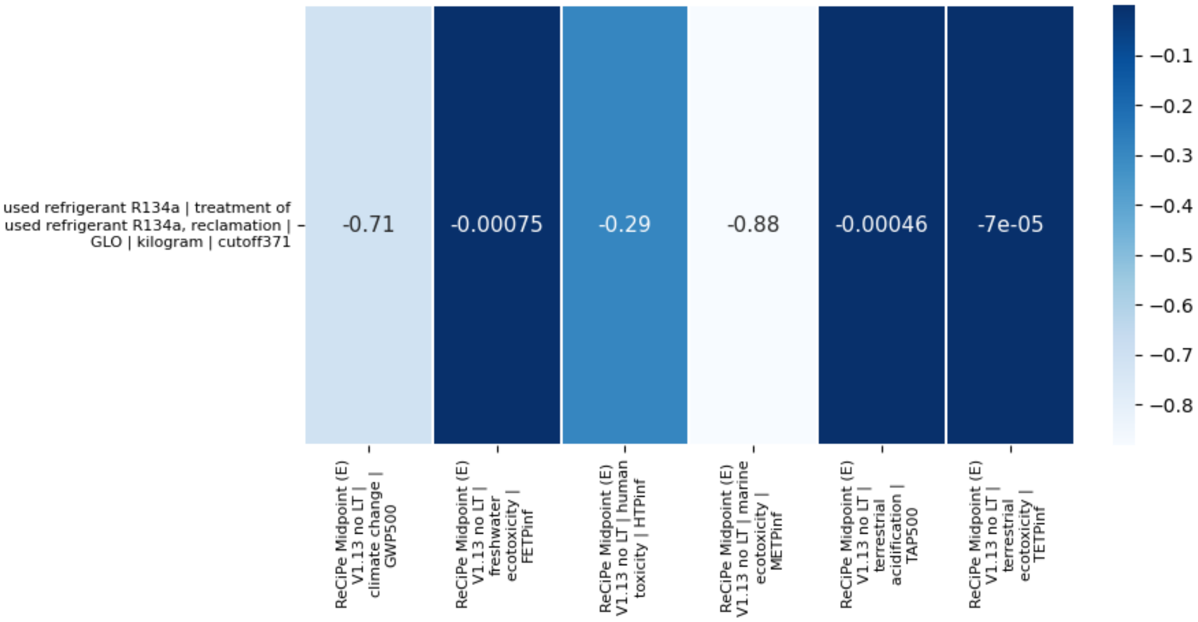


Figure D11 Screening LCA for Recycling of 1 kg HFC 134a. Climate change, Marine ecotoxicity and Human ecotoxicity are the key impacts.

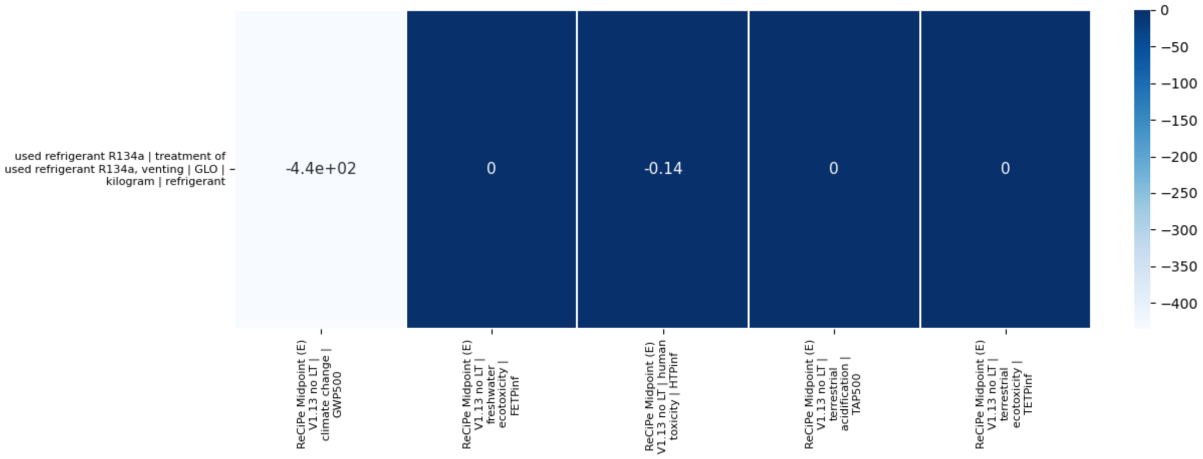


Figure D12 Screening LCA for Venting of 1 kg HFC 134a. Human toxicity Impact and climate change were the highest impacts.

Following climate change, toxicity impacts are next most relevant for all life stages of HFC 134a, and contributions to toxicity impacts are presented in subsection A for each process where they are particularly relevant (production and use phases). Use is the most concerning life cycle stage in terms of environmental impact, followed by production. The emissions of metals contribute the most to the toxicity impacts. A critical gap is lack of information to model shredding of HFC 134a blown foam, where toxicity impacts are likely to be present.

- ### Assessment of strategies

Substitution of HFC 134a - Predictive RA approaches

On providing the CAS number of DEHP, the Similarity tool provided the no chemicals with structural similarity to HFC 134a, probably because of low toxicity concerns.

Substitution with R12 refrigerant

Ecoinvent database was searched for refrigerants, and activities for incineration (Figure D13) and venting of R12 (Figure D14) refrigerant were found.

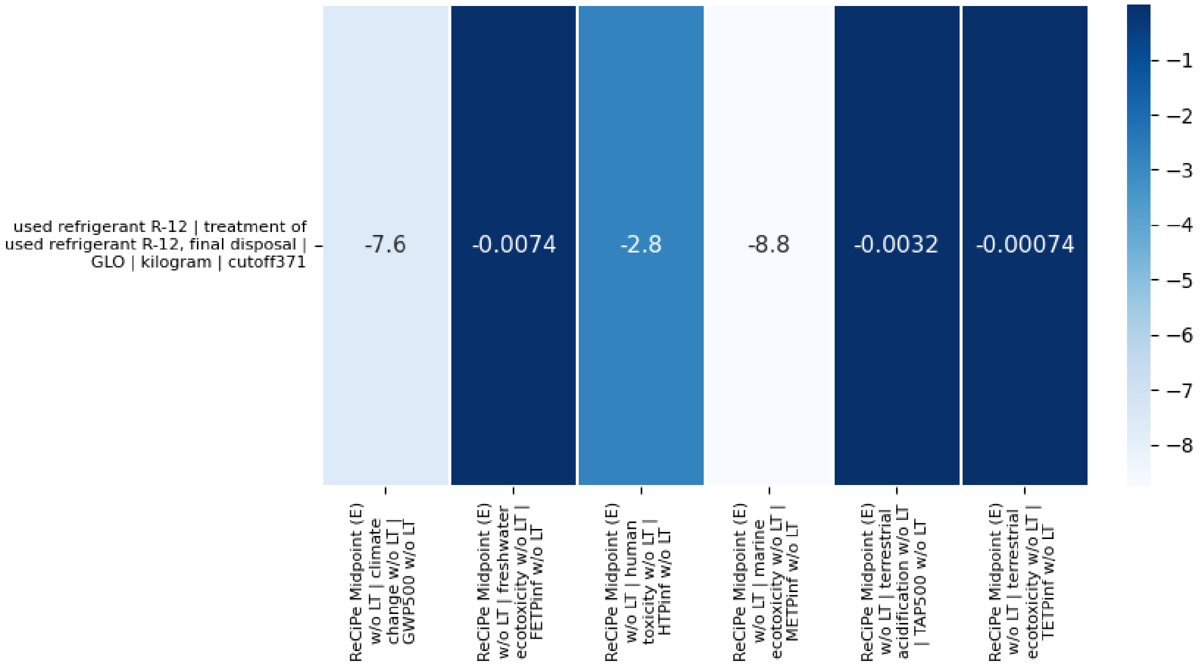


Figure D13 Screening LCA for Incineration of 1 kg R12. Climate change and Marine ecotoxicity are the key impacts.

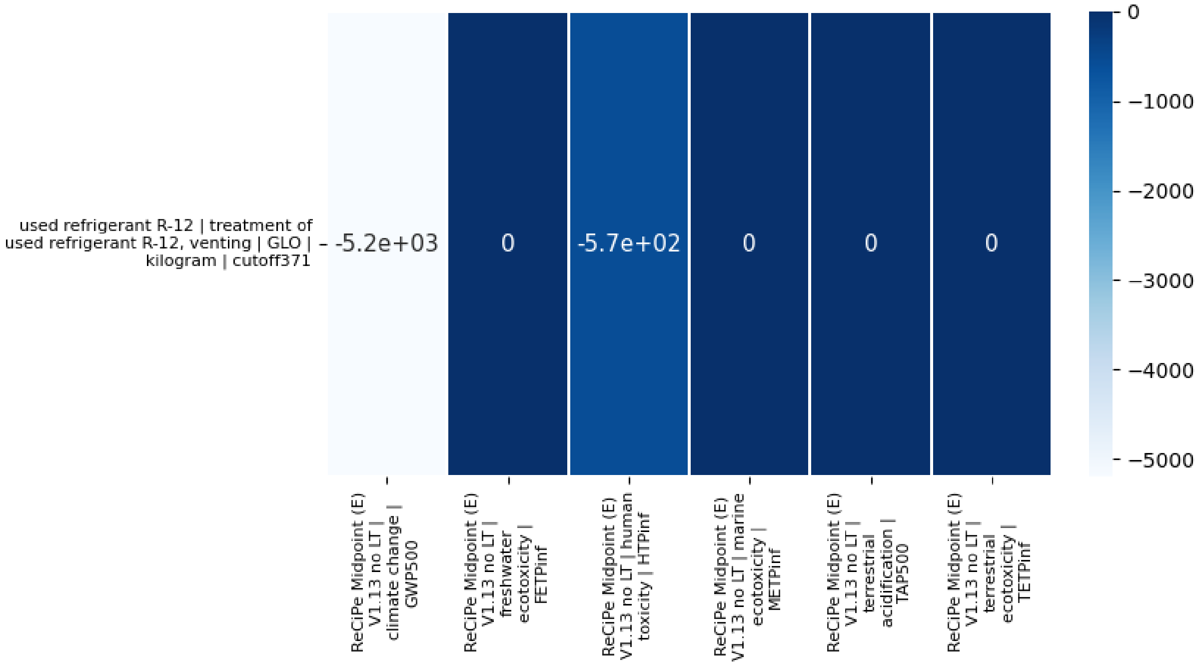


Figure D14 Screening LCA for Venting of 1 kg R12. Human toxicity was the highest impact.

Compared to HFC 134a, R12 shows worse climate change impacts. The human toxicity impacts are similar in case of incineration and worse for venting. Hence based on a comparison of these two ends of life phases, it is not a substitute for HFC 134a.

D.11 Conclusions – Main insights for designers

Table D4 provides a summary of the identified SbD strategies and their potential benefits and downsides according to literature and the RA, and LCA assessments when applicable.

Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int]

Safe by Design strategies to deal with HFC 134a in household refrigerators				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential downsides
Eliminate	Substitution of HFC 134a as a refrigerant	[LCA]	- Substitution with natural refrigerants and hydrocarbons may eliminate emissions of ODS as well as substances with high GWP and long atmospheric lifetimes [32], [33].	- Tradeoffs of substitution to be considered: no ODP, low GWP, flammability, toxicity, and energy efficiency [8], [32], [35]. - Reduced energy efficiency could lead to an increased indirect environmental impact [8].
	Substitution of HFC 134a as a blowing agent	[QE]	- Substitution with hydrofluoroolefins (HFOs), and natural inert gases, such as CO2, nitrogen, and hydrocarbons may eliminate emissions of ODS as well as substances with high GWP and long atmospheric lifetimes [32], [33].	- Higher costs in comparison to HFCs and require changes in the production methods [33]. - Risk of explosion and high flammability in the case of HCs, making it challenging to use safely in the use phase and during recycling processes [29]. - Tradeoffs of substitution to be considered: no ODP, low GWP, flammability, and toxicity [8], [32], [35].
Control/Prevent	Hermetic cooling units	[QE]	- If working as expected, hermetic systems can avoid emissions of refrigerant from the cooling system completely [18], [36].	- Leakage can occur due to faulty or loose components such as joints [18]. - Leakage can also occur when the system is serviced since it need to be punctured to re charge or release refrigerant [18].
	Leakage detection systems	[QE]	- Could detect and warn when leakages occur to be attended promptly [26].	- Only applied in commercial refrigerating equipment [26].
	Collection of refrigerants	[QE]	- Refrigerants are collected to then be recycled of destroyed, avoiding emissions of improper disposal [2], [6], [29].	- Emissions can still occur during the extraction process, due to faulty components or operations, since the cooling system needs to be punctured [6], [24], [18]. - Emissions can also occur if the cooling system breaks due to transportation or manipulation without care leakage [29].
	Collection of blowing agents	[QE]	- Blowing agents are collected during the shredding process to then be recycled of destroyed,	- Challenging process that can only be performed by specialized treatment plants due to explosion risk [6], [29].

			avoiding emissions of improper disposal [2], [6], [29].	
	Improving systems for extraction and recharge of refrigerants	[QE]	- The inclusion of a valve could avoid the need of puncturing the hermetic cooling system and avoid leakages during servicing and recycling processes [6].	- The cooling system is hermetic by regulation [11]. - The valve could increase risks of leakage during the use phase [6].
	Strengthening or protecting the components of the cooling system.	[QE]	- Protecting these components could prevent leakage cause by breakage when the equipment is not transported or handled with care [6], [29].	- Unknown consequences of this strategy over additional materials, costs, and ease of disassembly.
Reduce	Reducing the amount of refrigerant gas.	[QE]	- Reducing the overall amount of refrigerant in a cooling system has been mentioned as a way of reducing emissions and facilitating recycling processes [6], [18].	- The reduction is limited, since the mass of the refrigerant influences the energy efficiency of the cooling appliance [6]. - Reduced energy efficiency could lead to an increased indirect environmental impact [8].

Table D4. Summary of identified SbD strategies for HFC 134a in refrigerators.

Most relevant attention points - emission/exposure scenarios

Concerning emission scenarios include:

- Losses while filling up the hermetic cooling unit during production [18].
- Losses during the blowing process of insulation foams during production [18].
- Leakage from hermetically sealed cooling units during the use phase due to damaged, when frequently serviced, or when components are of low quality [18].
- Loses and leakage caused by inappropriate treatment and disposal of cooling and refrigerating equipment waste[29]. Including leakages during the process of extraction and storage of the refrigerant, accidental breakage or faulty operations and components, and the shredding of the foam components in uncontrolled environments, which causes the blowing agent to be released freely into the atmosphere [2], [6], [24], [18], [29].

Types of strategies, scope of the strategies, benefits, and downsides

Design strategies

Regulations have largely influenced the strategies that are currently being implemented to deal with HFC134a (and refrigerants and foaming agents in general) in refrigerators. Establishing norms and standards to control, reduce and eliminate emissions from HFC 134a, throughout the lifecycle of the product (with a focus on EoL), incentivizing substitution, and defining the design of refrigerating equipment and their components, as well as their production and recycling processes. This can explain why most of the strategies found during this study focus on controlling and preventing emissions of HFC 134a, including improvements in the engineering of the cooling systems to reduce leakage, better containment strategies/engineering, and controlled recovery of refrigerants and blowing agents at end of life.

Substitution of both, refrigerants and blowing agents, is a repeatedly found strategy. Substitution, however, comes with different tradeoffs with recommendations and regulations requiring no ODP, low GWP, low/no flammability, low/no toxicity, and comparable or improved energy efficiency to existing systems. These tradeoffs need to be further analyzed to avoid potential consequences throughout the different stages of the lifecycle of the refrigerator and indirect environmental impact.

Role of designers

Although designers may not directly influence the substitution of the refrigerant/blowing agent, they can focus on facilitating the use of the alternative substances in the product. The analysis of substitution tradeoffs can provide designers with further information over points of improvement of the product design and engineering, or the processes and systems around it.

As an example, current substitution strategies are focusing on the use of natural inert gases including CO_2 and HCs, such as Cyclopentane. Some of these substances are not ODS and have 0 GWP but may pose other challenges regarding safety due to possible risks of explosion during the use phase and recycling phase. To make the use of these substances possible, designers and engineers must update the design of refrigerators to mitigate the newfound risks as well as meeting the energy efficiency requirements. Similarly, reducing the amount of refrigerant gas also provides a design challenge to guarantee the energy efficiency of the appliance.

Additionally, designers could further explore elimination strategies by substitution of function, an example is the exploration of alternatives to guarantee the insulation of refrigerators without the use of foams (and their foaming agents).

Strategies to control/prevent emissions of HFC 134a also appear to be strongly related to the design of specific components to avoid leakages. These are relevant strategies for designers to further analyze. For example, the addition of a designated valve for servicing and extraction of refrigerants poses a challenge of possible emissions during the use phase, touching upon topics of design for safe repairs. While strengthening the refrigerator components to avoid breakage during transportation and recycling processes, may pose a challenge to avoid the unnecessary use of additional materials.

Limitations and challenges

One of the challenges identified for this case is the management and analysis of the tradeoffs of substitution. No alternative to HFC 134a has been identified to fulfill all the following characteristics: no Ozone Depletion Potential, low Global Warming Potential, no flammability, no toxicity, and energy efficient. The use of an alternative with all mentioned characteristics would avoid indirect environmental impacts, increased costs in comparison to currently used substances and processes, and safety risks during the use phase and recycling processes.

One of the most mentioned challenges in other cases, is the communication across stakeholders in the supply chain, and availability of information over substances of concern and their alternatives. In the case of refrigerants, it is notable that regulation addresses specific information requirements over substances and defines specific guidelines for the different stakeholders to follow, about the design of refrigerating equipment and the corresponding processes, facilitating and standardizing communication across the supply chain

D.12 Limitations of the case study

The global warming impacts of Refrigerants are more interesting than their toxicity impacts, so not much information could be found on their risks. EEGLs were calculated for atypical work environments like submarines and had to be adapted for human health risk prioritization.

Another limitation is that there was no information about risks from shredding blown foam, an occupational activity with the most potential for risks and impacts. Further, while there were enough Ecoinvent processes to study the life cycle of HFC 134a, there was not enough information to compare it to other refrigerants.

The functional unit is 1 kilogram of refrigerant, and the impacts of cooling or freeing or insulating function are not studied as information to study these in the scope of a screening exercise were not available.

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Appendix E – Extensive description of Case 5

This appendix presents the complete investigation of Case 5 – PFAS in synthetic textiles. A summary of this case is provided in Chapter 3.1.5 of the report. It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 3.1.5 of the report. This was done with the purpose of having the complete documentation of each one of the cases, and to present the structure followed to investigate them.

Case 5 – PFAS (Per- and polyfluoroalkyl substances) in synthetic textiles – Outdoor apparel

E.1 Introduction

Per- and polyfluoroalkyl substances, also known as PFAS, are a large group (over 4000) of man-made chemicals, widely used in industrial and consumer applications since the 1940s [1], [2]. The use of these chemicals has gained popularity due to their durable water, oil, and grease repellence properties, as well as high thermal stability [1], [2], [3].

Some PFAS have seen an increase in global and local regulatory action in recent years due to human health and environmental concerns [1], [2], [3]. PFAS are considered “forever chemicals” and have been found to be resistant to degradation, making them highly persistent in the environment; they are ubiquitous, being found in air, soil, water, plants, and organisms, and are also of concern due to their long-range mobility across the environment; they are bioaccumulative, and have been found to have diverse effects in wildlife and human health, including cancer, development effects during pregnancy, liver toxicity, reproductive harm, immunotoxicity, and endocrine disruption among others [1], [3], [4], [5]. In addition to regulatory and innovation actions to eliminate these substances, PFAS remediation has become a field of increasing interest to develop technologies that isolate and/or remove PFAS from contaminated environments [3].

PFAS are a very large group of chemicals, with ECHA’s database containing information of over 2 000 individual PFAS on the EU market [6]; each have different characteristics and functions, making it challenging to study their specific potential health and environmental risks, as well as identifying and classifying them [7].

Their oil, stain, and water repellency qualities make PFAS especially popular within the textile sector, which studies have calculated to account for approximately 50% of the total global use [8]. A study estimated 45,000 to 80,000 tones of the total PFAS use in Europe are consumed in textiles, with home textiles accounting for 50-53% and consumer apparel 34-39%, other application categories include professional apparel and technical textiles [2], [4].

The outdoor apparel sector uses PFAS to impregnate textiles and produce membranes that are dirt and water repellent to be used in shoes, jackets, backpacks and tents [8]. PFAS are released into the environment throughout all stages of the lifecycle of textile products, causing a number of exposure routes [4]. Even though a number of alternatives are available, including substitutes (e.g., paraffin and silicone based chemicals) and non-chemical alternatives (e.g., tight weaving) the use of PFAS in textiles prevails in certain applications [8]. Additionally, the presence of PFAS in textile products has been identified as a barrier to recycling and the circular economy, since they are difficult to trace and separate from textile fibers and may remain in output products [8].

Studies have found interest of a number of stakeholders across the textile industry in eliminating the use of hazardous substances, including PFAS, emphasizing the need for safe substitutions, classification and limited use, to lift the barriers for recycling and produce safe products for the circular economy [9].

This case study analyses the presence of PFAS in outdoor garments to understand their function, potential hazards, and emissions throughout the life cycle. Additionally, strategies implemented by manufacturers and policy makers to eliminate/control its use have been studied and assessed to identify their benefits and drawbacks.

E.2 What is the substance?

Chemical name: Per- and polyfluoroalkyl substances
Industrial designation: N/A CAS no.: N/A
PFAS are a large group of chemicals, most commonly used for products where durable water and oil repellency is needed [1], [2]. PFAS consist of a fully (per) or partly (poly) fluorinated carbon chain connected to other different functional groups. Based on the length of this fluorinated carbon chain, PFAS can be classified into short and long chain PFAS. The length of the fluorinated carbon chain can result in different physicochemical properties that influence their repellency properties as well as their behavior in the environment, long carbon chains are typically of higher concern [1].

Depending on their application PFAS can also be classified into Polymer and Non-polymer. The latter include for example, additives to hydraulic fluids, pesticides, flame retardants, and polishing products. Polymer applications can include additives for paints and coatings, insulating sleeves, stain, oil, and water repellents for textiles [1].

E.3 How is the substance currently regulated? In which applications?

The PFAS group includes thousands of chemicals, and they are found in many different consumer, commercial, and industrial products [7]. The following paragraphs mention some of the identified regulations and international agreements to control the production, place on the market and EoL of different sub-groups of PFAS.

EU Regulation 2019/1021 on Persistent Organic Pollutants [10], [6]. The manufacturing and placing in the market of perfluorooctane sulfonic acid and its derivatives (PFOS), are prohibited. The regulation covers, perfluorooctanoic acid (PFOA), its salts, and PFOA-related compounds.

Stockholm Convention [6], [11]**.** International agreement to regulate and eliminate perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexane sulfonic acid (PFHxS).

Madrid Statement [12]**.** International agreement to regulate and limit the production and use of PFAS and promote the collaboration among stakeholders to research PFAS and develop a global inventory as well as safe nonfluorinated alternatives.

(EC) No 1907/2006, Registration, Evaluation, Authorization and Restriction of Chemicals REACH [13]. The manufacture and use of some PFAS is restricted, additionally, a number of other PFAS are on the REACH Candidate List of substances of very high concern (SVHC) [6]. Two PFAS groups were identified as SVHCs: 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid, its salts, and its acyl halides (HFPO-DA), perfluorobutane sulfonic acid (PFBS) and its salts, which is a replacement for PFOS. Several additional PFAS are on the list for evaluation.

Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures [14]. Focuses on identifying hazardous chemicals and informing about their hazards through standardized symbols. A few PFAS already have a harmonized classification and labelling under the CLP Regulation. These include:

Perfluorooctanoic acid (PFOA)
Ammonium pentadecafluorooctanoate (APFO)
Perfluorononan-1-oic acid (PFNA)
Nonadecafluorodecanoic acid (PFDA)

E.4 What is the function of the substance in the product?

In textiles, the use of PFAS can include oil and water repellency finishings (applied during production or available in sprays for consumers), oil and water repellent membranes, and highly porous fabrics (Commonly known as Gore-Tex) for thermal resistance and breathability [1], [2]. Some of the technical functions of PFAS identified in textiles include, durable water and oil repellency, stain resistance, soil protection, and flame retardancy [2]. Several studies argue that the use of PFAS is not essential and alternatives are available, suggesting functional requirements of certain applications can be reevaluated [8], [15], [16].

E.5 Substance presence and release classification

- **How is the substance present in the product?**

In the case of polymer PFAS, durable water repellent (DWR) jackets contain Polytetrafluoroethylene (PTFE) a fluoropolymer formed into porous membranes that repel rainwater but allow sweat to pass through [2]. These membranes can be layered and laminated to additional fabrics [2], [17].

In the case of non-polymer PFAS, Perfluoroalkyl carboxylic acids (PFCAs) and Perfluoroalkane sulfonic acids (PFSA) can be used to treat textiles during production (submerging the textile into a solution) or by consumers using impregnation sprays [2], [17].

Concentrations of PFAS may vary per brand and garment type, for example, PFCASs ranges were found to be between 5 and 428 µg per m2 of textile, and 5 and 30 µg of PFSAs per m2 of textile [17].

- **How is the substance released in the environment? Through which mechanisms? Are these mechanisms aggravated by any other input?**

Some of the identified release mechanisms of PFAS include volatilization, migration, leaching, and release of textile particles by mechanical degradation [1], [2], [4], [17], [18]. [19] [20].

The amount and rate of release of PFAS can be influenced by several factors, including the specific physicochemical characteristics of the specific PFAS group, as well as the physicochemical characteristics of the material they are added to, the method or process in which PFAS are added or present in the material, handling and duration of use of the textile product, and environmental conditions (e.g., humidity and temperature) [18]. Depending on the strength of the bond between the PFAS and textile material releases can occur as molecules of the chemical leaving the textile, or as particles of the textile itself contaminated with the chemical [18].

E.6 What are the possible hazards to health and the environment?

The amount and variety of PFAS, as well as limitations on the available information of some PFAS groups, makes it challenging to study all the potential human health and environmental risks, generating uncertainty [7], [21]. There is, in cases, uncertainty over what substances classify as PFAS, as well as their relevance to human health and specific effects [21]. Additionally, health risk assessment is usually performed for exposure to a single chemical, whilst in realistic scenarios humans may be exposed to mixtures of known and unknow PFAS. Important differences in results have been noticed between studies over PFAS toxicity in animals and humans, adding to the uncertainty of their effects [21].

There is a general concern over PFAS being persistent and ubiquitous in the environment, which generates a variety of exposure paths, with exposure through contaminated drinking water and food being of most concern for humans [22]. Additionally, PFAS are bioaccumulative, which means concentrations in body tissues of humans and animals continues to increase, the effects of long term exposure are also unknown [1], [3], [4], [5].

Due to the complexity and variety of the PFAS groups the potential health and environmental hazards listed below have been identified for PFAS in general and do not belong to a single substance.

- **Health**

PFAS have been associated to the following health hazards (some with limited evidence) [2], [4], [8], [23], [22]:
- Thyroid disease and endocrine disruption.
- Increased cholesterol.
- Development effects on fetus.
- Reproductive damage.
- Carcinogenic (breast, kidney, testicular).
- Inflammatory bowel disease
- Liver damage
- Neurological disorders
- Overweight and obesity

- **Environment**

PFAS are ubiquitous contaminants and having been found in wastewater, groundwater, freshwater, rainwater, marine environments, soil, vegetation, humans, and animals, with ocean water being the largest global reservoir [24]. Different effects of PFAS have been observed in the environment, depending on the species of animals and plants, concentration, PFAS group, and length of exposure [22]. Observed effects include [3], [22]:

- Contamination of plants and animals
- Soil contamination, affecting soil quality
- Reduction of different species of worm population
- Biochemical effects on plants
- Gut disruption and reproductive toxicity have been observed in different species of fish
- Impacts on liver and kidneys of rats
- Growth disruption and mortality of benthic organisms

E.7 How and in which stage of the life cycle of the product do emissions of the substance occur? How much of the substance is emitted? And how does exposure occur?

In the following paragraphs the release of PFAS in different stages of the lifecycle of synthetic textiles used in the outdoor apparel industry, as well as their different exposure routes are discussed. PFAS groups have a complex interplay among them, making their origin unclear and hard to trace; it is a challenge to identify whether they were added intentionally or are generated as byproducts or impurities from precursors [2].

In addition to that, it is challenging to quantify emissions of single PFAS along the lifecycle, as well as the specific contribution of outdoor apparel to global emissions and exposure, due to their presence in a variety of applications and forms, uncertainty over their origin, and their mobility characteristics; they can be transported into other ecosystems, by water and air currents as well as precipitation [1], [17], [22].

As mentioned earlier, releases of chemicals from textiles can occur as molecules of the chemical leaving the textile, or as particles of the textile itself contaminated with the chemical; this depends on the strength of the bond between the PFAS and textile material, as well as the method of incorporation (e.g., membranes and impregnation) [18].

- **Production**

Emissions: PFAS may be released into waste water streams from manufacturing sites, contaminating surface and groundwater [1], [19]. PFAS may also be emitted into the air and dust settlements inside production sites during manufacturing [18]. Some manufacturing sites count with their own sewage treatment, however, not all waste water treatment plants count with specific technologies to capture and destroy PFAS [8].

The chemical manufacturing and formulation, as well as the industrial application of PFAS on textiles, were identified as steps with the largest contributions to PFAS emissions over the lifecycle, followed by landfill and use phase [2]. It is also relevant to highlight that it has been estimated that about 80% of the total environmental impact of textiles occurs on the production phase [25].

Exposure: Occupational exposure may occur via inhalation of air and dust, this is more significant in chemical production sites than textile manufacturing sites [19]. Indirect exposure via inhalation and ingestion, through contaminated food, contaminated water, dust, and precipitation, caused by emissions to waste water and air [1]. Chronic occupational exposure to PFAS is considered a concerning scenario with indirect exposure and indoor air inhalation being the most relevant [17].

- **Use**

Emissions: There are several pathways in which PFAS may be released during the use phase from textiles. PFAS can volatilize in interior and outdoor environments into air and dust [1]. Contaminated textile fibers may also be released from the wear and tear of garments, and settle into dust [18]. PFAS may be washed off and emitted into wastewater during laundry activities [1], [17], [18]. In addition to this, PFAS present in impregnating products need to be considered; these may be available as textile detergents and sprays and are used to replenish the waterproof characteristics of the textile; these can emit PFAS into the air and wastewater when used [17].

The use phase has been identified as the third largest contributor to PFAS emissions, specifically considering emissions to wastewater through washing [2], [4]. A study proposes, washing instructions for users to avoid washing with high temperatures, and reducing washing frequency, may reduce the release of PFAS during laundering and prevent the need to replenish the water repellent treatment, reducing and preventing the emission of PFAS [2]. The consumer use of impregnating sprays is considered to be less relevant [2], [4].

Exposure: Exposure can occur through dermal contact from wearing the treated clothes, where PFAS may be transferred into perspiration, which is then absorbed by the skin [17]. Consumers may also be directly exposed via inhalation of contaminated indoor air, as well as volatilized particles of impregnation sprays [17], [18]. Ingestion and inhalation of contaminated indoor dust may be an additional exposure pathway [17], [18]. The extensive use of clothing treated or composed by PFAS, as well as impregnating products will cause an increase in PFAS intake [17].

Indirect exposure via inhalation and ingestion, through contaminated food, contaminated water, dust, and precipitation, caused by emissions to waste water and air [1]. Indoor air inhalation, dust ingestion, and indirect exposure were found to be the most relevant pathways for consumer exposure [17].

- **EoL – Recycling**

Emissions: Specific data regarding emissions during the recycling phase were not found during this study. Only general information about the barriers PFAS pose to recycling can be provided.

Recycling rates of textiles in the EU remain low, with only a third of the textiles put in the market being separately collected, and only about 25 – 50 % of this portion being recycled [25]. Products containing PFAS may be recycled into new products, however PFAS are expected to remain and reintroduced into the lifecycle, continuing to be emitted into the environment [8]. The presence of PFAS hinders textile recycling since PFAS treated materials may be classified as hazardous by regulation and not recyclable [20].

- **EoL – Landfill and incineration**

Emissions: 73% of the global textile material flows is landfilled or incinerated in EoL [26], with two thirds of the textiles put on the market in the EU ending up as residual waste [25]. Inappropriate treatment of waste can cause volatilization and leaching in landfills, contaminating air, surface water and ground water [1]. PFAS have also been found to be emitted through incineration fumes and remain in ashes [8].

Landfilling is estimated to be the second largest contributing stage to PFAS emissions after production [2], [4]. Uncontrolled landfill is of most concern, considering landfills that do not count with systems that prevent releases into the air, soil, and water [2].

Exposure: Occupational exposure may occur via inhalation of air [19]. Indirect exposure via inhalation and ingestion, through contaminated food, contaminated water, dust, and precipitation, caused by emissions to waste water and air [1]. Chronic occupational exposure to PFAS is considered a concerning scenario with indirect exposure and indoor air inhalation being the most relevant [17].

E.8 Prioritizing risk hotspots

PFAS are emitted to all environmental compartments [29] and the potential for human and ecological exposure is ubiquitous. Prioritizing risk hotspots for PFAS in textiles is a challenge due to frequent degradation through their life cycle and knowledge gaps about degradation pathways [3], [27], [28]. Degradation of PFAS used in DWR during weathering is expected to yield a mixture of ionic and volatile PFAS (Figure E1); however, the mass balance analysis of PFAS types in DWR samples does not add up. This is attributed to analytic technique limitations, e.g. measurement of volatile emissions, existence of fluorotelomer polymer hydrolysis byproducts, degradation of the DWR polymers making non-extractable fluorine extractable, and degradation of unknown precursors. [29]. Therefore, it is difficult to monitor if DWR meets the European Commission PFOS and PFOA content limit in textile of 1 µg/m^2 and clear risk prioritization for ecological and human health is currently not feasible for individual PFAS.

Mixture-based risk assessment approaches are recommended to address PFAS risks [29][30][31]. One such approach includes the development of Relative Potency Factors (RPF). In one study, a multiplier for the hazard of 22 PFAS relative to PFOA [30]. The RPFs can be multiplied with PFAS quantities in an environmental media and summed to obtain PFOA equivalents that can be compared to PFOA concentration limits established for that media. The RFP for DWR relevant PFAS 6:2 FTOH and 8:2 FTOH are 0.02 and 0.04 respectively [30].

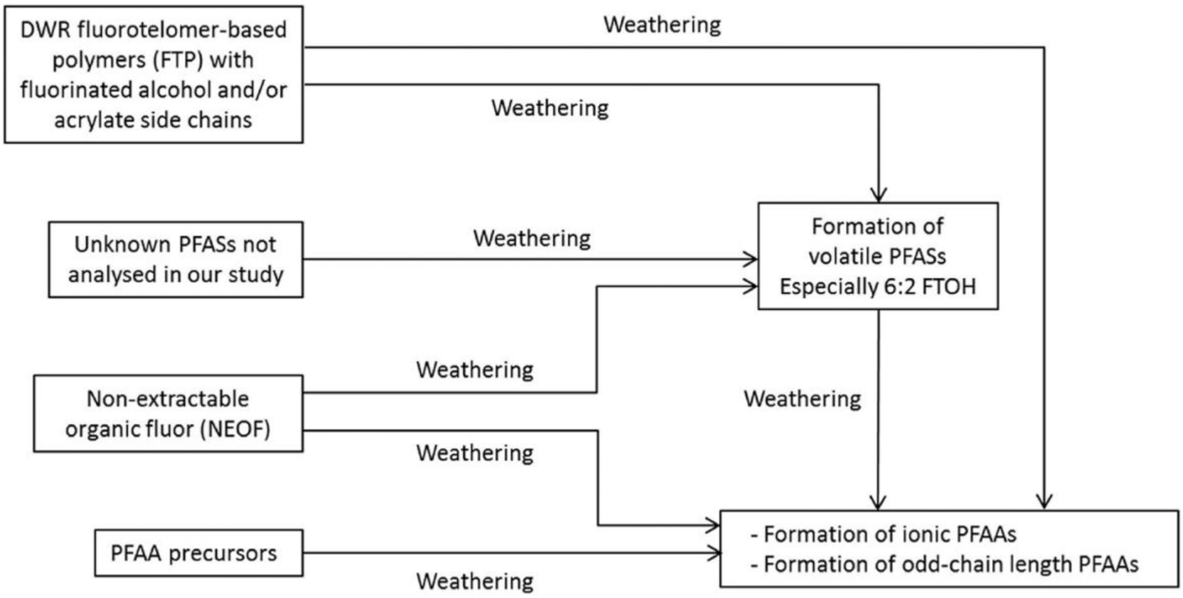


Figure E1. Potential degradation pathways of weathering of PFAS used in the DWR. From [29]

E.9 What are existing SbD strategies to deal with PFAS?

This section presents and discusses different strategies identified in literature to reduce, control, and or eliminate the use of PFAS in textiles. It provides further information on each strategy, when possible, to determine benefits and drawbacks, as well as unforeseen consequences or uncertainty.

- **Eliminate – Substitute the additive**

The elimination of substances of concern from textile products is considered of main priority to avoid negative impacts throughout the lifecycle and allow safe material flows in a circular economy, this premise considers substances added to the formulation of the product (e.g. PFAS and other additives) and substances that are released by the product (e.g. microplastics) [26].

When identifying potential replacements for PFAS in textiles, it is important to consider technical feasibility, performance, required processes and machinery, economic feasibility, availability and volume requirements, and environmental and health risks of alternatives [2], [32].

Some outdoor textile manufacturers have implemented several internal processes to phase out PFAS in their product line and communicate with their suppliers. Some examples include:

- The use of Restricted Substances List (RSL) – which consider substances in the final product that are regulated either by restricting content or banned [33], (interviewed sport clothing manufacturer) .

- The use of Manufacturing Restricted Substances List (MRSL) – Which considers substances present during production, that are either banned or have restricted values [33], (interviewed sport clothing manufacturer).

- Improved communication and transparency within stakeholders in the supply chain, through quality and safety certificates of materials (e.g. bluesign [34]), education of their teams, and testing for the presence of PFAS and other substances [33], [35].

There are three categories of potential PFAS replacements in the textile sector, including two chemical substitution types and a non-chemical.

A. Per or polyfluorinated: substances with shorter carbon chains

The concern for the environmental and health hazards caused by long chain (C8) PFAS, pushed the transition into shorter chain (C4 and C6) PFAS, which were believed to be less harmful for the environment [2]. However, shorter chain PFAS are still fluorinated substances, and have been identified to also be extremely persistent in the environment, bioaccumulative and concerning water contaminants [1], [15], [36]. In addition to this, further information about their potential effects remains to be unavailable, making it hard to assess them as suitable substitutes [1].

Non fluorinated alternatives are not considered to have performance characteristics equivalent to PFAS, by some manufacturers, who phased out long chain PFAS of their product lines, but continue to use short chain PFAS in applications they consider to be essential [34], [37]. This is proposed as a temporary solution while research for non-fluorinated alternatives continues to find suitable substitutes for high performance applications [34], [37].

B. Non-fluorine containing substances

Textiles treated with non- fluorine repellent substances were found to provide similar water repellency to those treated with long and short chain PFAS [32]. However, oil and stain repellency remain to be low among existing non-fluorinated alternatives, making them unsuitable for high performance textiles such as medical applications [15], [32]. Some examples of non-fluorinated repellent substances used in textiles include:

Hydrocarbons and paraffin – Provide water repellency but no oil repellency, poor comfort (breathability), lower costs against PFAS (but require higher dosage), low human hazard low environmental [2]. Hydrocarbon DWRs were found to be less hazardous in comparison to other non-fluorinated repellent alternatives [27].

Silicones – Provide water repellency but no oil repellency, very low durability of water repellency, good breathability, moderate to high human hazard (depending on the specific type), moderate environmental hazard (depending on type), similar costs to PFAS [2]. Silicones have been found to get easily contaminated by dirt and oil and have low durability, which raises concerns of reducing the lifetime of garments, causing them to be replaced more frequently [34].

Dendrimers – Provide water repellency but no oil repellency, may have health hazards and not enough information available regarding environmental hazards, and are more expensive than PFAS [2].

Polyurethanes – Provide water repellency, possible oil repellency (to be tested), not enough information is available over health and environmental hazards, have similar costs to PFAS [2].

- **Eliminate – Substitution of function / material**

A. Non- chemical techniques

Non chemical techniques include weaving and fiber control [2]. For example, polyethylene and polypropylene fibers that are naturally stain resistant, or wool fibers that are naturally hydrophobic, are weaved into structures that generate water repellent textiles [2]. This techniques provide high quality durable water repellency, but do not provide oil repellency [2], [8]. These hydrophobic textiles also count with self-cleaning performance, which is expected to reduce the number of launderings, preserving the functional performance of the garment [2].

With these techniques, garments are expected to maintain their water repellency properties for longer, when compared with PFAS treated textiles, which wear down and wash off over time [38]. On the negative side, the focus on hydrophobic properties has resulted in non-stretching textiles that may not provide the comfort required by the different applications [39], [38].

There are currently no existing alternatives that are comparable in performance to PFAS treated textiles, additionally, many of the alternative substances are still under research and information over their potential health and environmental hazards is limited or unavailable [40].

- **Eliminate – Phasing out PFAS by re-evaluating functional requirements**

An alternative strategy to phase out the use of PFAS is the re-evaluation of their use in different applications. It is proposed to limit the use of PFAS to applications where their functionality is considered essential, for example, applications were not only water repellency is necessary but also oils and dirt, such as textiles meant for professional use like medical and military, where these characteristics are critical [2], [4]. Phasing out all applications where alternatives are available or where the functionality of PFAS is not needed [4].

Some manufacturers of outdoor apparel continue to use short chain PFAS in applications they consider to be essential (e.g., garments that protect from life threatening weather conditions) and an alternative is not currently available [34], [37]. This is proposed as a temporary solution while research for nonfluorinated alternatives continues to find suitable substitutes for high performance applications [4], [34], [37], [41].

Two studies were found to propose a prioritization of PFAS application considering the need for technical performance. The first proposes three groups of applications, fashion, comfort user needs, and hazard management [27]. Prioritizing the possible PFAS applications as:

a) Chemical production – protective garments
b) Military
c) Ambulance / similar
d) Outdoor
e) Fishing
f) Sailing
g) Skiwear
h) Leisure rainwear

The second study provides the following classification [42]:

a) Non- essential – Applications driven by market opportunity and non-essential for the safety and health of the wearer. In this case the functionality of PFAS can be omitted overall.
b) Substitutable – Applications were the functionality of PFAS has been found to be relevant or essential, but alternatives are available, with similar functional characteristics and performance.
c) Essential – Applications necessary for health and safety of the wearer that require high performance for which alternatives are not available.

- Reduce - Increasing the useful life of textile products – waste prevention

Increasing the useful lifetime of clothes is considered to be the most effective strategy to capture value and design out waste and pollution in the textile industry [26]. This is consistent with the findings of emissions of PFAS being of most concern during production and EoL, by extending the useful life of garments these can be avoided. Clothing products in general have been found to be discarded in the EU before the end of their lifespan (due to fashion trends and desire to change wardrobes), some of which are fit enough for reuse and repair [25].

Some strategies used to increase the useful life of clothing, applicable to the outdoor apparel industry include:

A. Designing and manufacturing clothes of higher quality – durability [26].
Some companies prioritize durability over substitution of PFAS, to prevent the larger environmental impact of the production phase [34].

B. Provide access to clothes through new business models (e.g., clothing rental) [26].
This strategy is currently being implemented in clothing products of high quality and for special occasions (suits, dresses, etc.). This study identified a rental system for ski jackets in operation in the USA [43]. It is unclear what the effects of this strategy are over PFAS emissions, but it is expected it avoids or reduces emissions related to the production phase and accumulation at EoL.

C. Repair of clothes to increase their useful life [26].
This strategy is being implemented in outdoor garments. This study identified one example where garments are repaired by the manufacturer [44], and a similar program that takes back used garments, repairs them and re-sells them [45]. It is unclear what the effects of this strategy are over PFAS emissions, but it is expected it avoids or reduces emissions related to the production phase and accumulation at EoL.

- Control/Prevent - Prevent PFAS emissions from washing

Washing instructions for users to avoid washing with high temperatures, and reducing washing frequency, may reduce the release of PFAS during laundering and prevent the need to replenish the water repellent treatment, reducing and preventing the emission of PFAS [2].

E.10 Evaluation of the application of screening LCA and RA to assess SbD strategies (existing/historical alternatives)

Baseline scenario

The ecotoxicity and human toxicity impact of PFAS are challenging to include in LCAs due to uncertainty about the transformation of PFAS through the life cycle and missing (eco) toxicity information [27], [46], [47]. Among 4000 PFAS, degradation pathways and rates are missing for the most hazardous PFAS including the side chain fluorinate PFAS used in DWR. Human health impact assessment is also uncertain due to the divergence between Effect Factors calculated using epidemiological and rodent data [28]. Transformation fractions are calculated for ecotoxicology (cite) but its use requires careful evaluation in the case of some PFAS [28], [47] . It is not surprising that there is no information on key PFAS used in textile in Ecoinvent and other databases.

Assessment of strategies

Substitution-Predictive RA approaches

Predictive RA approaches based on the structure of chemical can assist designers in avoiding regrettable substitutions of SoCs. This is because certain chemical groups are associated with known toxic effects, and thus may be avoided. One such tool is RIVM's ZZS similarity tool (https://rvszoeksysteem.rivm.nl/ZzsSimilarityTool), which provides chemicals that are structurally similar to those on the ZZS list and may therefore exhibit similar toxicity profile. On providing the CAS number of DEHP, the Similarity tool provided the following chemicals (CAS numbers) that are likely to exhibit toxicity as common PFAS used in jackets (e.g., PFOA, FTOH, PTFE).

Substitutions to be avoided

PFAS	CAS numbers of chemicals likely to be reproductive toxins	CAS numbers of chemicals likely to be endocrine disruptor	CAS numbers of chemicals likely to be persistent and bioaccumulative
PFOA	3825-26-1, 375-95-1, 3108-42-7 3830-45-3 335-76-2	None	3825-26-1, 375-95-1, 3108-42-7 3830-45-3 335-76-2,307-55-1, 375-95-1, 376-06-7, 72629-94-8, 2058-94-8
FTOH	375-95-1,3108-42-7 3830-45-3 335-76-2, 3825-26-1 335-67-1	None	None
PTFE	None		

Table E1. ZZS Similarity Tool results for common PFAS used to provide DWR function in outdoor jackets

The similarity analysis shows that PFAS used in DWR and similar to other ZZS PFAS. No other chemical category is pinpointed in this analysis Together with the uncertainty on transformation pathways of PFAS, it is prudent to substitute with non-PFAS alternatives.

Substitution -Shorter Chain PFAS, Siloxane, Wax and Hyperbranched Polymers

A study assessed substitution (two types of side-chain fluorinated polymers (C4 and C6); one silicone-based DWR; one hydrocarbon-based wax and a non-fluorinated DWR based on hyperbranched polymers)[47] for the lifecycle of the jacket (Figure E2). The functional unit was for the standard jacket set to "keeping the wearer warm and dry during one use (30 min) of the jacket". The standard jacket was modelled as a lightweight weave PA jacket with a waterproof, breathable polyurethane (PU) interior coating.

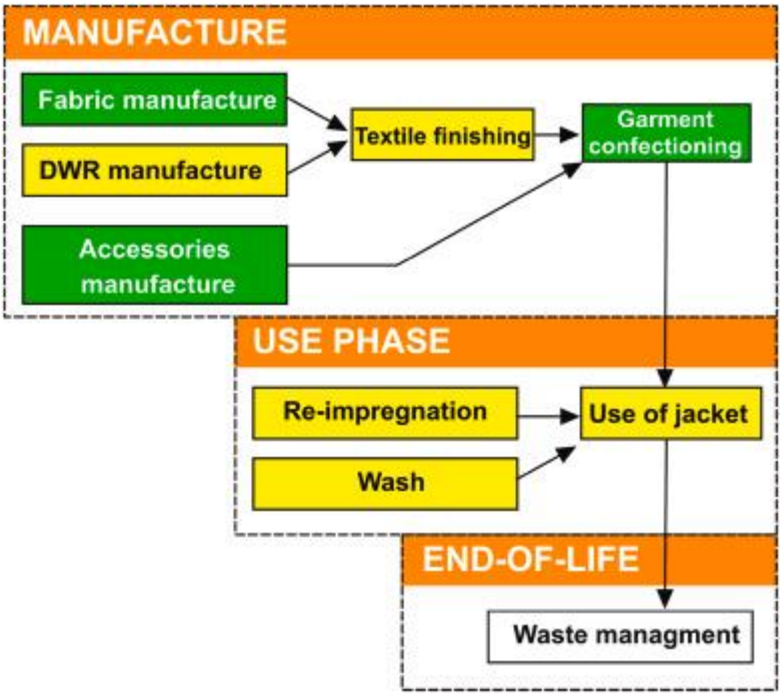


Figure E2. Lifecycle of DWR outdoor jackets. From [47]*. Weathering in use phase is shown in Figure E1.*

In comparison to long chain PFAS life cycle, non-cancer human toxicity impacts were reduced in the short chain PFAS and even more substantially in wax, hyperbranched polymers and siloxane based DWR. Wax based DWR may be the most feasible substitute.

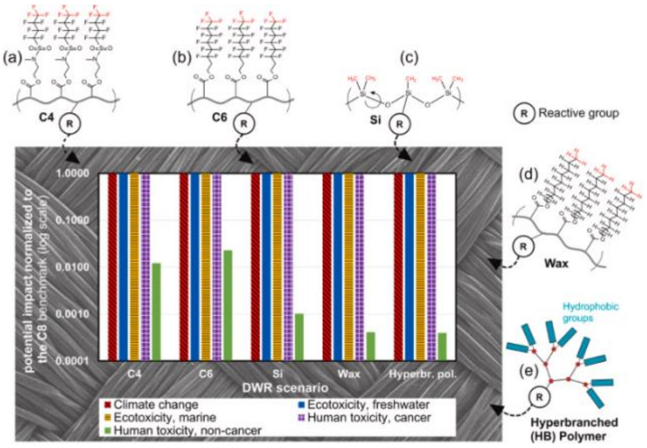
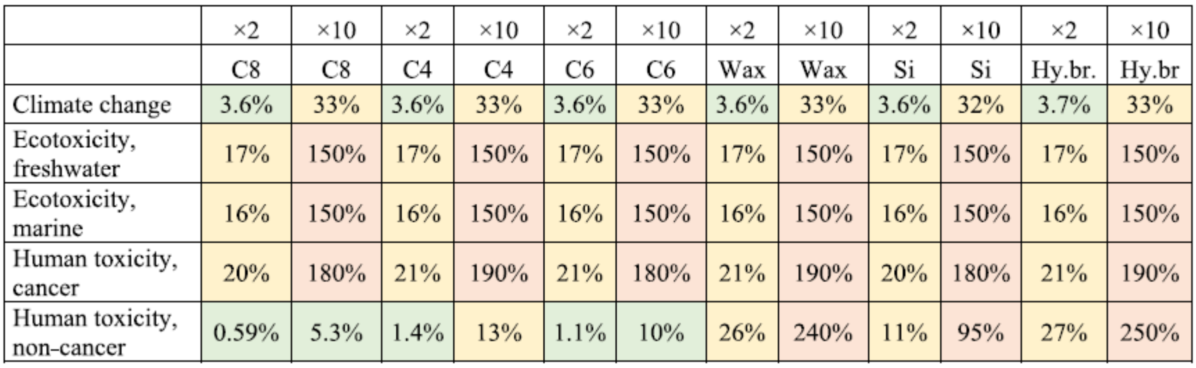


Figure E3 Lifecycle impacts of long chain (C8) based DWR jackets with short chain (C4 and C6), Siloxane, wax and hyperbranched polymers, From[47]*.*

In terms of activity, the most significant difference in impacts were found in washing of jackets (Table E2). Frequent washing (2x to 10x) has an impact on freshwater ecotoxicity, marine ecotoxicity and cancer based human ecotoxicity. Hence reducing number of washes is critical to limiting PFAS exposure in the use phase.



	×2	×10	×2	×10	×2	×10	×2	×10	×2	×10	×2	×10
	C8	C8	C4	C4	C6	C6	Wax	Wax	Si	Si	Hy.br.	Hy.br
Climate change	3.6%	33%	3.6%	33%	3.6%	33%	3.6%	33%	3.6%	32%	3.7%	33%
Ecotoxicity, freshwater	17%	150%	17%	150%	17%	150%	17%	150%	17%	150%	17%	150%
Ecotoxicity, marine	16%	150%	16%	150%	16%	150%	16%	150%	16%	150%	16%	150%
Human toxicity, cancer	20%	180%	21%	190%	21%	180%	21%	190%	20%	180%	21%	190%
Human toxicity, non-cancer	0.59%	5.3%	1.4%	13%	1.1%	10%	26%	240%	11%	95%	27%	250%

Table E2 Washing scenario assessment for the standard jacket showing increased impacts per functional unit (%) from increasing wash frequency by 2 or 10 times, From[47].

E.11 Conclusions – Main insights for designers

Table E3 provides a summary of the identified SbD strategies and their potential benefits and downsides according to literature and the RA, and LCA assessments when applicable.
Key: Qualitative Evaluation (from literature) [QE], Rough estimation [est], Life cycle assessment [LCA], Risk assessment [RA], Expert interview [int]

Safe by Design strategies to deal with PFAS in synthetic textiles				
Type of strategy	Identified SbD strategies	Assessment method	Potential benefits	Potential downsides
Eliminate	Substitute with per or poly fluorinated substances with shorter carbon chains	[QE]	- Lower environmental impact compared to long chain PFAS [2].	- Persistent in the environment, bioaccumulative and concerning water contaminants [1], [15], [36]. - Information about effects remains unavailable [1].
	Substitute with non-fluorine containing substances: Polyurethanes, Dendrimers, Silicones, Hydrocarbons, and paraffin	[QE]	- Similar water repellency to long and short chain PFAS [32].	- Oil and stain repellency remain to be low, not suitable for high performance applications [15], [32]. - Durability of water repellency is a concern [34]. - Hazards and effects are unknown for some alternatives [2]
	Substitute with non- chemical – techniques. Alternative function - weaving and fiber control	[QE]	- High quality durable water repellency [2], [8]. - Self-cleaning performance, expected to reduce laundering, preserving the functional performance of the garment [2].	- Do not provide oil repellency [2], [8]. - Non-stretching textiles that may not provide the comfort required by the different applications [39], [38].
	Phasing out PFAS by re-evaluating	[QE]	- Phase out all applications where alternatives are available or where the	N/A

	functional requirements		functionality of PFAS is not needed [4], [int].	
Reduce	Increasing the useful life of textile products – waste prevention through: - Durability - Access business models - Repair	[QE]	- Considered most effective strategy to capture value and design out waste and pollution in the textile industry, specifically relevant for emission in production and EoL [26]. - May avoid emissions from the production phase and accumulation during EoL.	- Does not target emissions during the use phase.
Control / Prevent	Prevent PFAS emissions from washing – washing instructions for users	[QE]	Reduce the release of PFAS during laundering and prevents the need to replenish the water repellent treatment [2], [int].	- Focuses on the use phase exclusively

Table E3. Summary of identified SbD strategies for PFAS in textiles (outdoor garments).

Most relevant attention points - emission/exposure scenarios
PFAS are released from textile products in all environmental compartments (air, water, wastewater, soil) through several release mechanisms (volatilization, leaching, migration, mechanical wear of textiles) throughout the lifecycle, with the most concerning emission scenarios being, in order of relevance, production, landfill and use phase. In addition, PFAS continue to accumulate in organisms and in the environment. People are exposed to PFAS through several possible channels, including inhalation, ingestion, and skin contact, with occupational exposure during chemical production, indirect exposure through contaminated water and food, and inhalation of indoor and outdoor air/dust being of most concern.

Types of strategies, scope of the strategies, benefits, and downsides
With such a large variety of release mechanisms and exposure channels as well as their accumulative and persistent characteristics, the strategies to deal with PFAS cannot be targeted on the basis of one scenario or product lifecycle stage in specific. Most strategies found in this case focus on elimination of the substance by substitution, with several substitutes having similar effects on human health and the environment as PFAS or unknown effects on health and the environment that need further research. Additionally, no substitutes have been found to have equal performance characteristics to PFAS. Therefore, the focus should shift away from finding a suitable PFAS substitute. Efforts should focus towards a re-evaluation of desired properties for different applications and the development of solutions that specifically target those.

Reduce strategies target specific emission scenarios neglecting other stages of the lifecycle. Additionally, their effectiveness in reducing PFAS emissions is unknown.

The role of designers
Although designers may have limited influence over the substitution of PFAS with alternative chemicals, further research and efforts could go into designing products that counteract some of the drawbacks of PFAS substitution and elimination through the re-evaluation of essential applications. These drawbacks include durability, performance issues, and lack of elasticity of the textiles.

In addition to that, designers also need a better understanding of PFAS and their potential alternatives, to be able to communicate in a transparent and effective way with suppliers. Some manufacturers were found to have internal policies that include adherence to restricted substances lists and educational programs for their development teams. Internal processes such as these are relevant for informed and safe substitution and elimination strategies.

Designers have a larger contribution space within strategies that aim to reduce the amount of PFAS emissions through the extension of the useful life of textile products, including repair, remanufacturing and business models that make clothes available to consumers through rental and leasing.

Limitations and challenges

Some of the mentioned challenges to deal with PFAS in textiles found in this study include, 1) Communication and transparency issues between PFAS and textile producers, and brands / manufacturers, 2) Lack of understanding and information about PFAS, including their classification and effects, and possible substitutes, 3) The lack of alternatives with similar performance characteristics has pushed manufacturers to continue to use PFAS for certain applications.

The elimination of PFAS and other substances of concern in textiles overall requires a collaborative approach across the supply chain since a great deal of innovation and development is needed to overcome all the presented challenges and scale up found solutions.

Several recommendations were found through literature and manufacturers reports to overcome these challenges, including 1) PFAS elimination policies and regulation, 2) Re-evaluating the essentiality of PFAS, 3) Improved transparency and communication within the supply chain through education and internal policies, 4) Availability of and further information about PFAS, their effects, classification etc., 5) Research and development of safe alternatives.

E.12 Limitations of the case study

This study was limited to the analysis PFAS as a group due to time constraints. Further studies are necessary considering a specific PFAS type and product combination(s) to obtain results that are particular to the selected case.

PFAS are very topical Substances of Concern and there is substantial research on them being published currently. However, there is still not enough information on transformation and degradation pathways of PFAS, which is needed to do a robust RA or LCA. There is also significant divergence in human toxicity of PFAS calculated from epidemiological data and animal data.

Further, as is the case with other widely used persistent and bioaccumulative chemicals in the study, human and environmental exposure to PFAS typically comes from a variety of consumer products. Assessing cumulative risks from relevant products over time represents a more valid risk prioritization than one time exposure to a single product.

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Appendix F – Extensive version of the evaluation of the SbD approach

This appendix presents the complete set of results of the internal evaluation of the SbD approach (Chapter 4.1). It is possible for the reader to encounter some repetition on sections of this appendix and Chapter 4.2, which includes one of the cases use for the evaluation. This was done with the purpose of presenting the complete documentation and process of the evaluation of the cases.

The evaluation was performed internally by one of the researchers. The evaluation was performed using 3 additional case studies:

1) Microplastic release from synthetic textiles
2) PUR foam in sleep and respiratory care devices
3) PFAS in food packaging

F.1 Microplastics release from synthetic textiles

Step 1. Analyze the product - substance combination

a) Identify the SoC and its type (if not identified already).

Present in the product – intentionally added	Generated by the product – byproducts generated throughout their Use/EoL	Used or added temporarily to the product for additional functions but not intended to be present in the end- product – Intermediates
	Microplastics released from synthetic textiles originate from the abrasion of the textile, which causes the unintentional release of small plastic particles or fibers directly into the environment [1].	

b) Describe the substance. Answers to the questions in Step 1b are shown in Table F1.

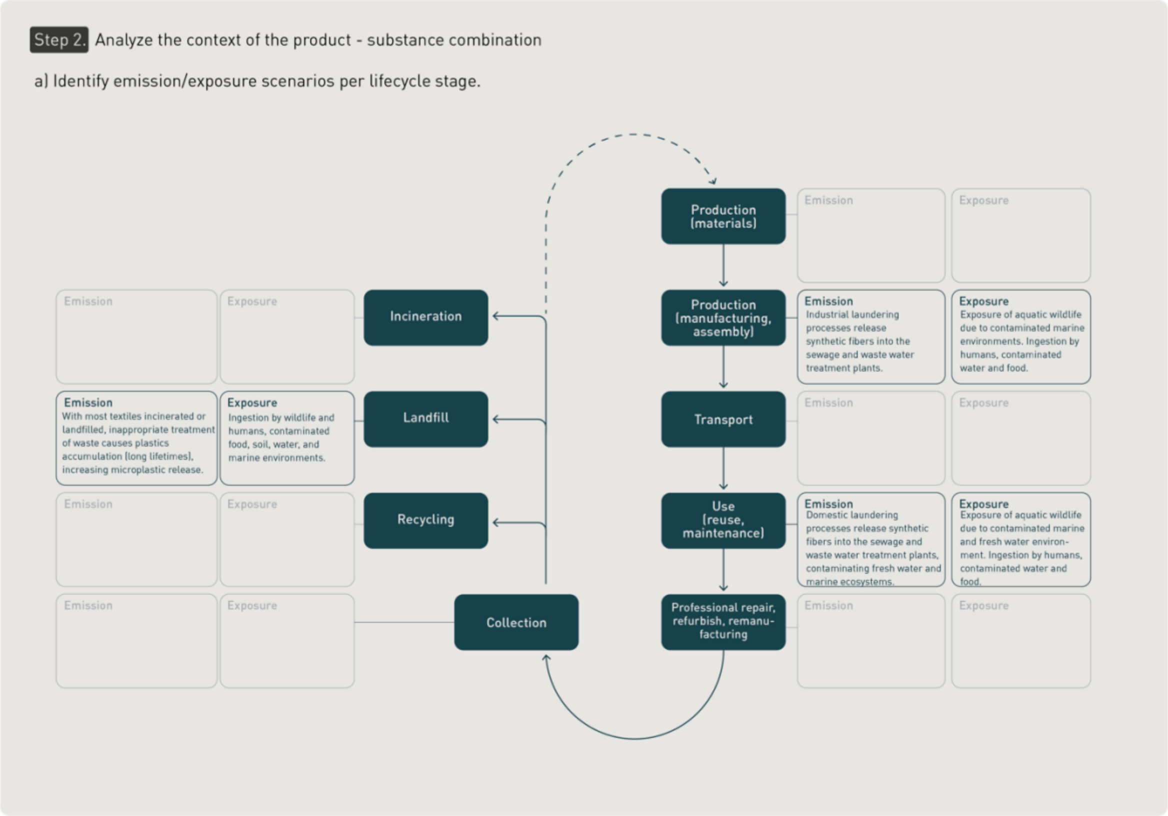
Question	
1. What is the SoC? Name(s), type of substance?	Microplastics are defined as small plastic particles of less than 5mm in diameter, released into the environment from plastic products [2], [3]. In the case of synthetic textiles, microplastics are usually referred to as fibers due to their elongated form [4]. Synthetic textiles are those of petrochemical origin with most common being, polyester, polyolefin (PE and PP), polyamide (nylon), and acrylic [4], [5], [6].
2. What is the function of the substance in the product?	Synthetic fibers constitute around 60% of the world's total textile production [6]. These are considered to have several advantages over natural fibers (cotton, wool, etc.), such as increased strength and durability, resistance to insects and chemicals, ease to dry, no shrinking, and lower costs. Additionally, synthetic fibers can be further chemically modified to add functions to them such as abrasion resistance, and water and stain repellency [6].
3. What kind of hazards does it have on health and the environment?	Microplastics are ubiquitous contaminants, increasingly present in the environment. Due to their resistance to degradation, they can remain for long periods of time in the environment [2], [7]. Microfibers are ingested by aquatic and terrestrial organisms, entering the food chain [8]. Additionally, they serve as transport to harmful additives (if present) and adhered pollutants and pathogens, having different effects in the environment and health [2], [4]. In wildlife, they have been found to have feeding and reproductive disruptions as well as metabolic disturbances [2], [7]. Some of the studied

	health impacts include respiratory problems, cardiovascular diseases, and obesity [2].
4. How is the substance currently regulated/banned?	No specific regulations in relation to the emission of microplastics from textiles was identified.
5. How much substance is in the product? (If possible and available)	N/A. The SoC (microplastics) is inherently bound to the composition of the material, as it is the plastic itself that breaks down into smaller particles.

Table F1. Answers Step 1b

Step 2. Analyze the context of the product – substance combination

a) **Identify emission/exposure scenarios throughout the lifecycle.** Figure F1 includes the identified emission/exposure scenarios for the case.



Step 2. Analyze the context of the product - substance combination

a) Identify emission/exposure scenarios per lifecycle stage.

Production (manufacturing, assembly) – **Emission** Industrial laundering processes release synthetic fibers into the sewage and waste water treatment plants.

Production (manufacturing, assembly) – **Exposure** Exposure of aquatic wildlife due to contaminated marine environments. Ingestion by humans, contaminated water and food.

Use (reuse, maintenance) – **Emission** Domestic laundering processes release synthetic fibers into the sewage and waste water treatment plants, contaminating fresh water and marine ecosystems.

Use (reuse, maintenance) – **Exposure** Exposure of aquatic wildlife due to contaminated marine and fresh water environment. Ingestion by humans, contaminated water and food.

Landfill – **Emission** With most textiles incinerated or landfilled, inappropriate treatment of waste causes plastics accumulation (long lifetimes), increasing microplastic release.

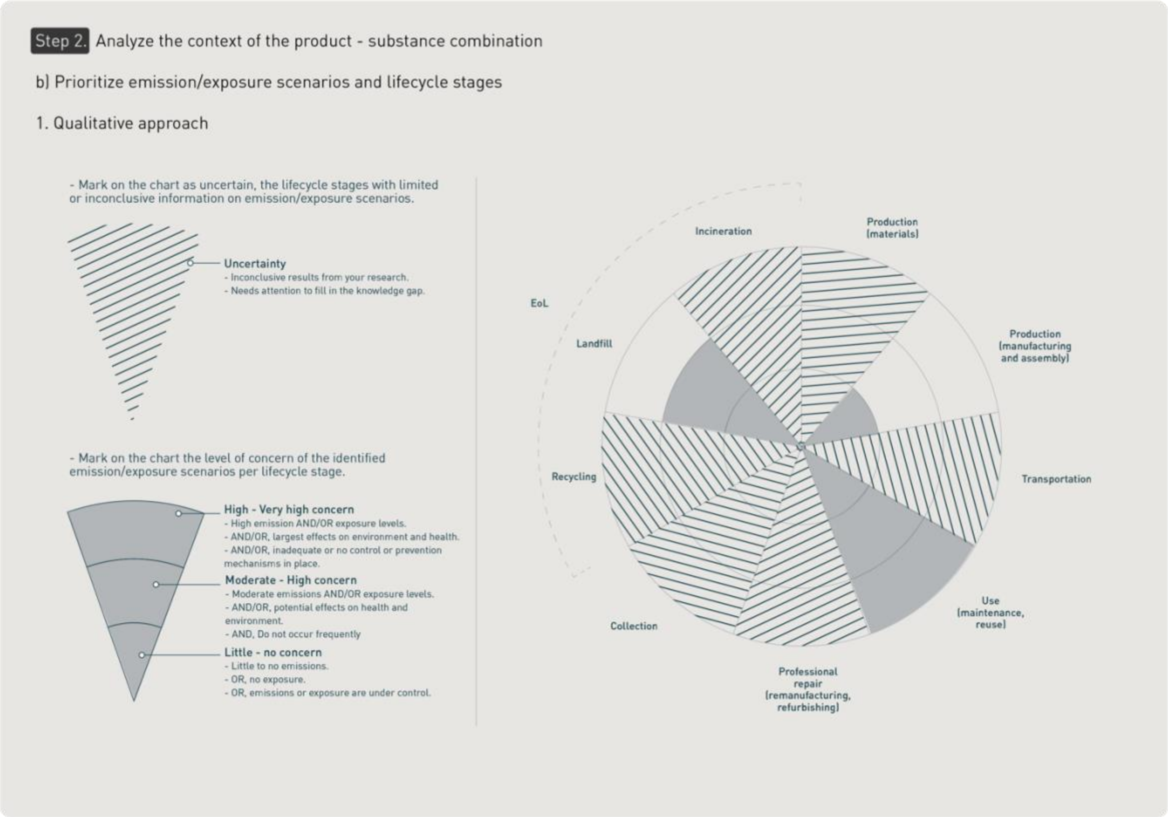
Landfill – **Exposure** Ingestion by wildlife and humans, contaminated food, soil, water, and marine environments.

Figure F1. Answers to Step 2a, Identification of emission/exposure scenarios

References for Step 2a: Information was found regarding emission/exposure scenarios of the manufacturing, use and landfill stages, no further information on the remaining life cycles stages could be found in this evaluation [1], [4], [8], [9], [10].

b) Prioritize emission/exposure scenarios and lifecycle stages

1. **Qualitative approach.** Figure F2 shows the qualitative evaluation of the emission/exposure scenarios of the case.



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from your research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

Figure F2. Most concerning emission/exposure scenarios

Explanation: Synthetic microplastic fibers are the most abundant form of microplastics found int the environment [8]. The most concerning emission scenario according to literature is the domestic laundering of synthetic textiles, with a typical 5 kg wash load of polyester textiles emitting more than 6,000,000 microfibers [1], [8], [10]. Synthetic fibers (microplastics) are released directly into the sewage during washing, due to their size, microplastics pass through filters in washing machines and waste water treatment plants, which cause them to be released into fresh water and marine ecosystems [1], [4], [8], [9], [10]. Washing activities during industrial processes could also generate microplastic releases into the sewage [8]. 73% of the global textile material flows is landfilled or incinerated in EoL [11], with two thirds of the textiles put on the market in the EU ending up as residual waste [12]. The landfilling of textiles as an EoL route could attribute to the accumulation and further generation of microplastics, into ground water or into the soil when the residual sludge is used as fertilizer [13], [14]. Step 2b will not be performed in a quantitative manner due to the lack of data and time restrictions for this evaluation.

c) **Detail emission/exposure scenarios in connection to the product.** Figure F3 shows a detail description of the priority emission/exposure scenarios for this case. The substance presence, the mechanisms of release, and the exposure channels identified for this case are the following:

1. **Describe the presence of the substance in the product. Tick the boxes.**

Examples of substance presence in the product (several may apply):

■ Part of the composition of a material
■ Single material (in some cases)
■ Composite material (in some cases)
☐ Separable component (non-destructive disassembly is possible)
☐ Non separable component (destructive disassembly is necessary)
☐ Contained/encapsulated
☐ Coated

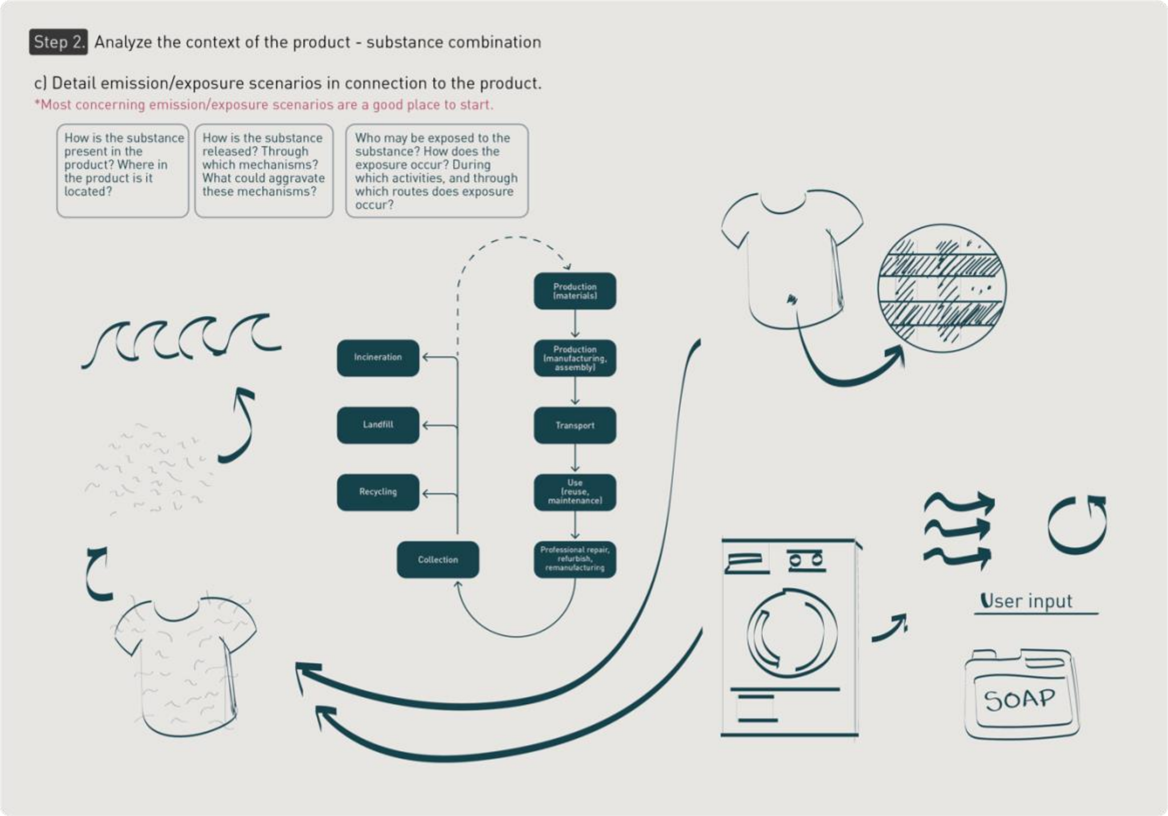
2. **Identify the release mechanisms of the substance and the input that causes and/or aggravates the mechanism. Tick the boxes.**

Examples of mechanisms of release:	Examples of inputs that may cause or aggravate mechanisms of release
☐ Volatilization ☐ Migration ☐ Leaching ☐ Leakage ■ Mechanical degradation ☐ UV degradation	■ High water temperatures ■ Mechanical input (E.g., type of machine, rotations per minute, amount of water) ■ User care (E.g., cycle selection and use of cleaning products) ■ Chemical input (detergents and others)

3. **Identify exposure channels. Tick the boxes.**

Exposure channels:

■ Ingestion
☐ Inhalation
☐ Skin contact



Step 2. Analyze the context of the product - substance combination

c) Detail emission/exposure scenarios in connection to the product.

*Most concerning emission/exposure scenarios are a good place to start.

How is the substance present in the product? Where in the product is it located?

How is the substance released? Through which mechanisms? What could aggravate these mechanisms?

Who may be exposed to the substance? How does the exposure occur? During which activities, and through which routes does exposure occur?

Figure F3. Detailed emission/exposure scenarios

Explanation: The release of synthetic fibers (microplastics) occurs mostly during the use phase through washing activities. The cleaning of textiles involves a combination of physical (mechanical input of the washing machine, water flow) and chemical inputs (detergents, bleach, etc.) to release dirt from the textile structure. These inputs progressively damage the textile and weaken the fibers, causing fiber release [4].

Different studies have identified a number of factors that influence the release of synthetic fibers:

- Fabric type, structure of the textile, type of yarn (staple fibers release more than filament yarns), density, thickness, finishings and treatments, and materials [4]. Woven polyester higher release than knitted polyester [10], [8].
- Aging, the older the garment is the more fibers it tends to release [8].
- Higher water temperature is also associated with an increase in fiber release because it progressively damages the structure of the textile [4], [10].
- Type of washing machine and cycle:
    - Axis position – top loader machines can release 430% more fibers than a front loader [4].
    - Central agitator could lead to more mechanical input, generating more friction and increasing the release of microplastics [4].
    - Rotations per minute, higher cycle duration and water consumption, can also generate more friction and microplastic release [4].
    - Type of filter (pore size) [4].

Inconclusive:

- Type of detergent, powder detergent increases microplastic release, while the use of softeners could decrease it. The quantity of these products used during laundry could also influence microplastic release [10], [4].
- High water hardness [10].

Step 3. Define strategies to avoid/control risks from the SoC. Due to time restrictions, this step will not be considered as a selection or development point for a SbD strategy. Instead, the identified existing, historical, and possible SbD strategies for the case are listed and classified (as previously proposed in Chapter 4.1).

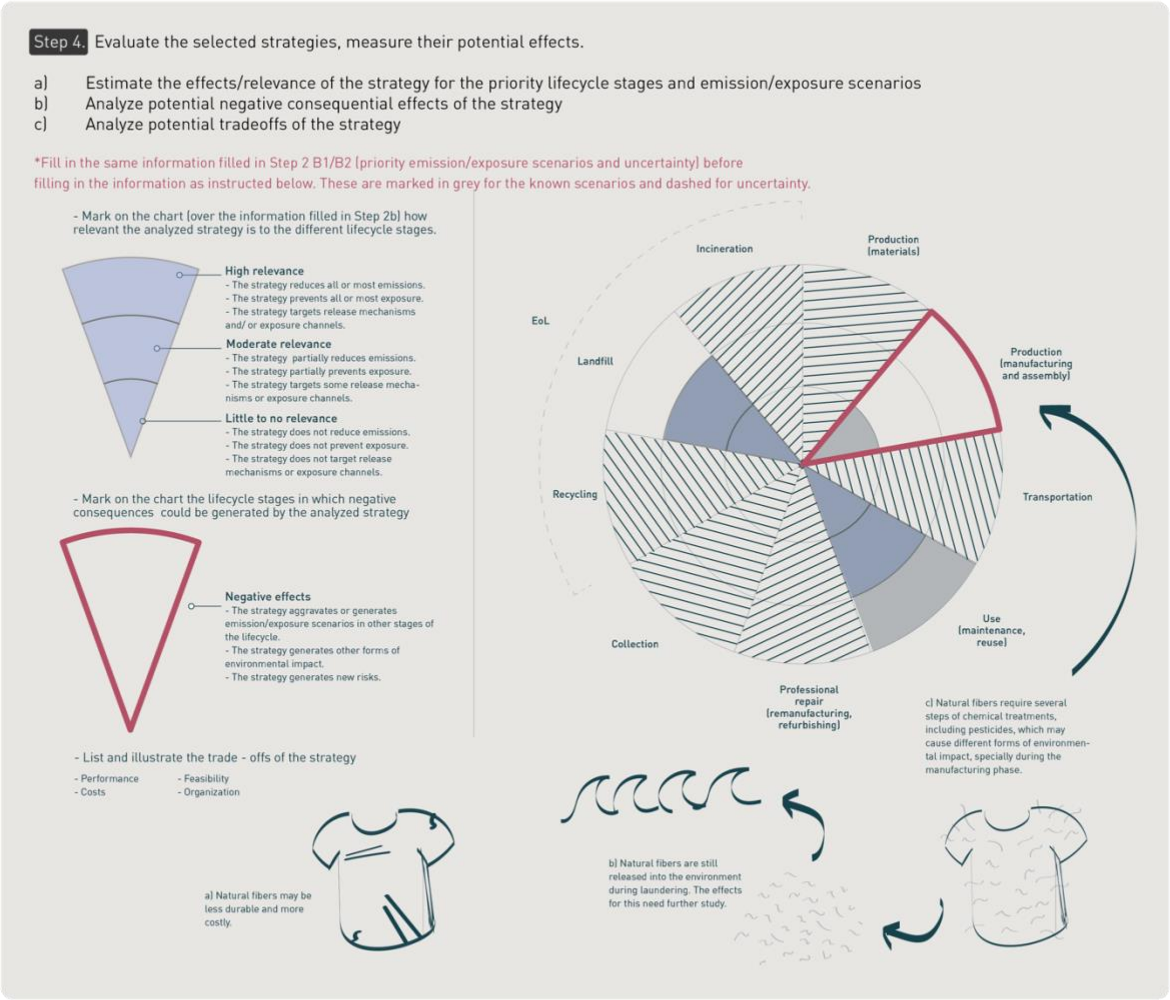
The case of microplastic release from synthetic textiles considers possible solutions at different levels and components. Including the design of the washing machine, the design of the textile or garment, user behavior, and possibly the design of cleaning products that support the reduction of friction and microplastic release as a consequence. Table F2 shows a summary of the found strategies.

Type of strategy	**Strategy**	**Description and possible benefits / drawbacks**
Eliminate	**Substitution with natural fibers (wool, cotton, etc.)** [8]**,** [15]**,** [16]**.**	Although natural fibers may be of less concern during the use and EoL phases, these usually have higher environmental impacts in comparison to synthetic textiles during the production phase. Most concerns from natural fibers are due to the presence of a variety of chemicals used for their treatment, including pesticides, moth proofing agents and anti-shrinking agents, all of which have toxicity concerns and can enter aquatic ecosystems throughout the life cycle. Further information about benefits and possible unintended consequences of substitution is necessary.
Reduce	**Designing textiles to reduce the shedding of fiber. E.g., types of knitting and weaving, material combinations - Blends of natural**	The type of fabric and its structure were found to influence the release of fibers. These could be further studied and specifically designed to reduce fiber shedding.

	and synthetic fibers (e.g., cotton – polyester blend) [1]**,** [9]**.**	Blends where found to shed less fibers in comparison to fully synthetic textiles when washes. However, this does not eliminate concerns completely.
	Washing less. Addition of treatments that inhibit the growth of bacteria (E.g., silver). [17]**,** [18]**.**	There is controversy over benefits and drawbacks. Existing concerns include toxicity and sewage treatment issues. Discussed benefits include, reduced environmental impact through reduced washing, reduced use of detergents, increased durability, and decreases in consumption, amongst others.
	Informing consumer behavior to reduce microplastic release – laundering guidance and washing machine purchase [4]**.**	A number of the influencing factors to microplastic release during laundering activities are directly dependent of user behavior. Further research is necessary to identify the best washing practices to avoid microplastic release from synthetic textiles. Additionally, consumers can be provided with more information about washing machine types (e.g., front loader vs top loader) and their influence in fiber release.
Control / Prevent	**Washing machine design – addition of filtering devices** [1]**.**	The addition of filtration devices to washing machines could prevent microplastics entering the water sewage. Further study is necessary.
	External filters [19]**,** [20]**.**	External filtration devices are currently available in the form of bags and plugs for washing machine outlet connections. These have a limited amount of loads and only retain a percentage of the released microplastics.

Table F2. Identified SbD strategies in the case

Step 4. Evaluate the selected strategies, determine/estimate their potential effects. Due to time restrictions, only one of the identified strategies in the case is selected for the evaluation. Figure F4 shows the results of the evaluation, depicting the relevance of the strategy, potential negative effects in other lifecycle stages, and a list of potential tradeoffs. The selected strategy to be assessed is the substitution of synthetic fibers for natural fibers such as wool or cotton.



Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.

High relevance
- The strategy reduces all or most emissions.
- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
- The strategy partially reduces emissions.
- The strategy partially prevents exposure.
- The strategy targets some release mechanisms or exposure channels.

Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy

Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy

- Performance
- Costs
- Feasibility
- Organization

a) Natural fibers may be less durable and more costly.

b) Natural fibers are still released into the environment during laundering. The effects for this need further study.

c) Natural fibers require several steps of chemical treatments, including pesticides, which may cause different forms of environmental impact, specially during the manufacturing phase.

Figure F4. Results of the strategy assessment

The substitution of synthetic textiles for natural fibers such as wool or cotton may be considered partially relevant for the concerns of the use phase. This is due to the fact that although these fibers are expected to degrade faster in natural environments, large amounts of them are released from domestic and industrial laundering [8], [15]. The effects of this requires further research to estimate possible hazards to health and the environment, since many of these fibers are treated with a variety of chemicals, some of which are considered toxic [15], [16]. The chemical treatment of natural fibers can include the use of pesticides, and other agents used to improve their performance, this is specially concerning during the production phase, indicated in red in Figure F4 [15].

F.2 PU foam in sleep and respiratory care devices

The case of PU foam in sleep and respiratory care devices is used to evaluate the SbD approach previously introduced (Chapter 4.1)

Step 1. Analyze the product - substance combination

a) Identify the SoC and its type (if not identified already).

Present in the product – intentionally added	**Generated by the product – byproducts generated throughout their Use/EoL**	**Used or added temporarily to the product for additional functions but not intended to be present in the end- product – Intermediates**
	The polyester based polyurethane foam used in the respiratory devices as a sound and vibration abatement component breaks down into small particles that can be inhaled or ingested by users [21], [22].	

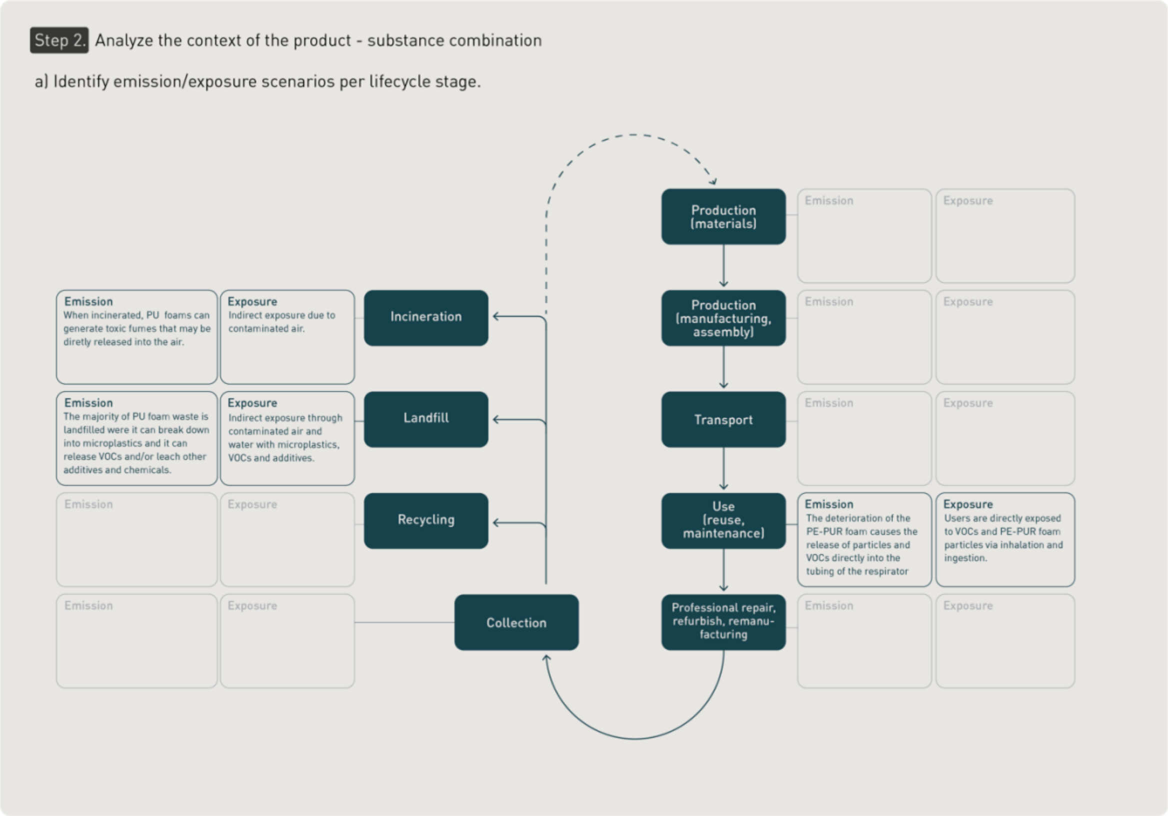
b) Describe the substance. Answers to the questions in Step 1b are shown in Table F3.

Question	
1. What is the SoC? Name(s), type of substance?	Polyurethane foam or PUR foam can be defined as a flexible polymer material with an open cellular or porous structure [23]. Polyester based polyurethane (PE-PUR) foam is a variant of PUR foam that is known to have higher durability, making it appropriate for technical applications [23]. During polymerization, foaming agents are added to generate the cellular structure [23]. When the PE-PUR foam degrades, it releases Volatile Organic Compounds (organic chemical compounds that evaporate under normal indoor atmospheric conditions due to their composition [24]), such as toluene diamine isomers and diethylene glycol, which may have toxic effects [23], [25].
2. What is the function of the substance in the product?	Respiratory care devices are prescribed to people with obstructive sleep apnea and are meant to pump air at constant or varying pressures to keep patients' airways open during sleep [21]. They come in different types and categories and may be used in domestic and professional settings [21]. The PE-PUR foam component is used to abate the vibration and sound caused by the turbine of the respiratory device [22].
3. What kind of hazards does it have on health and the environment?	When swallowed or inhaled, particles of PE-PUR foam can cause headaches, irritation (skin, eyes, airways), inflammation, respiratory issues (asthma), and possible toxic and carcinogenic effects (kidneys and liver) [21], [22]. Some of the identified health risks of exposure to the VOCs released from PE-PUR foam include headaches, irritation (skin, eyes, airways), hypersensitivity (allergic reactions), nausea/vomiting, and possible toxic and carcinogenic effects [21], [22].
4. How is the substance currently regulated/banned?	The study could not identify regulations specific to PE-PUR foam. Several regulations are present to limit the addition of certain chemicals to PUR foam including for example, phthalates and flame retardants [23]. Some existing certification programs define requirements for the emissions of VOCS from PUR foams [23] but these are not forcefully applied.
5. How much substance is in the product? (If possible and available)	N/A. The SoC is inherently bound to the composition of the material, as it is the foam itself that breaks down into smaller particles.

Table F3. Answers Step 1b

Step 2. Analyze the context of the product – substance combination

a) **Identify emission/exposure scenarios throughout the lifecycle.** Figure F5 includes the identified emission/exposure scenarios for the case.



Step 2. Analyze the context of the product - substance combination

a) Identify emission/exposure scenarios per lifecycle stage.

Emission
When incinerated, PU foams can generate toxic fumes that may be diretly released into the air.

Exposure
Indirect exposure due to contaminated air.

Emission
The majority of PU foam waste is landfilled were it can break down into microplastics and it can release VOCs and/or leach other additives and chemicals.

Exposure
Indirect exposure through contaminated air and water with microplastics, VOCs and additives.

Emission
The deterioration of the PE-PUR foam causes the release of particles and VOCs directly into the tubing of the respirator

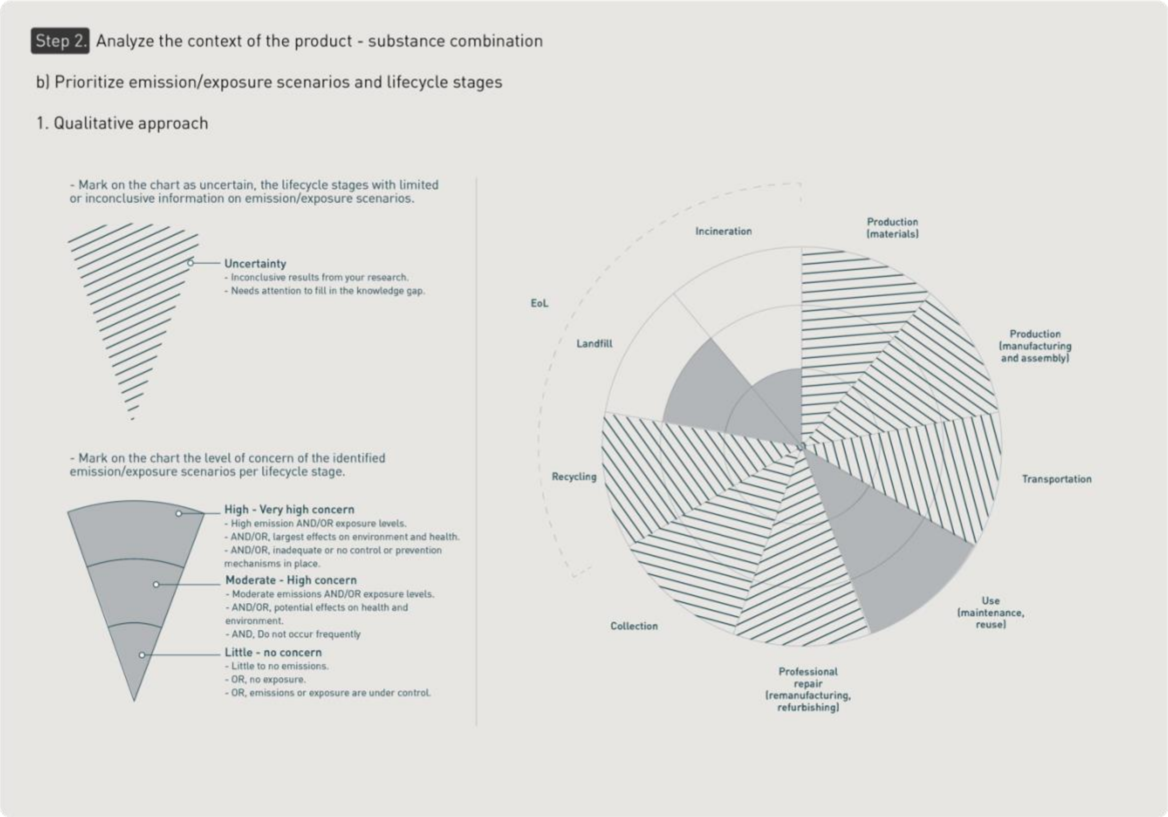
Exposure
Users are directly exposed to VOCs and PE-PUR foam particles via inhalation and ingestion.

Figure F5. Answers to Step 2a, Identification of emission/exposure scenarios

References for Step 2a: Information was found regarding emission/exposure scenarios of the use, landfill, and incineration stages, no further information specific to the PE-PUR foam component was identified, [21], [22], [26], [27].

b) Prioritize emission/exposure scenarios and lifecycle stages

1. **Qualitative approach.** Figure F6 shows the qualitative evaluation of the emission/exposure scenarios of the case.



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from your research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

Figure F6. Most concerning emission/exposure scenarios

Explanation: The most concerning emission and exposure scenario is the use phase, were PE-PUR foam particles and the VOCs resulting from its degradation are directly inserted in the device tubing were they are inhaled and/or ingested by users [21], [22], [25]. According to tests done on the devices, foam particles are most concerning, since VOCs emissions were measured within the allowable limits and are not expected to have effects on health [28]. The information over potential risks during the landfill and incineration phases correspond to general information and general concerns over all types of PU foams, not specific to the PE-PUR foam component of the respiratory device. These include the emission of toxic fumes during the incineration of PU foams and the deposition of microplastics, leaching of additives, and volatilization of VOCs during landfill [26], [27]. Step 2b will not be performed in a quantitative manner due to the lack of data and time restrictions for this evaluation.

c) **Detail emission/exposure scenarios in connection to the product.** Figure F7 shows a detail description of the priority emission/exposure scenarios for this case. The substance presence, the mechanisms of release, and the exposure channels identified for this case are the following:

1. **Describe the presence of the substance in the product. Tick the boxes.**

Examples of substance presence in the product (several may apply):	
■ Part of the composition of a material ■ Single material (in some cases) ☐ Composite material (in some cases) ☐ Separable component (non-destructive disassembly is possible)	■ Non separable component (destructive disassembly is necessary). According to observed disassembly videos the casing of the foam must be destroyed to extract the component, *Video visited on September 2022:* video . ☐ Contained/encapsulated ☐ Coated

2. **Identify the release mechanisms of the substance and the input that causes and/or aggravates the mechanism. Tick the boxes.**

Examples of mechanisms of release:	**Examples of inputs that may cause or aggravate mechanisms of release**
■ Volatilization. ☐ Migration ■ Leaching [26], [27]. ☐ Leakage ■ Chemical degradation.	■ High temperatures. ■ Humid environments. ■ User care (cleaning methods not recommended deteriorate the component) ■ Chemical input (ozone cleaners severely deteriorate the foam component)

3. **Identify exposure channels. Tick the boxes.**

Exposure channels:
■ Ingestion ■ Inhalation ☐ Skin contact

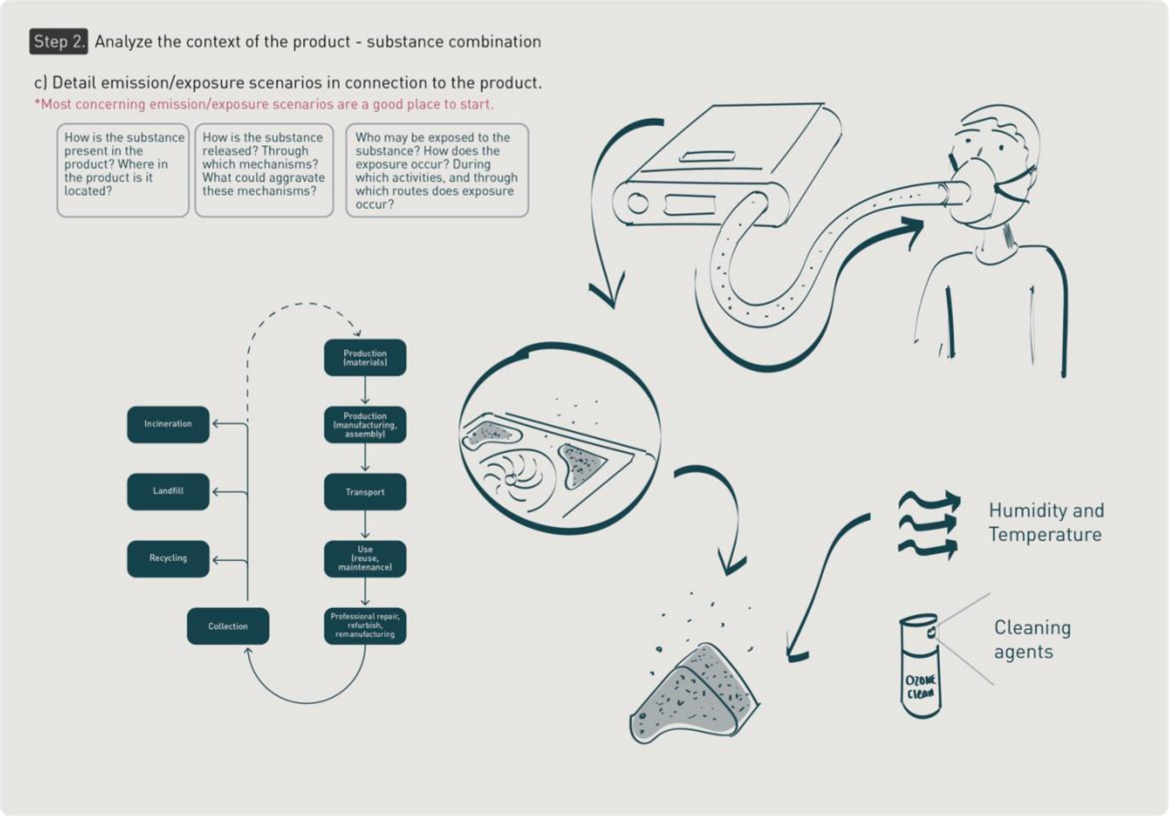


Figure F7. Detailed emission/exposure scenarios

Explanation: The foam component is located within a chamber together with the turbine, where it works as a damper for vibration and sound [21], [22]. The PE-PUR foam degrades throughout time causing the release of small particles of foam directly into the air ducts of the respiratory device , where they are inhaled and/or ingested by the user wearing the respirator mask [21], [22]. In addition to that, the degradation of the foam also generates VOCs, which volatilize to also inhaled by the consumer [21], [22]. The position of the foam component with respect to the turbine and air ducts may influence whether foam particles and VOCs enter the air stream. The degradation of the foam component is exacerbated by high temperatures and humidity [22], [23]. Most concerningly, the foam can rapidly degrade and break into particles when cleaning methods that are not approved by the manufacturer are used, specifically the use of ozone cleaners [28].

Step 3. Define strategies to avoid/control risks from the SoC. Due to time restrictions, this step will not be considered as a selection or development point for a SbD strategy. Instead, the identified existing, historical, and possible SbD strategies for the case are listed and classified (as previously proposed in Chapter 4.1) in Table F4.

Limited information over SbD strategies was found for this case during the evaluation, specifically those with some form of formal documentation. Informal strategies were found through desk research, including actions taken by consumers, such as the removal of the foam component, which is not recommended by the manufacturer and health agencies. The consequences over the removal of the foam component are unclear and need further study.

Type of strategy	**Strategy**	**Description and possible benefits / drawbacks**
Eliminate	**Substitution with silicon based foams**	The PE-PUR foam is being replaced by a silicon based foam. However, studies have found this type of foam also releases VOCs, which are still under study regarding emission requirements and possible health effects [22], [29].
Reduce	**Informing users about cleaning processes that do not severely deteriorate the foam component**	Manufacturers and health agencies have determined that the foam component is vulnerable to certain cleaning practices (Ozone cleaners) and recommends consumers to follow the maintenance and cleaning instructions provided in the user manual [21], [22]. However, this strategy does not consider the natural degradation of the foam.
Control / Prevent	**Relocation of the foam component inside the product to prevent particles entering the air ducts**	Not all respiratory care devices present issues with the presence of foam particles, this can be attributed to the positioning of the foam component with respect to the turbine and air ducts [22].

Table F4. Identified SbD strategies in the case

Step 4. Evaluate the selected strategies, determine/estimate their potential effects. Due to time restrictions, only one of the identified strategies in the case is selected for the evaluation. Figure F8 shows the results of the evaluation, depicting the relevance of the strategy, potential negative effects in other lifecycle stages, and a list of potential tradeoffs. The selected strategy to be assessed is the provision of information to users to avoid the deterioration of the foam component.

Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.

High relevance
- The strategy reduces all or most emissions.
- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
- The strategy partially reduces emissions.
- The strategy partially prevents exposure.
- The strategy targets some release mechanisms or exposure channels.

Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy

Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy
- Performance
- Costs
- Feasibility
- Organization

Figure F8. Results of the strategy assessment

The assessment of the strategy shows that providing information to users to prevent the use of cleaners that damage the foam component may alleviate some of the emissions of the use phase but not completely eliminate them. The foam deteriorates throughout time, regardless of the cleaning procedures due to aging, humidity, and high temperatures. The strategy also seems to fail at targeting concerning emissions in other phases.

F.3 PFAS in food packaging

The case of PFAS in disposable food packaging is used to evaluate the SbD approach previously introduced (Chapter 4.1). Most information found for this case is specific to the presence of PFAS in single use packaging, specifically those made of paper, carton, and molded pulp.

Step 1. Analyze the product - substance combination

a) Identify the SoC and its type (if not identified already).

Present in the product – intentionally added	**Generated by the product – byproducts generated throughout their Use/EoL**	**Used or added temporarily to the product for additional functions but not intended to be present in the end- product – Intermediates**
PFAS are added to disposable food packaging (especially in molded fiber and carton products) for water and grease repellency, where they can migrate into food [30].		

b) Describe the substance. Answers to the questions in Step 1b are shown in Table F5.

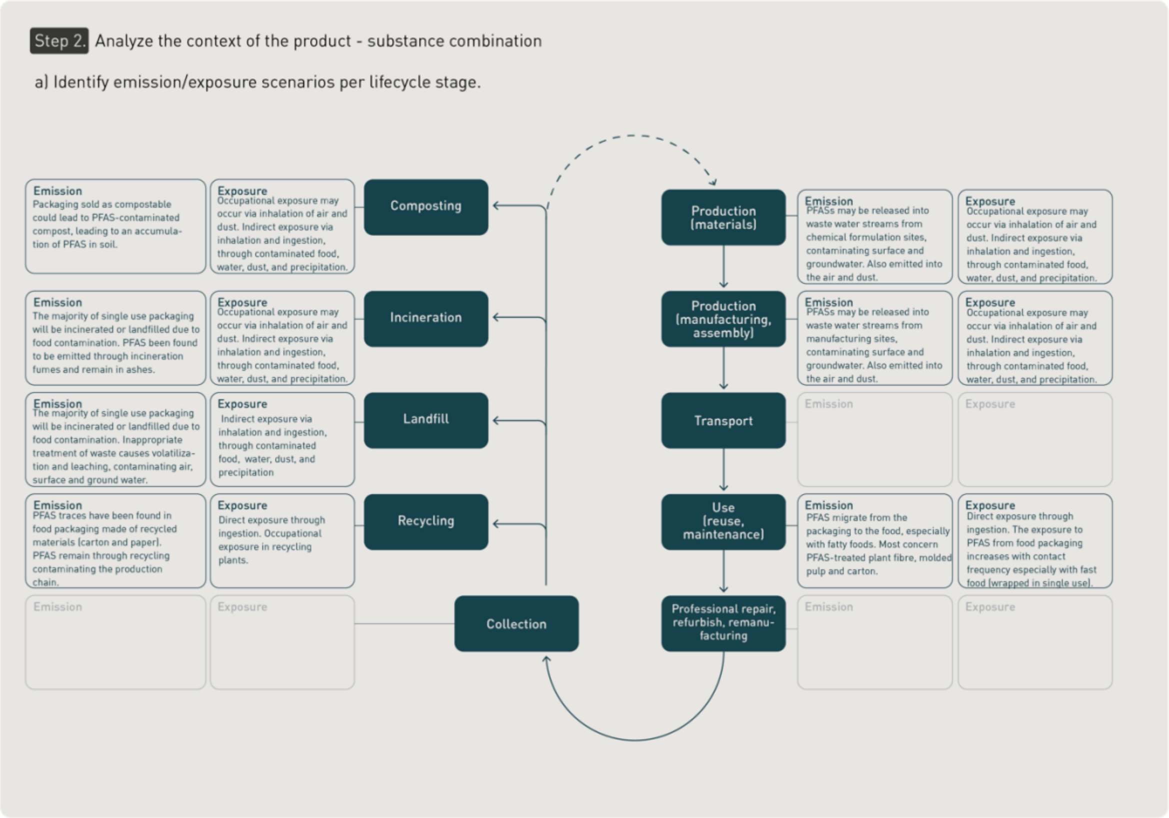
Question	
1. What is the SoC? Name(s), type of substance?	PFASs are a large group of chemicals, most commonly used for products where durable water and oil repellency is needed [31], [32]. PFASs consist of a fully (per) or partly (poly) fluorinated carbon chain connected to other different functional groups. Based on the length of this fluorinated carbon chain, PFASs can be classified into short and long chain PFASs. The length of the fluorinated carbon chain can result in different physicochemical properties that influence their repellency properties as well as their behavior in the environment, long carbon chains are typically of higher concern [31].
2. What is the function of the substance in the product?	PFAS are known to be widely used for food packaging. They are commonly used to produce disposable grease and water resistant food packaging and utensils. PFAS can be added to the paper pulp or applied as coatings on the surface of paper or cardboard [30].
3. What kind of hazards does it have on health and the environment?	PFAS are persistent and ubiquitous in the environment, which generates a variety of exposure paths, with exposure through contaminated drinking water and food being of most concern for humans [33]. Additionally, PFASs are bioaccumulative, which means concentrations in body tissues of humans and animals continues to increase, the effects of long term exposure are also unknown [31], [34], [35]. Observed effects in the environment include [34], [33]: - Contamination of plants and animals - Soil contamination, affecting soil quality - Reduction of different species of worm population - Biochemical effects on plants - Gut disruption and reproductive toxicity have been observed in different species of fish - Impacts on liver and kidneys of rats - Growth disruption and mortality of benthic organisms Observed health hazards (some with limited evidence) include [32], [36], [33]: - Thyroid disease and endocrine disruption. - Increased cholesterol. - Development effects on fetus.

	- Reproductive damage. - Carcinogenic (breast, kidney, testicular). - Inflammatory bowel disease - Liver damage - Neurological disorders - Overweight and obesity
4. How is the substance currently regulated/banned?	**EU Regulation 2019/1021 on Persistent Organic Pollutants** [37], [38]. The manufacturing and placing in the market of perfluorooctane sulfonic acid and its derivatives (PFOS), are prohibited. The regulation covers, perfluorooctanoic acid (PFOA), its salts, and PFOA-related compounds. **Stockholm Convention** [38], [39]**.** International agreement to regulate and eliminate perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexane sulfonic acid (PFHxS). **Madrid Statement** [40]**.** International agreement to regulate and limit the production and use of PFASs and promote the collaboration among stakeholders to research PFASs and develop a global inventory as well as safe nonfluorinated alternatives. **(EC) No 1907/2006, Registration, Evaluation, Authorization and Restriction of Chemicals REACH** [41]. The manufacture and use of some PFAS is restricted, additionally, a number of other PFAS are on the REACH Candidate List of substances of very high concern (SVHC) [38]. Two PFAS groups were identified as SVHCs: 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid, its salts, and its acyl halides (HFPO-DA), perfluorobutane sulfonic acid (PFBS) and its salts, which is a replacement for PFOS. Several additional PFAS are on the list for evaluation. **Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures** [42]. Focuses on identifying hazardous chemicals and informing about their hazards through standardized symbols. A few PFAS already have a harmonized classification and labelling under the CLP Regulation.
5. How much substance is in the product? (If possible and available)	This study could not identify specific concentrations of PFAS in food packaging. Information on concentrations and content of a specific PFAS type is very limited [30]

Table F5. Answers Step 1b

Step 2. Analyze the context of the product – substance combination

a) **Identify emission/exposure scenarios throughout the lifecycle.** Figure F9 includes the identified emission/exposure scenarios for the case.



Step 2. Analyze the context of the product - substance combination

a) Identify emission/exposure scenarios per lifecycle stage.

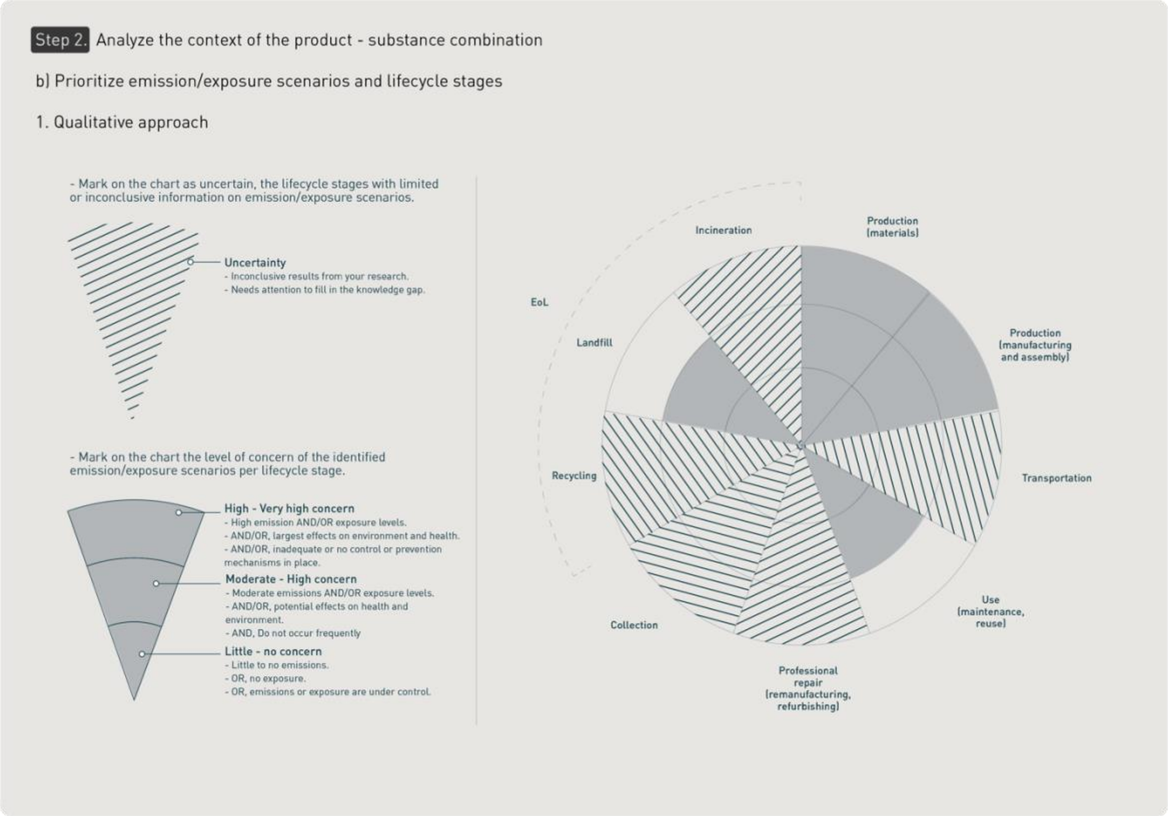
Lifecycle stage	Emission	Exposure
Production (materials)	PFASs may be released into waste water streams from chemical formulation sites, contaminating surface and groundwater. Also emitted into the air and dust.	Occupational exposure may occur via inhalation of air and dust. Indirect exposure via inhalation and ingestion, through contaminated food, water, dust, and precipitation.
Production (manufacturing, assembly)	PFASs may be released into waste water streams from manufacturing sites, contaminating surface and groundwater. Also emitted into the air and dust.	Occupational exposure may occur via inhalation of air and dust. Indirect exposure via inhalation and ingestion, through contaminated food, water, dust, and precipitation.
Transport		
Use (reuse, maintenance)	PFAS migrate from the packaging to the food, especially with fatty foods. Most concern PFAS-treated plant fibre, molded pulp and carton.	Direct exposure through ingestion. The exposure to PFAS from food packaging increases with contact frequency especially with fast food (wrapped in single use).
Professional repair, refurbish, remanufacturing		
Collection		
Composting	Packaging sold as compostable could lead to PFAS-contaminated compost, leading to an accumulation of PFAS in soil.	Occupational exposure may occur via inhalation of air and dust. Indirect exposure via inhalation and ingestion, through contaminated food, water, dust, and precipitation.
Incineration	The majority of single use packaging will be incinerated or landfilled due to food contamination. PFAS been found to be emitted through incineration fumes and remain in ashes.	Occupational exposure may occur via inhalation of air and dust. Indirect exposure via inhalation and ingestion, through contaminated food, water, dust, and precipitation.
Landfill	The majority of single use packaging will be incinerated or landfilled due to food contamination. Inappropriate treatment of waste causes volatilization and leaching, contaminating air, surface and ground water.	Indirect exposure via inhalation and ingestion, through contaminated food, water, dust, and precipitation
Recycling	PFAS traces have been found in food packaging made of recycled materials (carton and paper). PFAS remain through recycling contaminating the production chain.	Direct exposure through ingestion. Occupational exposure in recycling plants.

Figure F9. Answers to Step 2a, Identification of emission/exposure scenarios

References to step 2a: [30], [31]

b) Prioritize emission/exposure scenarios and lifecycle stages

2. **Qualitative approach.** Figure F10 shows the qualitative evaluation of the emission/exposure scenarios of the case.



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from your research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

Figure F10. Most concerning emission/exposure scenarios

Explanation: It is challenging to quantify emissions of single PFASs along the lifecycle, as well as the specific contribution of food packaging to global emissions and exposure, due to their presence in a variety of applications and forms, uncertainty over their origin, and their mobility characteristics; they can be transported into other ecosystems, by water and air currents as well as precipitation [31], [43]. However, three main scenarios can be highlighted in this case according to the information found through this short research, 1) the manufacturing phase, including both the formulation of the chemical and production of the food packaging [31], [43], 2) the landfill of food packaging waste [31], [43], and 3) the use phase, in which users and in direct contact with PFAS that migrated from the packaging into the food [30]. As for the use phase, concerns for exposure increase with the frequency in which users are exposed to single use packaging, which will depend on dieting habits [30]. Food is the largest identified human exposure pathway to PFAS [44].

c) **Detail emission/exposure scenarios in connection to the product.** Figure F11 shows a detail description of the priority emission/exposure scenarios for this case. The substance presence, the mechanisms of release, and the exposure channels identified for this case are the following:

1. **Describe the presence of the substance in the product. Tick the boxes.**

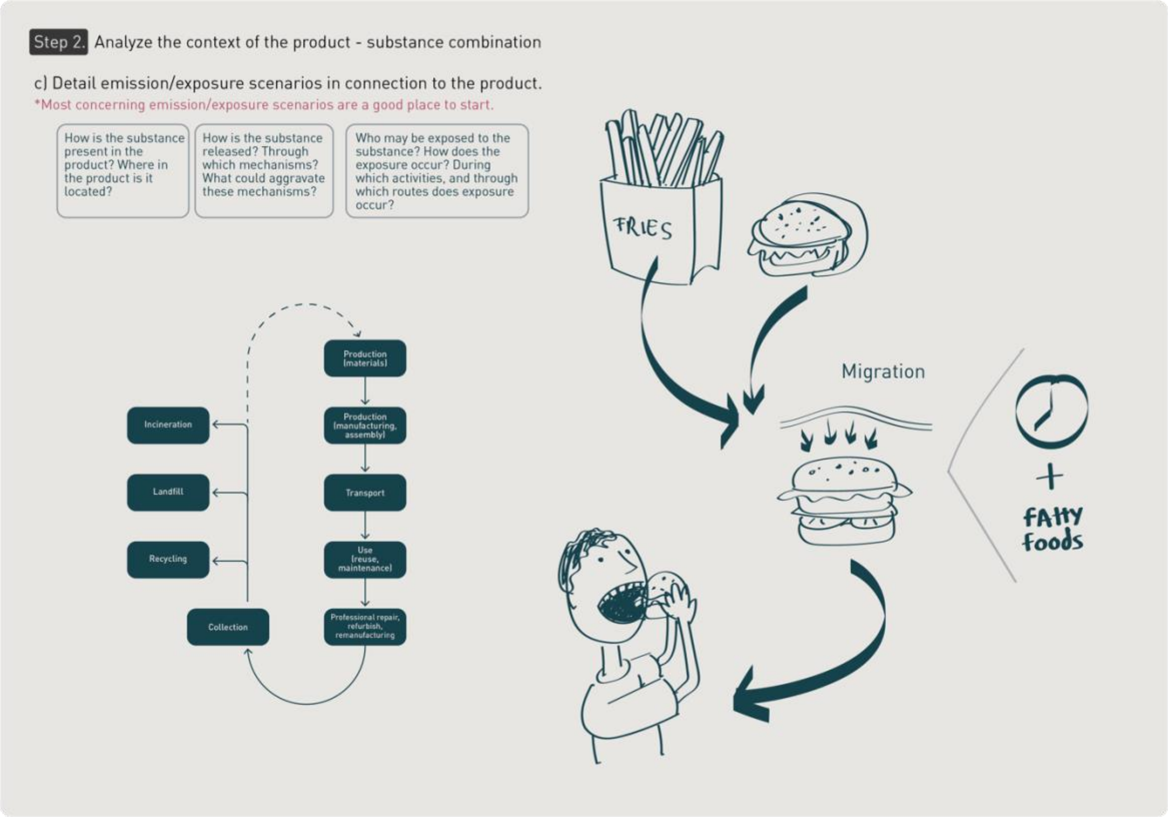
Examples of substance presence in the product (several may apply):
■ Part of the composition of a material ■ Single material (in some cases) ■ Composite material (in some cases) ☐ Separable component (non-destructive disassembly is possible) ■ Non separable component (destructive disassembly is necessary). ☐ Contained/encapsulated ☐ Coated

2. **Identify the release mechanisms of the substance and the input that causes and/or aggravates the mechanism. Tick the boxes.**

Examples of mechanisms of release:	**Examples of inputs that may cause or aggravate mechanisms of release**
■ Volatilization [30], [31] ■ Migration [44] ■ Leaching [30], [31] ☐ Leakage ■ Chemical degradation	■ High fat content [44] ■ Long periods of contact with food [44]

3. **Identify exposure channels. Tick the boxes.**

Exposure channels:
■ Ingestion [30], [31] ■ Inhalation [30], [31] ☐ Skin contact



Step 2. Analyze the context of the product - substance combination

c) Detail emission/exposure scenarios in connection to the product.

*Most concerning emission/exposure scenarios are a good place to start.

How is the substance present in the product? Where in the product is it located?

How is the substance released? Through which mechanisms? What could aggravate these mechanisms?

Who may be exposed to the substance? How does the exposure occur? During which activities, and through which routes does exposure occur?

Figure F11. Detailed emission/exposure scenarios

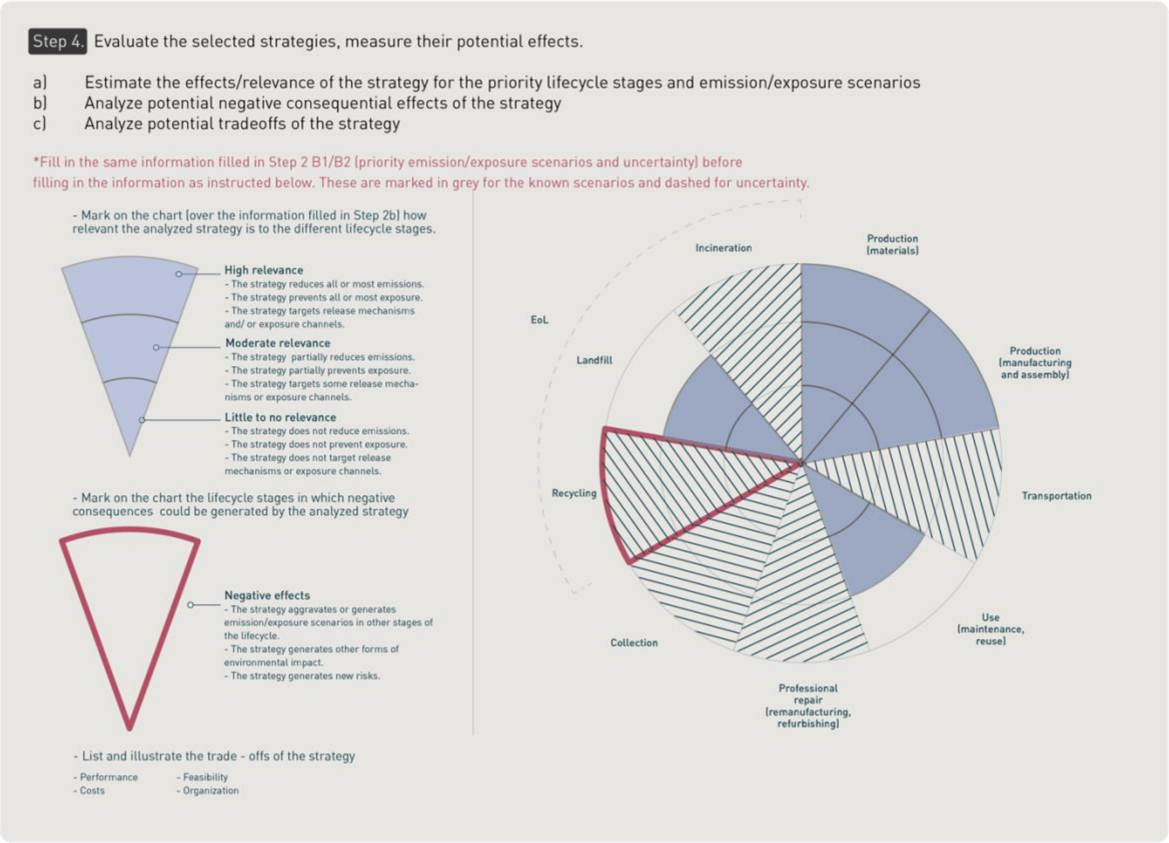
Explanation: Concerning emission/exposure scenarios include landfill, production, and the use phase. During the use phase there are several characteristics that can aggravate migration as a release mechanism, including fatty foods and time of contact with the food [44]. In addition to that frequency is another concerning factor, with people who continuously eat fast food being at most risk of exposure [30], [31].

Step 3. Define strategies to avoid/control risks from the SoC. Due to time restrictions, this step will not be considered as a selection or development point for a SbD strategy. Instead, the identified existing, historical, and possible SbD strategies for the case are listed and classified (as previously proposed in Chapter 4.1). Information about alternatives for the use of PFASs in food packaging was limited to substitution strategies. That being substitution of materials or substitution for coatings. Table F6 shows a summary of the found alternatives.

Type of strategy	**Strategy**	**Description and possible benefits / drawbacks**
Eliminate	**Substitution with a physical barrier. Laminated plastics and aluminum.**	Laminated materials require lamination equipment which is costly. Additionally, it results in a material that may not be easily recycled [45].
	Substitution with uncoated cellulose-based alternatives (compressed and dense network of refined cellulose fibers).	High water and fat resistance. Still under study and development [45].
	Substitution of the additive, synthetic biopolymers, or bio-waxes.	Recognized as safe by different health agencies. More costly than PFAS [45].
	Substitution with silicone coatings.	Under study as potential substances of very high concern [45].

Table F6. Identified SbD strategies in the case

Step 4. Evaluate the selected strategies, determine/estimate their potential effects. Due to time restrictions, only one of the identified strategies in the case is selected for the evaluation. Figure F12 shows the results of the evaluation, depicting the relevance of the strategy, potential negative effects in other lifecycle stages, and a list of potential tradeoffs. The selected strategy to be assessed is the substitution of PFAS with a physical barrier (plastic and or aluminum).



Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.

High relevance
- The strategy reduces all or most emissions.
- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
- The strategy partially reduces emissions.
- The strategy partially prevents exposure.
- The strategy targets some release mechanisms or exposure channels.

Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy

Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy

- Performance
- Costs
- Feasibility
- Organization

Figure F12. Results of the strategy assessment

The assessment of the strategy shows that the substitution of PFAS with alternative materials used as water and fat barriers may solve many of the emission and exposure concerns found in step 2b. However, concerns may rise towards the recyclability of this new composite materials.

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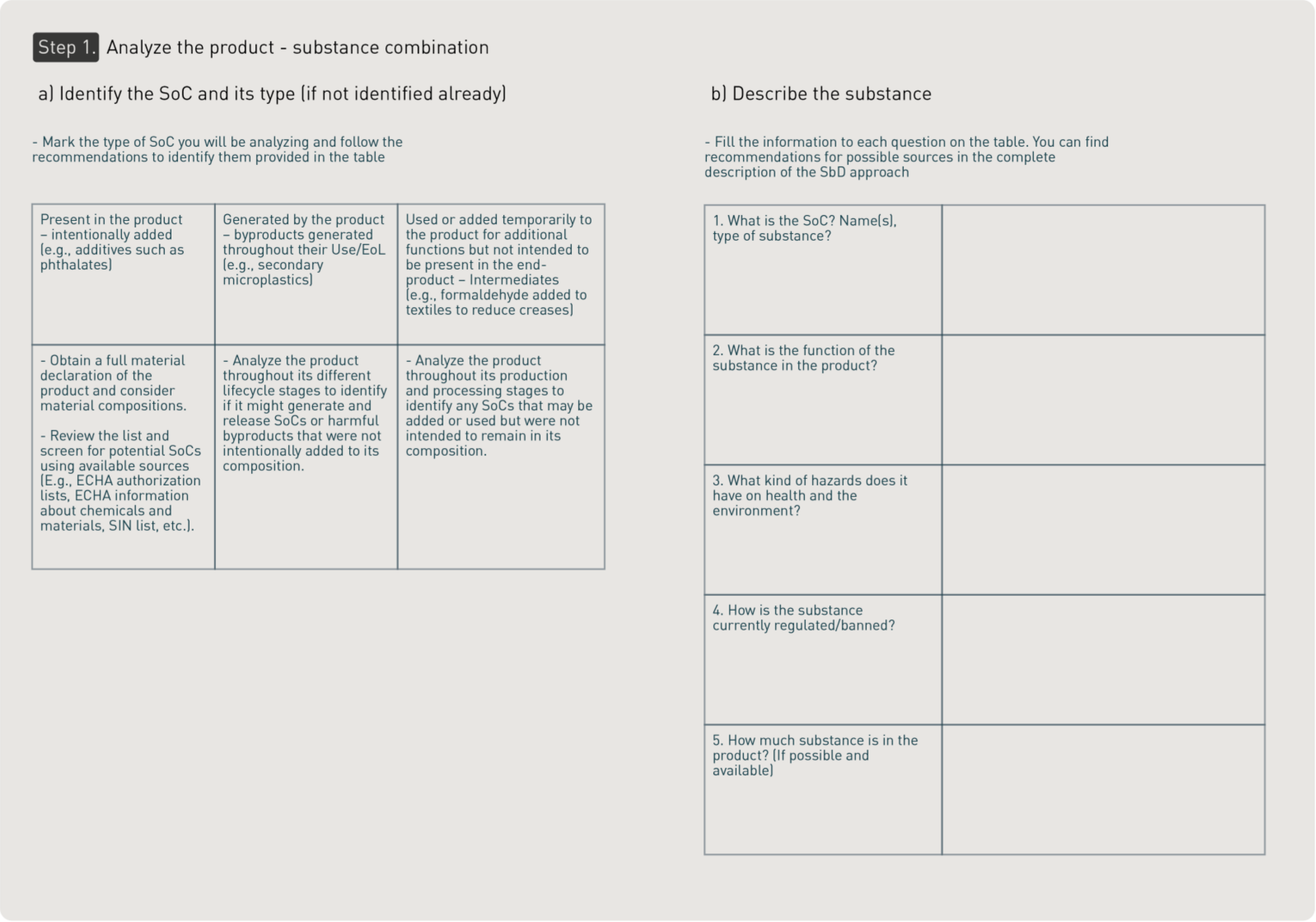
Appendix G – Safe by Design approach - Templates for the Safe by Design approach

This Appendix includes fillable templates to support designers following the Safe by Design approach. The templates can be printed for designers to fill out. Designers can refer to Section 4.1 for further information on the approach.

G.1 Template 1



Step 1. Analyze the product - substance combination

a) Identify the SoC and its type (if not identified already)

- Mark the type of SoC you will be analyzing and follow the recommendations to identify them provided in the table

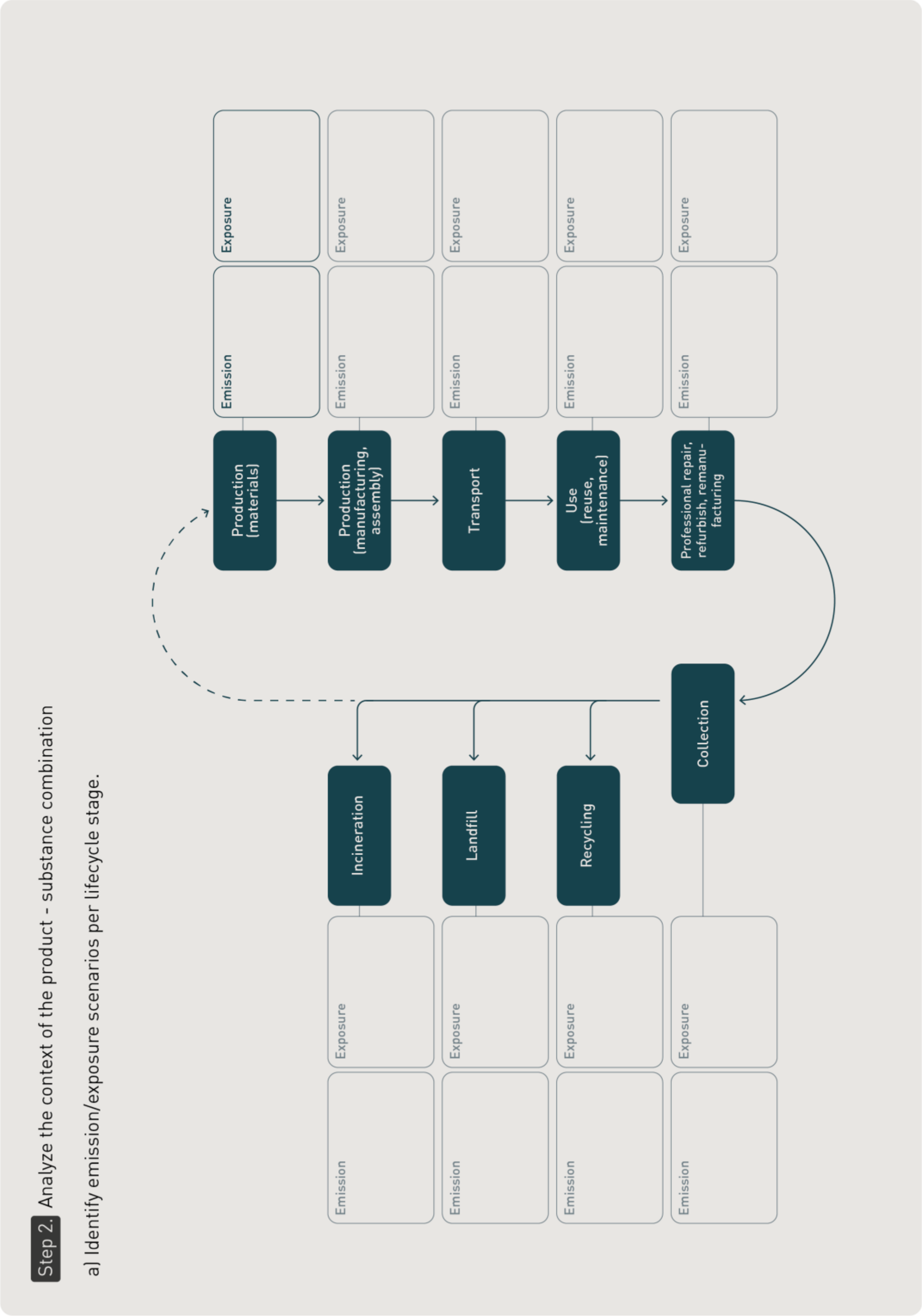
Present in the product – intentionally added (e.g., additives such as phthalates)	Generated by the product – byproducts generated throughout their Use/EoL (e.g., secondary microplastics)	Used or added temporarily to the product for additional functions but not intended to be present in the end-product – Intermediates (e.g., formaldehyde added to textiles to reduce creases)
- Obtain a full material declaration of the product and consider material compositions. - Review the list and screen for potential SoCs using available sources (E.g., ECHA authorization lists, ECHA information about chemicals and materials, SIN list, etc.).	- Analyze the product throughout its different lifecycle stages to identify if it might generate and release SoCs or harmful byproducts that were not intentionally added to its composition.	- Analyze the product throughout its production and processing stages to identify any SoCs that may be added or used but were not intended to remain in its composition.

b) Describe the substance

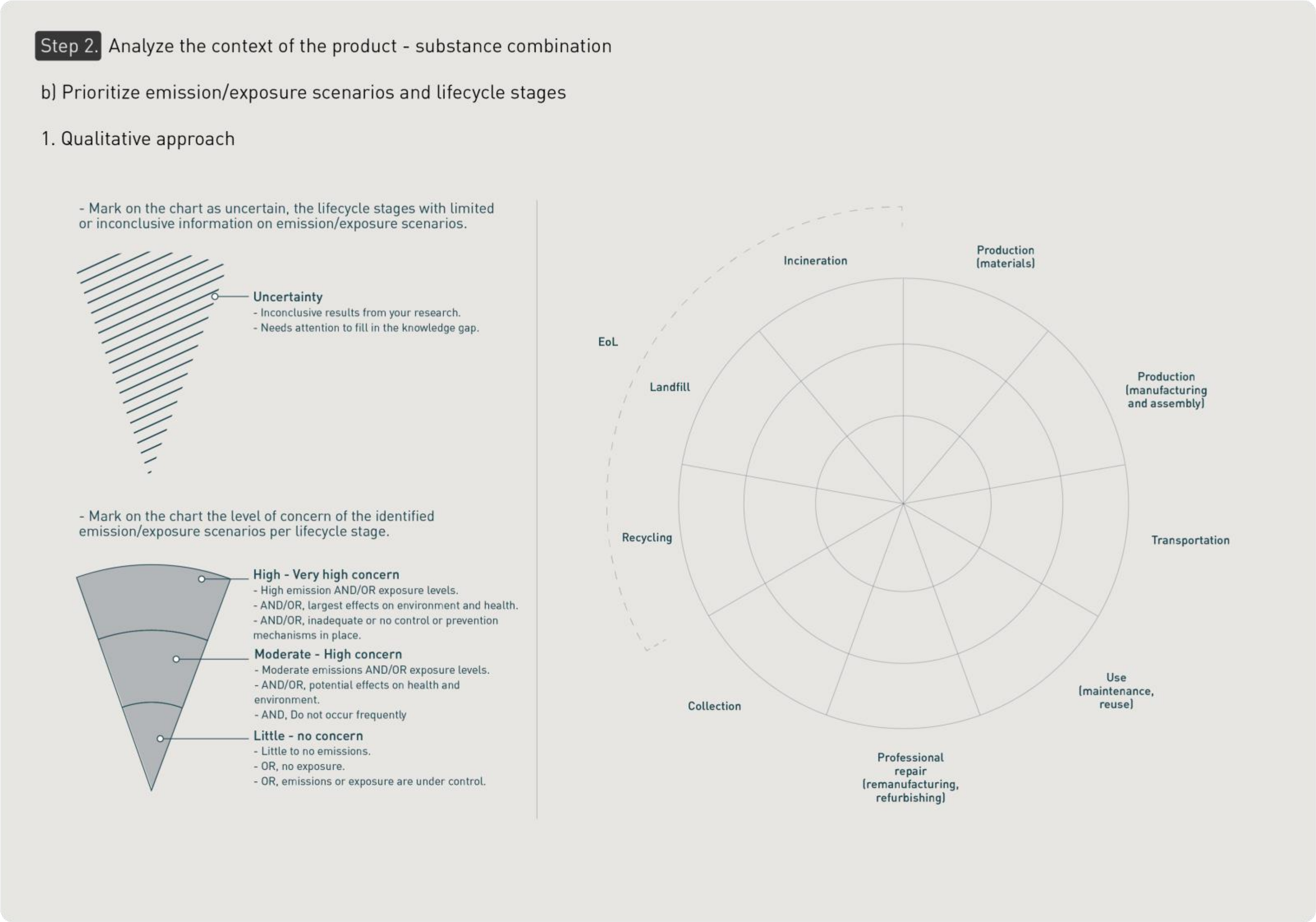
- Fill the information to each question on the table. You can find recommendations for possible sources in the complete description of the SbD approach

1. What is the SoC? Name(s), type of substance?	
2. What is the function of the substance in the product?	
3. What kind of hazards does it have on health and the environment?	
4. How is the substance currently regulated/banned?	
5. How much substance is in the product? (If possible and available)	

G.2 Template 2



G.3 Template 3



Step 2. Analyze the context of the product - substance combination

b) Prioritize emission/exposure scenarios and lifecycle stages

1. Qualitative approach

- Mark on the chart as uncertain, the lifecycle stages with limited or inconclusive information on emission/exposure scenarios.

Uncertainty
- Inconclusive results from your research.
- Needs attention to fill in the knowledge gap.

- Mark on the chart the level of concern of the identified emission/exposure scenarios per lifecycle stage.

High - Very high concern
- High emission AND/OR exposure levels.
- AND/OR, largest effects on environment and health.
- AND/OR, inadequate or no control or prevention mechanisms in place.

Moderate - High concern
- Moderate emissions AND/OR exposure levels.
- AND/OR, potential effects on health and environment.
- AND, Do not occur frequently

Little - no concern
- Little to no emissions.
- OR, no exposure.
- OR, emissions or exposure are under control.

G.4 Template 4

Step 2. Analyze the context of the product - substance combination

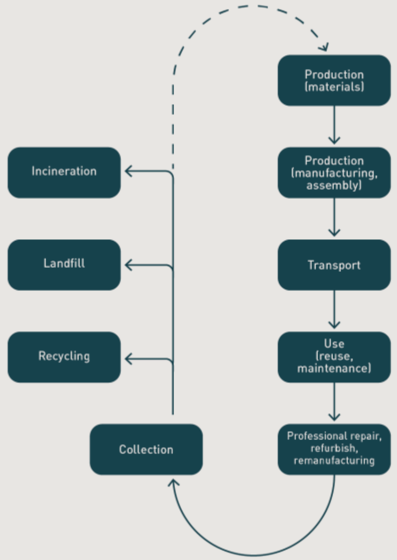
c) Detail emission/exposure scenarios in connection to the product.

*Most concerning emission/exposure scenarios are a good place to start.

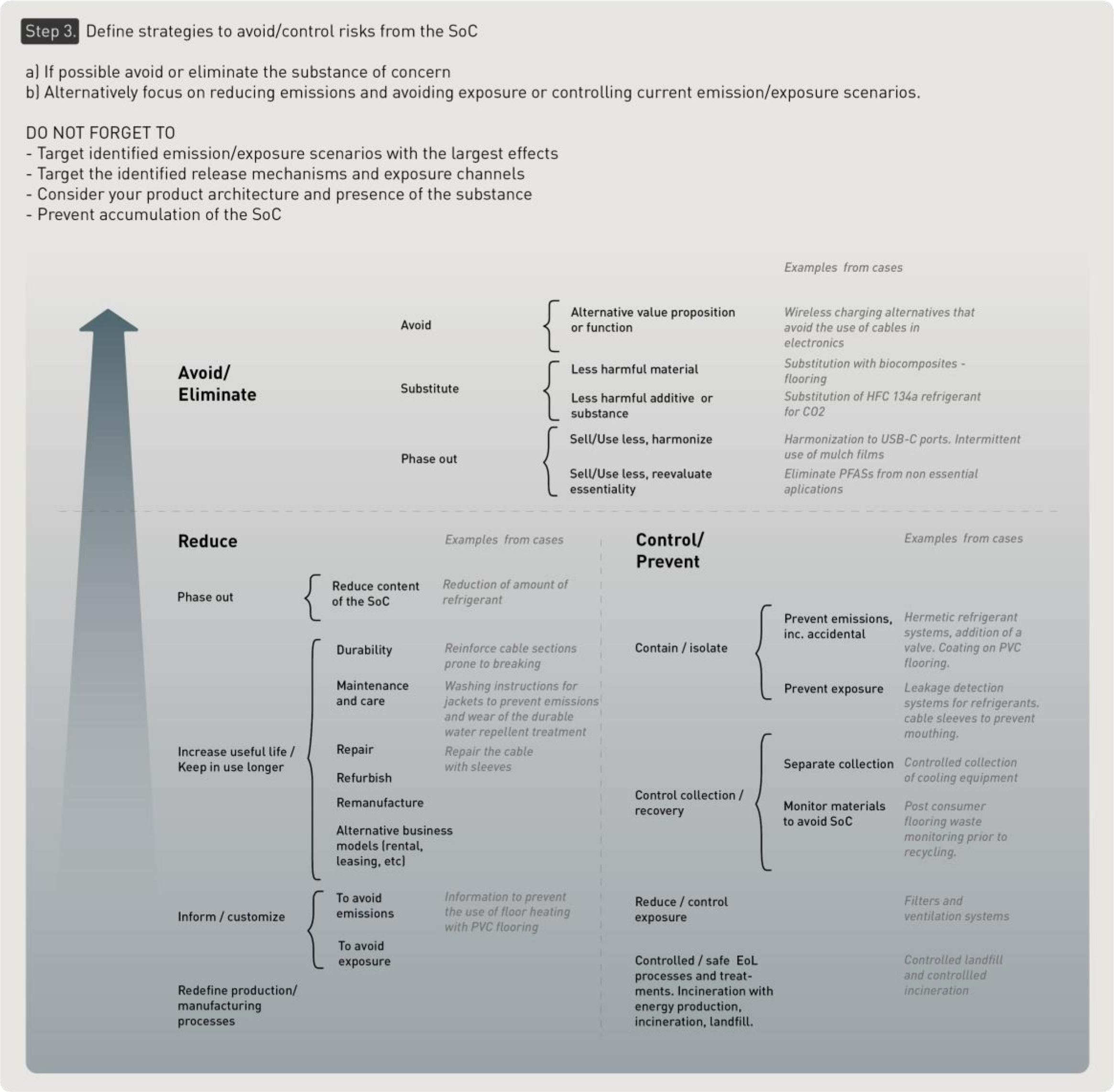
How is the substance present in the product? Where in the product is it located?

How is the substance released? Through which mechanisms? What could aggravate these mechanisms?

Who may be exposed to the substance? How does the exposure occur? During which activities, and through which routes does exposure occur?



G.5 Template 5



Step 3. Define strategies to avoid/control risks from the SoC

a) If possible avoid or eliminate the substance of concern
b) Alternatively focus on reducing emissions and avoiding exposure or controlling current emission/exposure scenarios.

DO NOT FORGET TO
- Target identified emission/exposure scenarios with the largest effects
- Target the identified release mechanisms and exposure channels
- Consider your product architecture and presence of the substance
- Prevent accumulation of the SoC

Avoid/ Eliminate

		Examples from cases
Avoid	Alternative value proposition or function	*Wireless charging alternatives that avoid the use of cables in electronics*
Substitute	Less harmful material	*Substitution with biocomposites - flooring*
	Less harmful additive or substance	*Substitution of HFC 134a refrigerant for CO2*
Phase out	Sell/Use less, harmonize	*Harmonization to USB-C ports. Intermittent use of mulch films*
	Sell/Use less, reevaluate essentiality	*Eliminate PFASs from non essential aplications*

Reduce

		Examples from cases
Phase out	Reduce content of the SoC	*Reduction of amount of refrigerant*
Increase useful life / Keep in use longer	Durability	*Reinforce cable sections prone to breaking*
	Maintenance and care	*Washing instructions for jackets to prevent emissions and wear of the durable water repellent treatment*
	Repair	*Repair the cable with sleeves*
	Refurbish	
	Remanufacture	
	Alternative business models (rental, leasing, etc)	
Inform / customize	To avoid emissions	*Information to prevent the use of floor heating with PVC flooring*
	To avoid exposure	
Redefine production/ manufacturing processes		

Control/ Prevent

		Examples from cases
Contain / isolate	Prevent emissions, inc. accidental	*Hermetic refrigerant systems, addition of a valve. Coating on PVC flooring.*
	Prevent exposure	*Leakage detection systems for refrigerants. cable sleeves to prevent mouthing.*
Control collection / recovery	Separate collection	*Controlled collection of cooling equipment*
	Monitor materials to avoid SoC	*Post consumer flooring waste monitoring prior to recycling.*
Reduce / control exposure		*Filters and ventilation systems*
Controlled / safe EoL processes and treatments. Incineration with energy production, incineration, landfill.		*Controlled landfill and controllled incineration*

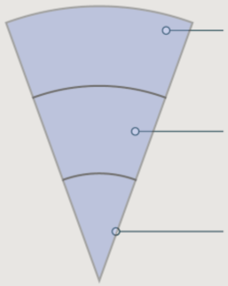
G.6 Template 6

Step 4. Evaluate the selected strategies, measure their potential effects.

a) Estimate the effects/relevance of the strategy for the priority lifecycle stages and emission/exposure scenarios
b) Analyze potential negative consequential effects of the strategy
c) Analyze potential tradeoffs of the strategy

*Fill in the same information filled in Step 2 B1/B2 (priority emission/exposure scenarios and uncertainty) before filling in the information as instructed below. These are marked in grey for the known scenarios and dashed for uncertainty.

- Mark on the chart (over the information filled in Step 2b) how relevant the analyzed strategy is to the different lifecycle stages.



High relevance
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- The strategy prevents all or most exposure.
- The strategy targets release mechanisms and/ or exposure channels.

Moderate relevance
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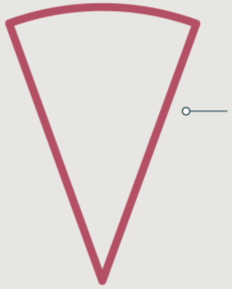
Little to no relevance
- The strategy does not reduce emissions.
- The strategy does not prevent exposure.
- The strategy does not target release mechanisms or exposure channels.

- Mark on the chart the lifecycle stages in which negative consequences could be generated by the analyzed strategy



Negative effects
- The strategy aggravates or generates emission/exposure scenarios in other stages of the lifecycle.
- The strategy generates other forms of environmental impact.
- The strategy generates new risks.

- List and illustrate the trade - offs of the strategy

- Performance
- Costs
- Feasibility
- Organization