TU Delft

Delft University of Technology

Document Version
Final published version

Citation (APA)
Bolanos Arriola, J. (2026). *Safe Circular Design: Design approaches for safe cycling of resources in a Circular Economy*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:b89bf4fa-9ae7-4e20-8b44-aab33bd91a27

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.



Safe Circular Design

Julieta Bolaños Arriola

Delft University of Technology

Safe Circular Design

Design approaches for safe cycling of resources in a Circular Economy

Julieta BOLAÑOS ARRIOLA

Safe Circular Design

Design approaches for safe cycling of resources in a Circular Economy

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus,
Prof.dr.ir. H. Bijl,
chair of the Board for Doctorates
to be defended publicly on
Monday, 20 April 2026, at 15:00

By

Julieta BOLAÑOS ARRIOLA

This dissertation has been approved by the promotors.
Composition of the doctoral committee:

Rector Magnificus	chairperson
Prof.dr. A.R. Balkenende	Delft University of Technology, promotor
Prof.dr.ir. C.A. Bakker	Delft University of Technology, promotor
Independent members:	
Prof.dr.ir. I.R. van de Poel	Delft University of Technology
Prof.dr. A. Rashid	KTH Royal Institute of Technology, Sweden
Prof.dr.ir. J.B. Guinee	Leiden University, the Netherlands
Prof.dr. J.C. Slootweg	University of Amsterdam, the Netherlands
Dr.ir. S.F.J. Flipsen	Delft University of Technology
Prof.dr.ir. K.M.B. Jansen	Delft University of Technology, *reserve member*

TU Delft

Keywords: Circular economy, Safe and sustainable by design, Product design, Substances of Concern, Hazardous Substances, Design method, Design Strategies, Repair, Repair safety, Right to repair, Risk assessment

Cover by Julieta Bolaños Arriola and Ayşegül Özçelik
Cover and chapter photos by Martijn Roelofs and Julieta Bolaños Arriola
Printing: Ridderprint, ridderprint.nl
Layout and design: Richard Guenne, persoonlijkproefschrift.nl
Published by Delft University of Technology

Copyright © 2026 by Julieta Bolaños Arriola. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, without prior written permission of the author.

ISBN: 978-94-6518-277-3

An electronic version of this dissertation is available at http://repository.tudelft.nl

Table of Content

Glossary **8**

Summary **9**

Samenvatting **12**

1 Chapter 1: Introduction **17**

1.1. Safety in circular product design 20

1.2. Aim and scope 24

1.3. Outline 25

1.4. References 29

2. Chapter 2: Designing for safe repairs - Identifying and mitigating repair safety risks in washing machines **33**

Abstract **34**

2.1. Introduction 35

2.2. Method 37

2.3. Results 42

2.4. Discussion 60

2.5. Conclusion 63

2.6. Appendices 64

2.7. References 65

3. Chapter 3: Strategies for Dealing with Substances of Concern in Product Design – A review of five cases **69**

Abstract **70**

3.1. Introduction 71

3.2. Methodology 74

3.3. Results 77

3.4. Discussion 86

3.5. Conclusion 91

3.6. Appendices 92

3.7. References 93

4. Chapter 4: Safe and circular Design - A design method for dealing with substances of concern in products **101**

Abstract **102**

4.1. Introduction 103

4.2. Method 104

4.3. Results 105

4.4. Discussion and Conclusion 113

4.5. References 115

5. Chapter 5: Safe and sustainable by design - Co-creating a design method for dealing with harmful substances in product design **119**

Abstract **120**

5.1. Introduction 121

5.2. Background 122

5.3. Method 126

5.4. Results 133

5.5. Discussion 144

5.6. Conclusion 149

5.7. Appendices 150

5.8. References 151

6. Chapter 6: Mapping uncertain risks and impacts of substances of concern in product life cycles - an SSbD tool for product developers **155**

Abstract **156**

6.1. Introduction 157

6.2. Method – Tool development process 160

6.3. Results – the Mapping Assessment for Product Substance Safety and Sustainability Tool 165

6.4. Discussion 187

6.5. Conclusion 191

6.6. Appendices 192

6.7. References 193

7. Chapter 7: Discussion **199**

7.1. Design for safe repairs – discussion of main findings 203

7.2. Mitigating the risks of SoC in product lifecycles through design – discussion of main findings 204

7.3. Safety in circular product design – connections between the two approaches 208

7.4. Contributions to scientific knowledge 209

7.5. Societal relevance 210

7.6. Recommendations for future research 212

7.7. References 214

8. List of Publications **216**

9. Acknowledgements **218**

10. About the Author **221**

Glossary

Substances of Concern (SoC). Chemicals or materials that pose risks to human health and the environment. Often restricted by regulation due to their hazardous effects.

(Chemical) Risk Assessment (RA). Evaluation method of potential safety risks caused throughout the lifecycle of chemicals, materials, and/or products.

Life Cycle Assessment (LCA). Evaluation method of environmental impacts throughout all stages of a product's life cycle.

Hazard. Intrinsic properties of a chemical with the potential of harming health and/or the environment.

(Safety) Risk. The probability of harm occurring from exposure to a hazard. Throughout this dissertation we refer to risks as: substance risks, SoC risks, repair risks, risks during repair, and post repair risks.

Circular Economy (CE). An economic model that keeps products and materials in use, reducing waste.

Method Content Theory (MCT). Framework for evaluating the efficacy and effectiveness of design methods.

Summary

Today, products are purchased, used, and discarded when they become obsolete, damaged, or no longer desirable. This pattern continues to tie economic growth to environmental losses, leading to increased waste, resource scarcity, and other environmental and societal impacts. Transitioning to a circular economy could instead support the preservation of the value of resources and products, eliminating waste and pollution. Achieving this transition requires products to be intentionally designed to fulfill these requirements. For instance, by extending the useful life to maintain the value of products and materials, by making them suitable for reuse, repair, refurbishment, or recycling. While numerous ongoing efforts focus on achieving this, a significant challenge in circular product design has received limited attention: safety.

By overlooking safety in circular transitions, we risk encountering aggravated or unforeseen risks and limitations when implementing circular strategies. Safety should be explicitly addressed in circular product design throughout all stages of the product lifecycle, enabling materials, products, and their components to be safely cycled. However, awareness, information, and methods for designers to address safety in circular product design are currently limited and absent from the literature. This dissertation addresses this gap by developing methods to support designers in developing products that can safely cycle in a circular economy.

This work is a first exploration of safety aspects in the circular economy from a product design perspective. It examines two angles: first, how product design can influence risks associated with product lifetime extension; and second, how it can influence risks arising throughout the product's lifecycle from the materials it contains. We explored these angles through research on designing for safe non-professional repairs and on mitigating the risks posed by Substances of Concern (SoC) throughout product lifecycles. We studied non-professional repairs because safety is often cited as the reason for restricting this group from performing them, thereby limiting the potential of this circular strategy. We studied SoC risks across product lifecycles, as SoC can harm human health and the environment, prevent materials from cycling if contaminated, and, if recirculated, reintroduce contaminants, amplifying existing risks. Both topics take the product as the unit of analysis, but the SoC topic also applies a broader lifecycle perspective. Together, they provide complementary perspectives on safety in circular product design.

This dissertation presents five studies that 1) examine how design influences the safety of circular products and 2) present the development of methods to support designers in addressing safety in circular product design. Chapter 2 focuses on design for safe repairs, while Chapters 3 to 6 are dedicated to SoC risks. At the start

of this PhD research, the topic of SoC risks in products was largely unexplored. In contrast, safe repairs had been investigated in two previous projects within our research group, which provided a foundation for this work. For this reason, four chapters focus on SoC, and one addresses safe repair.

Chapter 2 is dedicated to designing for safe repairs. In this study, two washing machines were disassembled and analysed to identify potential safety risks associated with repair, yielding a compendium of risks and their relationships to product design and architecture. The study found that product design plays a critical role in reducing repair risks and making repairs accessible to non-professionals, and that relatively small design interventions can reduce risks that occur during and post repair. The chapter also presents a method for designers to identify and assess repair safety risks in product architecture, along with a set of preliminary design guidelines to address them.

Chapter 3 presents a first exploration of design approaches to mitigate SoC in products. Five cases of products containing SoC were investigated to identify strategies used to mitigate risks throughout their lifecycle and to examine their implications for design. The study shows that the risks posed by SoC in products may not be addressed solely at the chemical or material level, but also at the component, product, and system levels. The study also provides a classification of SoC that is suitable for product designers and expands on current ones that rely on hazard evidence. It also introduces three design strategies to mitigate SoC risks: Avoid, Control, and Reduce, and offers recommendations for developing future design methods and guidelines.

In Chapter 4, we present the first version of the Design for Substance Safety and Sustainability (DSSS) Method, developed based on the recommendations and results from Chapter 3 and the analysis of the five cases. This first version was further developed in Chapter 5, which presents the co-creation of a second version of the method in collaboration with design professionals. The resulting method is suitable for design practice. It supports designers in addressing SoC in products through a holistic approach that considers the entire product lifecycle and subsequent lifecycles, accounting for trade-offs and unintended consequences. In addition, Chapter 5 offers insights into the challenges designers face when addressing SoC and defines requirements and recommendations for further development of the DSSS Method and other design-specific resources to address SoC risks.

Building on the insights of Chapter 5, Chapter 6 addresses the challenge of assessing the impact and risks of SoC at the product level and presents the development of the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) Tool. The tool combines essential elements of chemical risk assessment

and life cycle assessment. It addresses the need for resource-efficient assessments of substance-related risks in the early stages of product development. MAPSSS is a semi-quantitative assessment and visualization tool that enables designers to identify and evaluate SoC risks while accounting for uncertainty.

This research introduces novel practical approaches that support designers in integrating safety into the development of circular products. It also provides further insights for continued exploration and development of approaches to safety in circular product design.

Samenvatting

Tegenwoordig worden producten gekocht, gebruikt en weggegooid wanneer ze verouderd, beschadigd of niet langer gewenst zijn. Dit patroon blijft economische groei koppelen aan milieuschade, wat leidt tot meer afval, schaarste aan grondstoffen en andere milieu- en maatschappelijke gevolgen. De transitie naar een circulaire economie kan daarentegen bijdragen aan het behoud van de waarde van grondstoffen en producten, en afval en vervuiling elimineren. Om deze transitie te realiseren moeten producten bewust worden ontworpen om aan deze eisen te voldoen. Door bijvoorbeeld het verlengen van de gebruiksduur om de waarde van producten en materialen te behouden, door ze geschikt te maken voor hergebruik, reparatie, refurbishment of recycling. Hoewel tal van lopende initiatieven zich hierop richten, heeft een belangrijke uitdaging in circulair productontwerp beperkte aandacht gekregen: veiligheid.

Door veiligheid over het hoofd te zien bij circulaire transities, lopen we het risico verergerde of onvoorziene risico's en beperkingen tegen te komen bij het implementeren van circulaire strategieën. Veiligheid moet expliciet worden meegenomen in circulair productontwerp gedurende alle fasen van de productlevenscyclus, zodat materialen, producten en hun componenten veilig kunnen circuleren. Het bewustzijn, de informatie en de methoden voor ontwerpers om veiligheid in circulair productontwerp aan te pakken zijn momenteel echter beperkt en afwezig in de literatuur. Dit proefschrift adresseert dit gebrek door methoden te ontwikkelen die ontwerpers ondersteunen bij het ontwikkelen van producten die veilig kunnen circuleren in een circulaire economie.

Dit werk is een eerste verkenning van veiligheidsaspecten in de circulaire economie vanuit een productontwerp-perspectief. Het onderzoekt twee invalshoeken: ten eerste hoe productontwerp risico's kan beïnvloeden die samenhangen met levensduur-verlenging van producten; en ten tweede hoe het risico's kan beïnvloeden die gedurende de levenscyclus van het product voortkomen uit de materialen die het bevat. We hebben deze invalshoeken verkend door middel van onderzoek naar het ontwerpen voor veilige niet-professionele reparaties en naar het beperken van de risico's van Zeer Zorgwekkende Stoffen (ZZS) gedurende productlevenscycli. We bestudeerden niet-professionele reparaties omdat veiligheid vaak wordt aangehaald als reden om deze groep te beperken in het uitvoeren ervan, waardoor het potentieel van deze circulaire strategie wordt beperkt. We bestudeerden ZZS-risico's over productlevenscycli, aangezien ZZS schadelijk kunnen zijn voor de menselijke gezondheid en het milieu, kunnen voorkomen dat materialen circuleren als ze verontreinigd zijn, en bij hercirculatie verontreinigingen opnieuw kunnen introduceren, waardoor bestaande risico's worden versterkt. Beide onderwerpen nemen het product als analyse-eenheid, maar het ZZS-onderwerp past ook een

breder levenscyclus-perspectief toe. Samen bieden ze complementaire perspectieven op veiligheid in circulair productontwerp.

Dit proefschrift presenteert vijf studies die 1) onderzoeken hoe ontwerp de veiligheid van circulaire producten beïnvloedt en 2) de ontwikkeling presenteren van methoden om ontwerpers te ondersteunen bij het aanpakken van veiligheid in circulair productontwerp. Hoofdstuk 2 richt zich op ontwerp voor veilige reparaties, terwijl de hoofdstukken 3 tot en met 6 gewijd zijn aan ZZS-risico's. Aan het begin van dit promotieonderzoek was het onderwerp van ZZS-risico's in producten grotendeels onontgonnen. Daarentegen was veilig repareren onderzocht in twee eerdere projecten binnen onze onderzoeksgroep, wat een basis vormde voor dit werk. Om deze reden richten vier hoofdstukken zich op ZZS en één op veilige reparatie.

Hoofdstuk 2 is gewijd aan het ontwerpen voor veilige reparaties. In deze studie werden twee wasmachines gedemonteerd en geanalyseerd om potentiële veiligheidsrisico's in verband met reparatie te identificeren, wat resulteerde in een compendium van risico's en hun relaties met productontwerp en -architectuur. De studie toonde aan dat productontwerp een cruciale rol speelt bij het verminderen van reparatierisico's en het toegankelijk maken van reparaties voor niet-professionals, en dat relatief kleine ontwerp-ingrepen risico's kunnen verminderen die optreden tijdens en na reparatie. Het hoofdstuk presenteert ook een methode voor ontwerpers om reparatie-veiligheidsrisico's in productarchitectuur te identificeren en te beoordelen, samen met een set voorlopige ontwerprichtlijnen om deze aan te pakken.

Hoofdstuk 3 presenteert een eerste verkenning van ontwerpbenaderingen om ZZS in producten te beperken. Vijf casussen van producten met ZZS werden onderzocht om strategieën te identificeren die worden gebruikt om risico's gedurende hun levenscyclus te beperken en om hun implicaties voor ontwerp te onderzoeken. De studie toont aan dat de risico's van ZZS in producten mogelijk niet alleen op chemisch of materiaalniveau kunnen worden aangepakt, maar ook op component-, product- en systeemniveau. De studie biedt ook een classificatie van ZZS die geschikt is voor productontwerpers en een uitbreiding vormt op huidige classificaties. Daarnaast introduceert het drie ontwerpstrategieën om ZZS-risico's te beperken: Vermijden, Beheersen en Verminderen, en biedt het aanbevelingen voor de ontwikkeling van toekomstige ontwerpmethoden en -richtlijnen.

In hoofdstuk 4 presenteren we de eerste versie van de Design for Substance Safety and Sustainability (DSSS) Method, ontwikkeld op basis van de aanbevelingen en resultaten uit hoofdstuk 3 en de analyse van de vijf casussen. Deze eerste versie werd verder ontwikkeld in hoofdstuk 5, dat de co-creatie presenteert van een tweede versie van de methode in samenwerking met ontwerpprofessionals. De resulter-

ende methode is geschikt voor de ontwerppraktijk. Het ondersteunt ontwerpers bij het aanpakken van ZZS in producten door middel van een holistische benadering die rekening houdt met de gehele productlevenscyclus en daaropvolgende levenscycli, waarbij afwegingen en onbedoelde gevolgen worden meegenomen. Daarnaast biedt hoofdstuk 5 inzichten in de uitdagingen waarmee ontwerpers worden geconfronteerd bij het aanpakken van ZZS en definieert het vereisten en aanbevelingen voor de verdere ontwikkeling van de DSSS-methode en andere ontwerpspecifieke hulpmiddelen om ZZS-risico's aan te pakken.

Voortbouwend op de inzichten uit hoofdstuk 5, adresseert hoofdstuk 6 de uitdaging van het beoordelen van de impact en risico's van ZZS op productniveau en presenteert het de ontwikkeling van de Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) Tool. De tool combineert essentiële elementen van chemische risicobeoordeling en levenscyclusanalyse. Het voorziet in de behoefte aan efficiënte beoordelingen van stofgerelateerde risico's in de vroege stadia van productontwikkeling. MAPSSS is een semi-kwantitatief beoordelings- en visualisatie-instrument dat ontwerpers in staat stelt ZZS-risico's te identificeren en te evalueren, rekening houdend met onzekerheid.

Dit onderzoek introduceert nieuwe praktische benaderingen die ontwerpers ondersteunen bij het integreren van veiligheid in de ontwikkeling van circulaire producten. Het biedt ook verdere inzichten voor de voortgezette verkenning en ontwikkeling van benaderingen van veiligheid in circulair productontwerp.



Chapter 1

Introduction

Our society has an ever-fluctuating approach towards safety. Our perception of danger is the product of a social construction and agreement. We are surrounded by ambiguous signs of danger in our environment, and danger is not always observable, leading to a mismatch between the objective danger (a real, external condition, independent of perception) and our perception of it (Simpson, 1996; Slovic, 1987). This means that, as a society, we inconsistently define what is considered dangerous, and our approach to safety does not always align with the objective danger we face. Psychology offers a far more extensive explanation of why this is the case, but to introduce this dissertation, we would like to highlight two things: sometimes things are dangerous but are not dealt with as such, and sometimes things are not necessarily dangerous but are perceived and treated as if they were.

There is no single definition of safety; it is an evolving term, with available definitions reflecting different perspectives and approaches across sectors (Raheemy et al., 2025). The scope of these definitions ranges from preventing injuries to avoiding damage or loss, covering people, goods, and other assets, and includes both proactive and more passive, descriptive interpretations. For this research, we define safety as "the ability for a system to perform its intended purpose, whilst preventing harm to people and the environment", adapted from Provan et al. (2020). This definition aligns with our focus on products in the circular economy, which serve a function and are part of a complex system that aims to retain their value.

In this dissertation, we address two topics related to safety in the circular economy, for which our societal approach is inconsistent with the objective danger: 1) the presence of hazardous chemicals in products and 2) safety risks resulting from non-professionals performing repairs. Both topics are relevant to sustainable development and to our transition from a linear to a circular economy, which we cover in depth later. We examine both from a product design perspective, with the first adopting a lifecycle perspective that examines the materials contained in the product, and the second focusing on product lifetime extension.

Throughout the dissertation, we focus on better understanding how the engineering and embodiment of the products that surround us influence the objective dangers they pose and shape our approaches to mitigating them. Consider, for instance, that a metal object weighing 1.5 tons moving at over 100 km/h is undeniably dangerous. Yet humans have spent over 100 years designing entire systems that make driving an accepted everyday activity. Although road safety remains an ongoing challenge (World Health Organization, 2023), advancements in vehicle design, among other interventions, have significantly contributed to saving lives (Farmer & Lund, 2006). This example illustrates how design influences the risks posed by inherently dangerous objects and our perception of danger.

The dangers of hazardous chemicals in everyday products are not directly observable, or their effects may only become apparent over time, but they are nonetheless present. There is a shocking amount of uncertainty on the potential effects of the majority of the chemicals we produce. When examining Figure 1.1, we observe that among the hundred thousand chemicals currently circulating in the EU market, some of which are subject to volume restrictions, only about five hundred have been thoroughly studied for safety (European Environment Agency, 2020). One would expect our society to adopt a preventive approach to this uncertainty, given the potentially devastating effects of these chemicals on human health and the environment, and their widespread presence in everyday products. However, we currently often rely on reactive measures, which address chemicals already proven to be hazardous, leaving unknown risks unaddressed, for instance, in regulation. As such, many hazardous substances continue to circulate for their functional and economic benefits. This is concerning, as we are currently unable to estimate whether their detrimental effects are reversible. This exemplifies a situation in which something dangerous is not treated as such, which highlights the need to shift to a preventive approach, even in the absence of immediate evidence and despite our false perception of safety.

The topic of safety in non-professional repairs, on the other hand, presents a different approach to danger. Today, the repair of consumer products is almost exclusively restricted to professional repairers. Although expanding the possibility of repairing products to non-professionals could have several circularity and sustainability-related benefits, manufacturers justify such restrictions by citing safety concerns, often without clear or available evidence of the risks involved. This exemplifies a situation in which something may not necessarily be dangerous but is treated as such. Given the considerable debate on the matter from groups advocating for the Right to Repair and the potential environmental and societal benefits of expanding repair practices, it may be necessary to assess the objective dangers associated with non-professional repairs and adjust our approach accordingly.

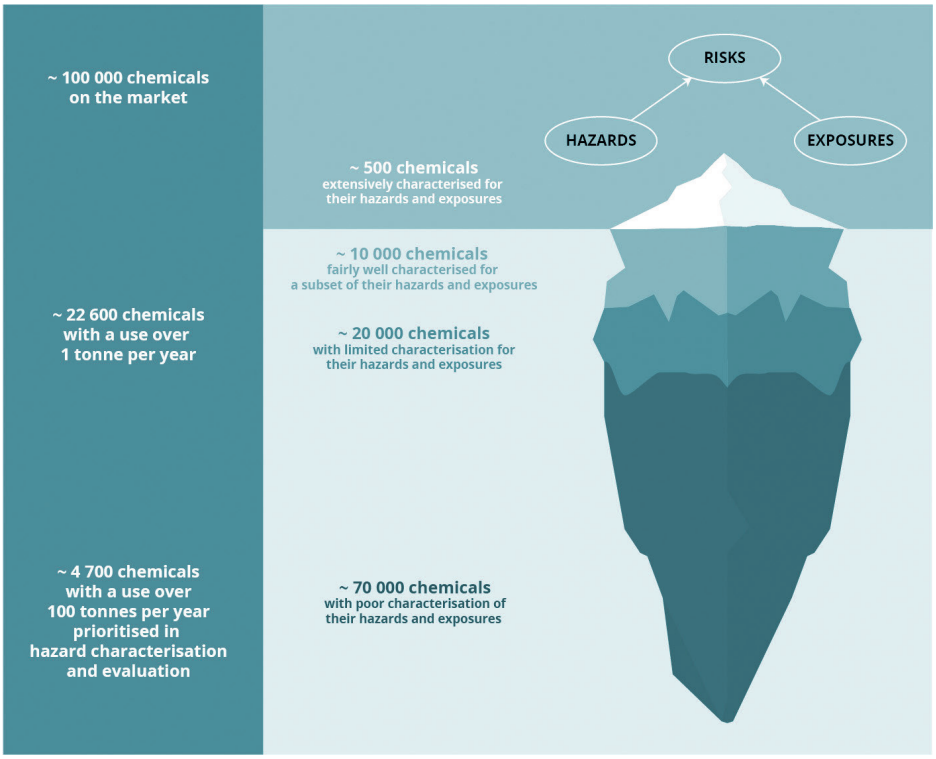


Figure 1.1. The unknown territory of chemical risks (European Environment Agency, 2020)

In both cases, it can be argued that additional factors may be influencing our perception and approach to danger, be it performance, costs, currently installed mechanisms and processes, or reluctance to change. Nevertheless, an inconsistent approach to danger can either put us at a larger risk or pose limitations to practices that may benefit us. Throughout this dissertation, we investigate and propose alternative approaches to address the safety risks associated with hazardous substances in products and with non-professional repairs, adopting a circular design perspective.

1.1. Safety in circular product design

In today's linear economy, products are purchased, used, and discarded once they become obsolete, damaged, or no longer desirable. This economic model directly links growth to environmental losses, leading to increased waste, resource scarcity, and other environmental and societal impacts. To address these challenges, governmental initiatives worldwide are increasingly inclined to transition into a circular economy (CE) (Elia et al., 2017; McDowall et al., 2017), a model that has also been

found relevant in contributing to the United Nations Sustainable Development Goals (Rodriguez-Anton et al., 2019; Schroeder et al., 2019).

The circular economy revolves around three principles: 1) Preserve and enhance natural capital, 2) Maintain the value of resources and products, and 3) Eliminate waste and pollution (Ellen MacArthur Foundation, 2015). The transition towards a circular economy requires products designed to meet these principles. This can be achieved by extending the useful life and maintaining the value of products and materials, for instance, by making them suitable for reuse, repair, refurbishment, or recycling. Strategies that preserve the value of products and materials without requiring extra energy or reprocessing (e.g., maintenance and repair) should be prioritized over those that result in a reduction in value or require reprocessing and additional resources (e.g., remanufacturing and recycling) (Achterberg et al., 2016; Bakker et al., 2019). The butterfly diagram (Figure 1.2) illustrates how renewable and non-renewable products, components, and materials are reintroduced into the economy through various strategies and processes (Ellen MacArthur Foundation, 2015). As the advantages of this transition become more evident, such as the environmental benefits of prolonging the lifespan of textiles (Gray et al., 2025) and prioritizing repair over the replacement of electric and electronic equipment (Bovea et al., 2020), it's essential to acknowledge a significant challenge that is often overlooked: safety.

Safety issues can arise in any of the processes portrayed in Figure 1.2. The circular nature of the system may aggravate them, or risks can limit the implementation of circular strategies. Below, we further illustrate this and the importance of addressing safety in a circular economy. Products that harm the environment or human health throughout their lifecycle do not align with the principles of the circular economy. Safety should then be explicitly addressed in circular product design, throughout all stages of the product lifecycle.

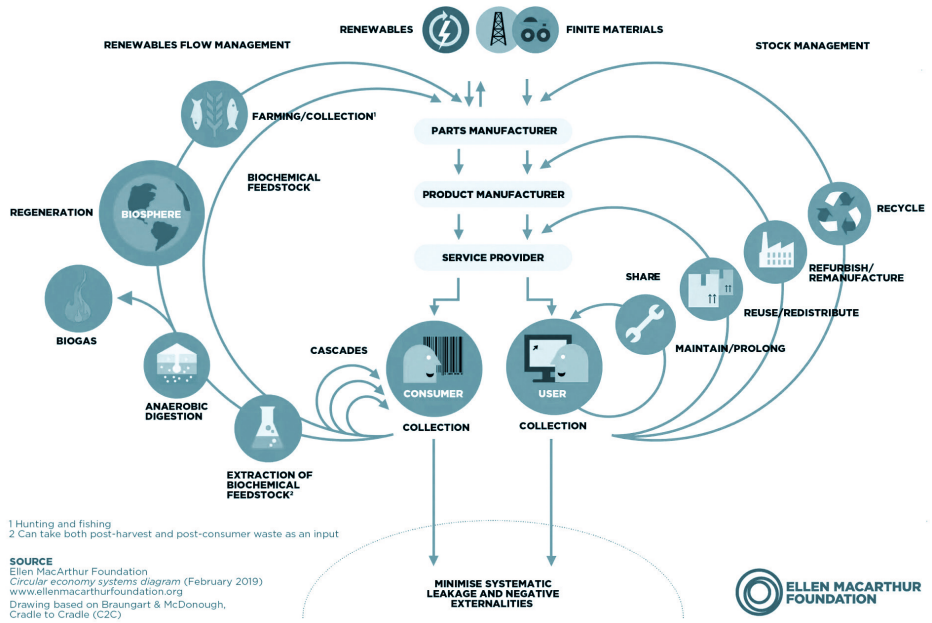


Figure 1.2. Circular economy butterfly diagram (Ellen MacArthur Foundation, 2015).

Substances of Concern in everyday products – Risks and current approaches

Hazardous substances, also known as Substances of Concern (SoC), are chemicals known to have harmful effects on human health, such as carcinogenicity, or are resistant to degradation and toxic to the environment (UNECE, 2023). Current classifications of substances as hazardous are based solely on evidence and exclude substances not yet identified as hazardous, as well as pollutants generated by products throughout their lifecycles. In this research, we take a broader perspective based on the planetary boundary for chemical pollution (novel entities) (Rockström et al., 2009; Steffen et al., 2015), and consider a larger array of compounds of human origin (e.g., plastics) that may be used or generated throughout the product lifecycle. SoC are present in a wide range of everyday products, often because they provide specific functional properties (Holmquist et al., 2016; Schaider et al., 2017). While some of these substances are currently regulated to reduce or eliminate their use, many others remain in use, especially when safer alternatives do not meet similar performance (Hill et al., 2017; Schellenberger et al., 2019). Nevertheless, regulatory efforts and public awareness on this issue continue to increase, as evident from, for example, the European Chemicals Strategy for Sustainability (European Commission, 2020) and the Ecodesign for Sustainable Products Regulation (European Commission, 2024), which establishes requirements in products to phase out substances that hinder circularity.

From a circularity perspective, SoC pose additional challenges: material recirculation can reintroduce contaminants or amplify existing risks (Beekman et al., 2020; Bodar et al., 2018; Wassenaar et al., 2017), and resources may not be recirculated because they are contaminated. For instance, PVC flooring products are often incinerated rather than recycled due to contamination (Miliute-Plepiene et al., 2021). Figure 1.3 shows a hypothetical example of the lifecycle of a PVC charging cable containing DEHP (Bis(2-ethylhexyl) phthalate), a plasticizer known to be carcinogenic and an endocrine disruptor (European Commission, 2008; Luís et al., 2021). The presence of DEHP in the cable creates various exposure scenarios throughout its lifecycle, generating risks for workers, vulnerable people, and the environment. At the end of its life, as with PVC flooring, the PVC in the cable may not be recycled due to safety concerns and is therefore incinerated or landfilled. However, if recycled, it could introduce new risks in subsequent lifecycles.

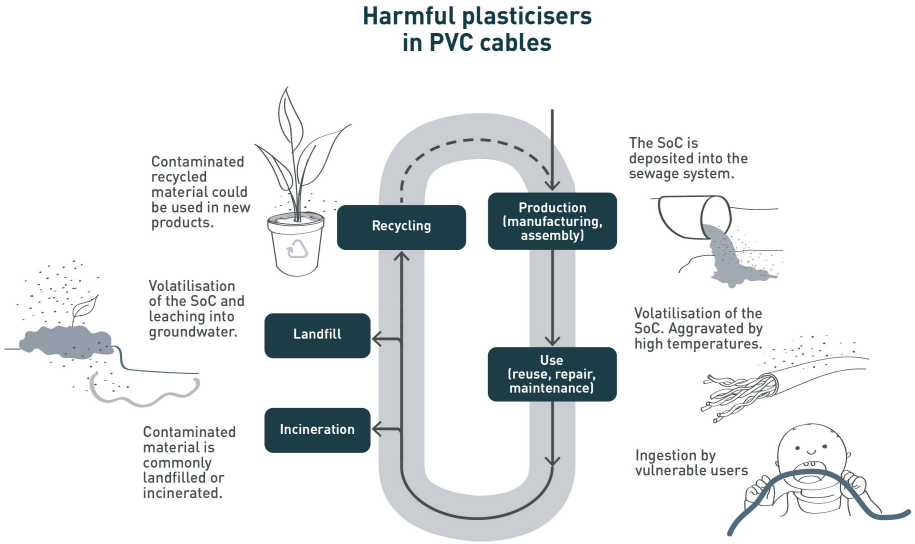


Figure 1.3. Risks of SoC throughout the lifecycle, and potential subsequent lifecycles (if recycled), of a PVC cable contaminated with harmful plasticizers (DEHP).

Informed and effective management of SoC in the early stages of product development can help mitigate these risks while maintaining the value of products and materials. Current research, however, predominantly focuses on the development of non-toxic chemicals and material alternatives (Bodar et al., 2018; Dumée, 2022; Keijer et al., 2019), with the example of the Safe and Sustainable by Design (SSbD) approach, which seeks to consider safety from early stages of the development process (Apel et al., 2024; Soeteman-Hernández et al., 2024). The guidance and resources available to identify, assess, and mitigate SoC risks remain strongly chemically focused, are not suited to product design practices, and often lack a broader

perspective on the product lifecycle and circularity, leaving a gap in achieving safe and circular products.

Safety risks in non-professional repairs – A limitation to enhancing circular practices

Design for repair is increasingly recognized as essential for extending product lifetimes and supporting a circular economy (Alfieri et al., 2019; Bakker et al., 2014; Bracquené et al., 2021). Policies are increasingly promoting the repairability of products, as seen, for example, in the Ecodesign for Sustainable Products Regulation (European Commission, 2024b) and the Directive on common rules promoting the repair of goods (European Commission, 2024a). However, these are primarily targeted at professional repairers, limiting non-professional repairs (Right to Repair Europe, 2024b). Barriers such as restricted access to spare parts and repair information (Dangal et al., 2021; Svensson-Hoglund et al., 2021) are often justified on safety grounds (Brannon & Seyfert, 2023; Right to Repair Europe, 2024b; Svensson-Hoglund et al., 2021). This has sparked debate over which groups should be allowed to perform repairs, for example, from groups like the Right to Repair Europe (Right to Repair Europe, 2024a). Repair, as a strategy for product lifetime extension, could have a greater impact on circularity targets if non-professional repairs were enabled, allowing, for example, consumers and volunteer groups to perform repairs on everyday products such as washing machines and coffee makers.

Design choices can significantly impact the repairability of products, influencing both repair safety and the ability to enable non-professionals to repair (Right to Repair Europe, 2024a; Svensson-Hoglund et al., 2021). However, although research on design for repair is expanding, the safety of repair remains largely overlooked. As a result, product designers lack dedicated tools and methods to anticipate and mitigate repair risks. This gap highlights the need to integrate safety considerations explicitly into design for repair, ensuring that circular design strategies do not compromise user safety.

1.2. Aim and scope

Designing for a safe, circular economy enables materials, products, and their components to be safely cycled. This can be achieved, for example, by eliminating or reducing the risks posed by SoC in products and by allowing non-professionals to conduct repairs safely. Although safety has been widely explored in design, considering, for example, ergonomics and the safe use of products, it has not yet been considered and implemented from a circular design perspective. By overlooking safety in the circular transition, we risk encountering limitations to the implementation of circular strategies and unforeseen risks. Awareness, information, and meth-

ods for designers to address substances of concern in products and to consider safety during repairs are currently limited. The main aim of this PhD is therefore:

To develop methods that support designers in developing products that can safely cycle in a circular economy.

Towards this aim, we explored the following two main topics regarding safety:
1) designing to mitigate the risks of substances of concern in products
2) designing for safe non-professional repairs.

This dissertation presents a first exploration of safety aspects in circular product design. We focus on two topics that take the product as the unit of analysis and have recently experienced a peak in research and public interest, as discussed above. We explore safe repairs to address safety from a product lifetime extension perspective, and on SoC in products, to adopt a broader lifecycle perspective that examines the materials contained in the product. Other circular strategies or safety aspects of circular product design are not covered.

This work takes an interdisciplinary approach, utilizing diverse methodologies, including literature research, co-creation approaches for method development, the integration of risk assessment and life cycle assessment, and empirical research for risk identification in products. Figure 1.4 provides an overview of the dissertation structure and the studies conducted to achieve the defined goal. The figure illustrates our approach to investigating the two topics: beginning with an exploratory stage, followed by the development of design methods, and then delving into their detailed development. At the start of this PhD research, the topic of SoC risks in products was practically unexplored. In contrast, the topic of safe repairs had already been examined in two projects within our research group, which this research used as a starting point. For this reason, four chapters focus on SoC, and one addresses safe repair. Finally, throughout this dissertation, we use the terms “design method” and “design tool” interchangeably. Our reasoning for this follows Daalhuizen (2014), who suggests design methods are mental tools that provide structure and help designers think and approach a specific problem.

1.3. Outline

This dissertation presents five studies, each focusing on a specific research aim. All studies are presented as stand-alone articles throughout Chapters 2-6. Chapter 2 addresses design for safe repairs, while Chapters 3-6 are dedicated to substances of concern. Chapter 7 presents an overarching discussion, bringing both safety-related topics together, and providing recommendations for future research on designing safe and circular products. The contents of Chapters 2-6 have not

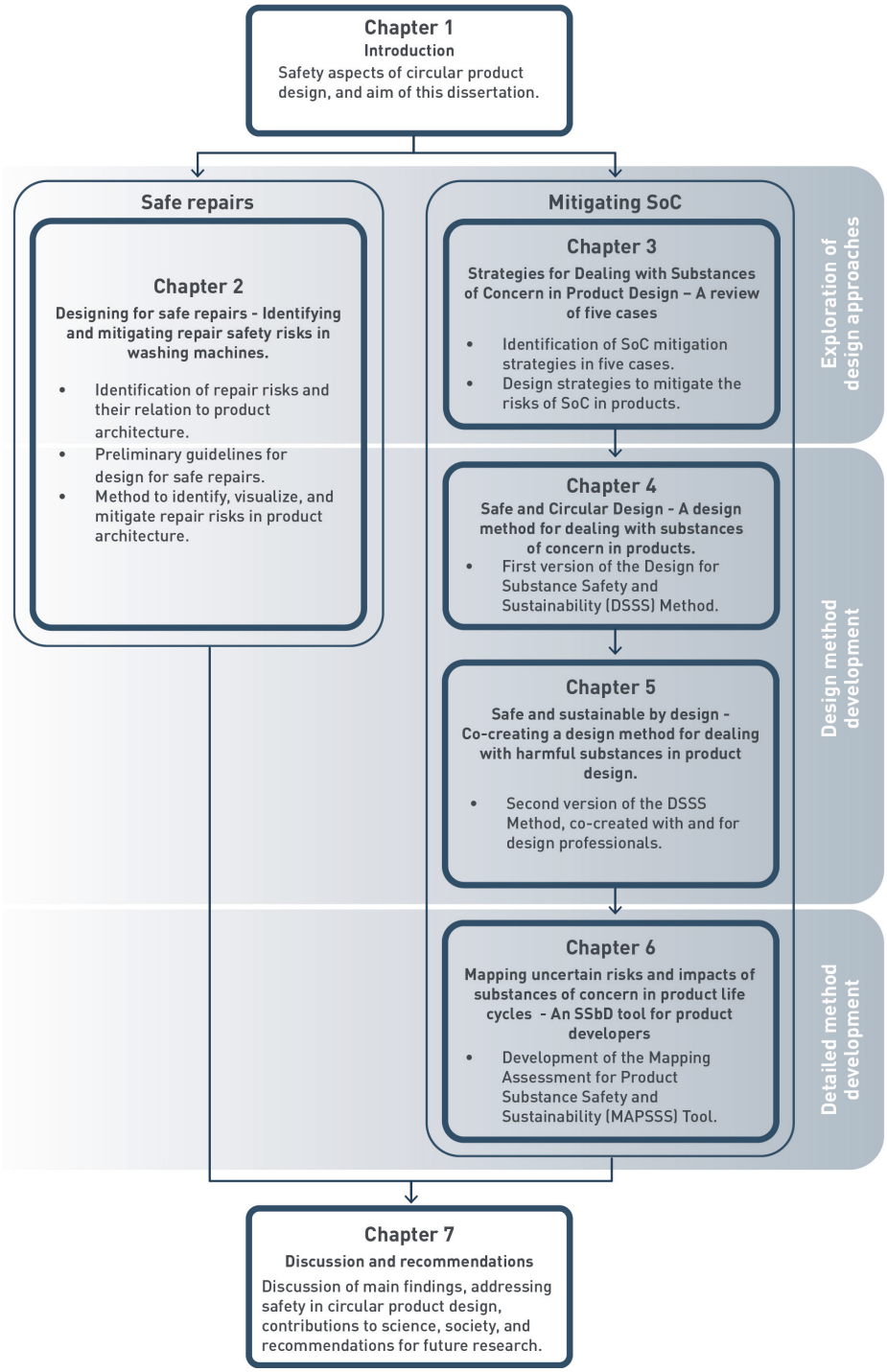


Figure 1.4. Overview and structure of the studies conducted in this research

been modified for this dissertation, except for small modification made on spelling, referencing style, and the labels sections, tables, and figures for consistency. The footnote at the beginning of each chapter mentions the original reference and all authors involved. For Chapters 2-5 I acted as main author and researcher. I collaborated with a colleague for the study presented in Chapter 6 for which we both made equal contributions to research and writing, acting as first authors.

Chapter 2 – Designing for safe repairs – Identifying and mitigating repair safety risks in washing machines.

Chapter 2 explores safety in repairs performed by non-professionals from a product design perspective. The study addresses the following research aim: To develop a method for identifying, assessing, and mitigating repair safety risks from a product design perspective to ensure safe repairs by non-professional repairers. To achieve this aim, two washing machines were disassembled and analysed to identify potential safety risks associated with repair. The study resulted in a compendium of potential risks, their relationship to product architecture, and corresponding design guidelines to address them, along with a method to help designers identify and assess repair safety risks in products.

Chapter 3 - Strategies for Dealing with Substances of Concern in Product Design – A review of five cases

Chapter 3 presents a first exploration of design approaches to mitigate SoC in products. It addresses the following research aim: Identify the contribution designers can offer in dealing with SoC in products and derive requirements for the future development of design methods and guidelines. To do this, five cases of products containing SoC were investigated to identify strategies used to mitigate risks throughout their lifecycle and their implications for design. Three resulting groups of mitigation strategies that are relevant to product design are presented: Avoid, Reduce, and Control. Chapter 3 defines a broader classification of SoC relevant to circular product design, establishes the potential contribution of designers in mitigating SoC in products, and provides a basis for developing methods or guidelines to address SoC from a product design perspective.

Chapter 4 – Safe and Circular Design - A design method for dealing with substances of concern in products.

Chapter 4 builds on the results of Chapter 3 and addresses the following research aim: to develop a method for designers to deal with SoC in products, to mitigate or manage health and environmental risks, and make them fit the circular economy. Chapter 4 presents the first version of the Design for Substance Safety and Sustainability (DSSS) Method. Throughout this chapter the DSSS Method is referred to as the Safe and Circular Design Method. This first version is primarily based on

the results obtained from Chapter 3 and the process of investigating each of the five cases.

Chapter 5 - Safe and sustainable by design - Co-creating a design method for dealing with harmful substances in product design.
Chapter 5 builds on the results of Chapter 4 and addresses the following research aim: To co-create a Design for Substance Safety and Sustainability (DSSS) Method with and for design professionals. Chapter 5 presents the co-creation of the second version of the DSSS method in collaboration with professionals from two design agencies. While the first version was based on desk research and insights from the investigation of the five cases, this study focused on incorporating input from design professionals to enhance its suitability for professional design practice. The resulting method supports designers in addressing SoC in products comprehensively, through a holistic approach that considers the entire product lifecycle and subsequent lifecycles. In addition, Chapter 5 offers insights and recommendations on the challenges designers face when dealing with SoC in products.

Chapter 6 - Mapping uncertain risks and impacts of substances of concern in product life cycles - an SSbD tool for product developers.
Chapter 6 builds on the results of Chapter 5, addressing the challenge of assessing the impact and risks of SoC at the product level. The chapter addresses the following research aim: To develop a pragmatic tool that operationalizes the principles of LCA and RA in a manner directly applicable to real-world design practice and the product development process. By combining essential elements of chemical risk assessment and life cycle assessment, we created a new tool for designers that addresses the need for resource-efficient, substance-risk assessments in the early stages of product development. Chapter 6 presents the development of the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) Tool.

Chapter 7 – Discussion and recommendations for future research
This chapter presents a summary and overarching discussion of the main findings of this research. We expand on the findings from the two topics: safe repairs and mitigating SoC risks. We then discuss several aspects relevant to safe circular product design, including dealing with trade-offs and uncertainty. Finally, we present our contributions to scientific knowledge and design practice, and propose areas for future research.

1.4. References

Achterberg, E., Hinfelaar, J., & Bocken, N. (2016). Master Circular Business with the Value Hill. www.circle-economy.com

Alfieri, F., Cordella, M., & Sanfelix, J. (2019). Analysis and development of a scoring system for repair and upgrade of products : final report. Publications Office of the European Union.

Apel, C., Kümmerer, K., Sudheshwar, A., Nowack, B., Som, C., Colin, C., Walter, L., Breukelaar, J., Meeus, M., Ildefonso, B., Petrovykh, D., Elyahmadi, C., Huttunen-Saarivirta, E., Dierckx, A., Devic, A. C., Valsami-Jones, E., Brennan, M., Rocca, C., Scheper, J., ... Soeteman-Hernández, L. G. (2024). Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives. Current Opinion in Green and Sustainable Chemistry, 45, 100876. https://doi.org/10.1016/J.COGSC.2023.100876

Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production, 69, 10–16. https://doi.org/10.1016/J.JCLEPRO.2014.01.028

Bakker, C., Hollander, M. den., Hinte, E. van., & Zijlstra, Yvo. (2019). Products that last. 2.0 : product design for circular business models. BIS Publishers.

Beekman, M., Bakker, J. B. C., van Leeuwen, L., Waaijers-van der Loop, S., Zijp, M., & Verhoeven, J. (2020). Coping with Substances of Concern in a Circular Economy.

Bodar, C., Spijker, J., Lijzen, J., Waaijers-van der Loop, S., Luit, R., Heugens, E., Janssen, M., Wassenaar, P., & Traas, T. (2018). Risk management of hazardous substances in a circular economy. Journal of Environmental Management, 212, 108–114. https://doi.org/10.1016/J.JENVMAN.2018.02.014

Bovea, M. D., Ibáñez-Forés, V., & Pérez-Belis, V. (2020). Repair vs. replacement: Selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. Journal of Environmental Management, 254. https://doi.org/10.1016/j.jenvman.2019.109679

Bracquené, E., Peeters, J., Alfieri, F., Sanfélix, J., Duflou, J., Dewulf, W., & Cordella, M. (2021). Analysis of evaluation systems for product repairability: A case study for washing machines. Journal of Cleaner Production, 281, 125122. https://doi.org/10.1016/J.JCLEPRO.2020.125122

Brannon, I., & Seyfert, K. (2023). The Economic Downsides of "Right-to-Repair." https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/

Daalhuizen, J. (2014). Method Usage in Design (Doctoral dissertation). Delft University of Technology. https://doi.org/10.4233/UUID:4AC01165-C6B5-4057-A2FE-3418907F251E

Dangal, S., Balkenende, R., Faludi, J., Den Berge, V., & Arcos, P. (2021). Perceived Capabilities and Barriers for Do-It-Yourself Repair. Product Lifetimes and the Environment (PLATE). https://www.researchgate.net/publication/361074098

Dumée, L. F. (2022). Circular materials—An essay on challenges with current manufacturing and recycling strategies as well as on the potential of life cycle integrated designs. Circular Economy and Sustainability: Volume 2: Environmental Engineering, 359–372. https://doi.org/10.1016/B978-0-12-821664-4.00008-X

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. Journal of Cleaner Production, 142, 2741–2751. https://doi.org/10.1016/J.JCLEPRO.2016.10.196

Ellen MacArthur Foundation. (2015). Towards a Circular Economy: Business rationale for an accelerated transition | Shared by Business. https://emf.thirdlight.com/link/ip2fh05h21it-6nvypm/@/preview/1?o

European Commission. (2008). Priority List European Union Risk Assessment Report bis(2-ethylhexyl)phthalate (DEHP). http://www.jrc.cec.eu.int

European Commission. (2020). Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN

European Commission. (2024a). Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828. http://data.europa.eu/eli/dir/2024/825/oj

European Commission. (2024b). Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401781

European Environment Agency. (2020). The European environment-state and outlook 2020. https://doi.org/10.2800/96749

Farmer, C. M., & Lund, A. K. (2006). Trends over time in the risk of driver death: What if vehicle designs had not improved? Traffic Injury Prevention, 7(4), 335–342. https://doi.org/10.1080/15389580600943369

Gray, S., Sadhukhan, J., Druckman, A., & James, K. (2025). A comparison of circular business models using life cycle assessment, focusing on clothing retail, distribution and use. The International Journal of Life Cycle Assessment 2025, 1–22. https://doi.org/10.1007/S11367-025-02468-1

Hill, P. J., Taylor, M., Goswami, P., & Blackburn, R. S. (2017). Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance. Chemosphere, 181, 500–507. https://doi.org/10.1016/J.CHEMOSPHERE.2017.04.122

Holmquist, H., Schellenberger, S., van der Veen, I., Peters, G. M., Leonards, P. E. G., & Cousins, I. T. (2016). Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing. Environment International, 91, 251–264. https://doi.org/10.1016/J.ENVINT.2016.02.035

Keijer, T., Bakker, V., & Slootweg, J. C. (2019). Circular chemistry to enable a circular economy. Nature Chemistry 2019 11:3, 11(3), 190–195. https://doi.org/10.1038/s41557-019-0226-9

Luís, C., Algarra, M., Câmara, J. S., & Perestrelo, R. (2021). Comprehensive insight from phthalates occurrence: from health outcomes to emerging analytical approaches. In Toxics (Vol. 9, Issue 7). https://doi.org/10.3390/toxics9070157

McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., & Doménech, T. (2017). Circular Economy Policies in China and Europe. Journal of Industrial Ecology, 21(3), 651–661. https://doi.org/10.1111/JIEC.12597

Miliute-Plepiene, J., Fråne, A., & Almasi, A. M. (2021). Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries. In Cleaner Engineering and Technology (Vol. 4, p. 100246). Elsevier. https://doi.org/10.1016/j.clet.2021.100246

Provan, D. J., Woods, D. D., Dekker, S. W. A., & Rae, A. J. (2020). Safety II professionals: How resilience engineering can transform safety practice. Reliability Engineering & System Safety, 195, 106740. https://doi.org/10.1016/J.RESS.2019.106740

Raheemy, Y., Sherratt, F., & Hallowell, M. R. (2025). What is safety? contemporary definitions and interpretations across North America. Safety Science, 185, 106798. https://doi.org/10.1016/J.SSCI.2025.106798

Right to Repair Europe. (2024a). Feedback on the Discussion Paper on Product Safety in the Circular Economy.

Right to Repair Europe. (2024b). The Current State of Right to Repair in the EU. https://repair.eu/resources/

Rockström, J., Steffen, W. L., Noone, K., Persson, Å., Stuart, F., Iii, C., Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C. A., Hughes, T., … Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Planetary Boundaries: Exploring the Safe Operating Space for Humanity Space for Humanity Citation Details Citation Details.

Rodriguez-Anton, J. M., Rubio-Andrada, L., Celemín-Pedroche, M. S., & Alonso-Almeida, M. D. M. (2019). Analysis of the relations between circular economy and sustainable development goals. International Journal of Sustainable Development & World Ecology, 26(8), 708–720. https://doi.org/10.1080/13504509.2019.1666754

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., Lunderberg, D. M., Lang, J. R., & Peaslee, G. F. (2017). Fluorinated Compounds in U.S. Fast Food Packaging. Environ. Sci. Technol. Lett. https://doi.org/10.1021/acs.estlett.6b00435

Schellenberger, S., Hill, P. J., Levenstam, O., Gillgard, P., Cousins, I. T., Taylor, M., & Blackburn, R. S. (2019). Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. Journal of Cleaner Production, 217, 134–143. https://doi.org/10.1016/J.JCLEPRO.2019.01.160

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology, 23(1), 77–95. https://doi.org/10.1111/JIEC.12732

Simpson, R. (1996). Neither clear nor present: The social construction of safety and danger. Sociological Forum, 11(3), 549–562. https://doi.org/10.1007/BF02408392/METRICS

Slovic, P. (1987). Perception of risk. Science (New York, N.Y.), 236(4799), 280–285. https://doi.org/10.1126/SCIENCE.3563507

Soeteman-Hernández, L. G., Apel, C., Nowack, B., Sudheshwar, A., Som, C., Huttunen-Saarivirta, E., Tenhunen-Lunkka, A., Scheper, J., Falk, A., Valsami-Jones, E., Rocca, C., Brennan, M., Igartua, A., Mendoza, G., Midander, K., Strömberg, E., & Kümmerer, K. (2024). The safe-and-sustainable-by-design concept: innovating towards a more sustainable future. Environmental Sustainability 2024 7:3, 7(3), 363–368. https://doi.org/10.1007/S42398-024-00324-W

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223). https://doi.org/10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. Journal of Cleaner Production, 288, 125488. https://doi.org/10.1016/J.JCLEPRO.2020.125488

UNECE. (2023). Globally Harmonized System of Classification and Labelling of Chemicals. https://unece.org/transport/dangerous-goods/ghs-rev10-2023

Wassenaar, P., Janssen, N., de Poorter, L., & Bodar, C. (2017). Substances of very high concern and the transition to a circular economy: An initial inventory. https://doi.org/10.21945/RIVM-2017-0071

World Health Organization. (2023). Despite notable progress, road safety remains urgent global issue. https://www.who.int/news/item/13-12-2023-despite-notable-progress-road-safety-remains-urgent-global-issue



Chapter 2

Designing for safe repairs Identifying and mitigating repair safety risks in washing machines

This chapter was submitted as:

Bolaños Arriola, J., Ingemarsdotter, E., Bakker, C., Balkenende, R., Designing for safe repairs - Identifying and mitigating repair safety risks in washing machines. *Sustainable Production and Consumption.*

Abstract

Non-professional repairs could contribute to an upscale in repair, supporting circular economy goals, yet they raise safety concerns. While recent regulatory actions promote repair, they focus mainly on advancing access to professional repair, rather than enabling repairs by non-professionals, such as consumers and volunteers. This study investigates how product design can mitigate repair safety risks and enable safe non-professional repairs. A washing machine and a washer-dryer combo were analysed through repeated disassembly and reassembly to identify mechanical, electrical, thermal, and chemical risks occurring during and after repair, as well as risk-inducing and risk-preventing design features and product architecture. Identified risk-inducing features include exposed components, vulnerable electrical and water connections, lack of reassembly guidance, and differences between disassembly and reassembly sequences. Based on the analysis insights, we developed a method for identifying, assessing, and mitigating repair safety risks. The method provides elements to visualize repair safety risks as an additional layer on disassembly maps and design recommendations to mitigate risk. The repair-risk mapping method allows designers to systematically analyse and anticipate repair safety risks and identify relevant risk-inducing design features and architecture. The findings show that relatively small design interventions, such as visual guidance, reusable connectors, robust connections, and enforced disassembly and reassembly sequences, can reduce risks and make repairs more accessible to non-professionals. Our research suggests that product design plays a crucial role in expanding repair opportunities to a broader range of users while maintaining safety.

2.1. Introduction

The safety of repairs performed by non-professionals remains controversial. The debate focuses on who should be allowed to repair everyday products, the role of regulation, and how to balance the right to repair with consumer safety and manufacturers' interests. Although non-professional repair could contribute to an upscale in repair, necessary to meet CE and sustainability ambitions (Svensson-Hoglund et al., 2021), it also raises safety concerns. This paper addresses the issue from a product design perspective, focusing on how products can be designed to enable safe non-professional repairs.

Design for repair is widely recognized as a key strategy for extending product lifetimes and advancing the circular economy (Alfieri et al., 2019; Bakker et al., 2014; Bracquené et al., 2021). The importance of advancing repair is reflected in evolving regulations. Most recently, the European Commission's Ecodesign for Sustainable Products Regulation (European Commission, 2024b), which sets ecodesign requirements, including repair, for specific product groups sold on the European market. Its predecessor, the Ecodesign Directive (European Commission, 2009), introduced repair provisions for ten product categories, including washing machines, refrigerators, and televisions, focusing on ease of disassembly, spare part availability, and repair information. Building on this, a European repairability scoring system was developed and first applied to smartphones (Spiliotopoulos et al., 2022). From June 2025, manufacturers must display these repairability scores alongside energy labels in physical and online stores across Europe (European Commission, 2023a). Similar requirements are expected to follow for other products. France has already implemented a similar approach through its Repairability Index, introduced in 2021 (Ministères Aménagement du territoire Transition écologique, 2024). In parallel, the Directive on common rules promoting the repair of goods (European Commission, 2024a) s to improve access to repair by obliging manufacturers to offer reasonably priced, timely repair services and clear information on repair options and spare parts.

These regulatory actions, however, focus mainly on increasing access to professional repairs services, rather than enabling repairs by non-professionals, such as consumers and volunteer repairers in Repair Cafés. This has triggered debate over who should be enabled to repair products, and the implications of broadening the scope to non-professionals. The Right to Repair Europe coalition argues that consumers are largely excluded as potential repairers (Right to Repair Europe, 2024b). Studies likewise show that consumers face significant barriers to repair, including limited access to spare parts and repair information, lack of knowledge and experience, high repair costs, a tendency to replace rather than repair, and product designs that hinder repairability (Barros & Dimla, 2023; Dangal et al., 2021;

Svensson-Hoglund et al., 2021). Manufacturers often reinforce these barriers by restricting spare parts and repair information to authorized repairers (Right to Repair Europe, 2021, 2024b). Restrictions on non-professional repairs are often justified on the grounds of consumer safety and liability, and manufacturers also cite economic and intellectual property concerns (Brannon & Seyfert, 2023; Right to Repair Europe, 2024b; Svensson-Hoglund et al., 2021). Further, safety aspects of transitioning to the circular economy, including repair, are increasingly addressed in regulation. The General Product Safety Regulation, for instance, specifies that consumer repairs should be considered only when they can be performed easily and safely (European Commission, 2023b). Yet terms such as "easily," "safely," and "professional repairer" remain undefined or vague in EU policy. As a result, the role of non-professionals in repair remains ambiguous, hindering the development of concrete support measures. Manufacturers control product design, which defines who can perform a repair and determines repair-related risks. This highlights the role of design in determining whether repair remains limited to professionals or can be safely extended to non-professionals (Right to Repair Europe, 2024a; Svensson-Hoglund et al., 2021).

Research on design for repair is expanding and explores diverse approaches, including for example, methods to assess repairability and ease of disassembly (Bracquene et al., 2019; De Fazio et al., 2021; Vanegas et al., 2018), design guidelines for fault diagnosis (Pozo Arcos et al., 2020, 2021), design aspects in repairability scoring systems (Barros & Dimla, 2023; Dangal et al., 2022), the effects of modular design in repair behavior (Amend et al., 2022), the influence of design in repair and the experience of repair (Lee & Wakefield-Rann, 2021), and 3D printing of spare parts (van Oudheusden et al., 2023a; van Oudheusden et al., 2023b). Yet repair safety is rarely addressed, and when it is, it is only briefly considered. Dangal et al. (2022) point to a link between ease of disassembly and safety, and note that some repairability scoring systems include factors such as protected batteries, safe working environments, skill requirements, and product warnings. This suggests that scoring systems consider certain safety aspects of the repair procedure but overlook, for example, the consequences of a faulty repair. Van Oudheusden et al., (2023b) emphasize the need to review the quality of 3D-printed spare parts to avoid safety risks, while Pozo Arcos et al., (2020) show that built-in safety features, such as safety switches, can sometimes hinder correct fault diagnosis, suggesting potential tensions between safety and repairability. Overall, we observe a clear gap: repair safety has received little design attention, with no academic literature dedicated to studying repair safety aspects from a product design perspective.

Therefore, this research addresses the potential of product design to reduce repair safety risks in non-professional repairs, such as those performed by consumers. We aim to develop a method for identifying, assessing, and mitigating repair safety

risks from a product design perspective, to ensure safe repairs by non-professional repairers. We build on previous exploratory work on Safe by Design and design-for-safe-repair, where we analysed design aspects influencing repair safety in products, and proposed a preliminary design-based approach (Bolaños Arriola et al., 2019; Ingemarsdotter et al., 2021). In this paper, we present an analysis of one washing machine and one washer-dryer combo to identify repair safety risks, risk-inducing and risk-preventing design features, and product architecture. Based on this, we (1) developed a method for designers to assess and visualize repair safety risks, and (2) derived a set of design recommendations to address such risks.

2.2. Method

Below, we present the process that we followed to address our research aim. First, Section 2.1 presents the process to analyse the washing machine and the washer-dryer combo to identify repair safety risks in relation to the product architecture. Second, Section 2.2. outlines how we built previous work and applied the findings of the analysis to develop a method for designers to identify and assess repair safety risks (Bolaños Arriola et al., 2019; Ingemarsdotter et al., 2021). Third, Section 2.3 explains how we derived design recommendations to address repair safety risks.

This research distinguishes between risks that occur during the repair process (referred to as: risks during repair) and risks that may arise after the repair is completed (referred to as: post repair risks). This distinction helps us identify specific product characteristics that contribute to risks to the repairer while performing the repair and potential risks to repairers, users, the product, and its surroundings resulting from a faulty repair (e.g., short circuits, fires, etc.). We also distinguish four different types of repair safety risks, as previously defined by Bolaños Arriola et al. (2019):

- Mechanical Risks: when a component or disassembly/assembly action can cause any sort of mechanical injury to the repairer/user (e.g., cuts or bruising) or mechanical damage to the surrounding environment of the product.
- Electrical risks: risk of electrocution and electric shock during the repair procedure, as well as possible short circuits and consequences for the surrounding environment (e.g., fire caused by a faulty repair).
- Thermal risks: the risk of a component or a disassembly/assembly action causing burns to the repairer/user or fires/damage to the surroundings of the product.
- Chemical risks: the risk of contact (e.g., through skin or inhaling) between the repairer/user and hazardous substances caused by a component and/or a disassembly/assembly action.

2.2.1. Analysis to identify Repair Safety Risks

Selection of products for analysis

A washing machine and a washer-dryer combo were selected as cases to analyse repair safety risks (AEG Electrolux front loading washing machine, and Hisense washer dryer combo). Washing machines were considered a suitable product category, due to several characteristics: they operate with several systems (i.e., electromechanical system, water and electrical system combination, parts that move at high revolutions, and heating system), have a high complexity, are heavy, and are typically difficult to handle, all of which showcase a variety of potential repair safety risks (e.g., electrical, mechanical, thermal, and potential combinations). Furthermore, washing machines are typically repaired by professional repairers, and repair and service information is rarely available to the public. The washer-dryer combo was also selected due to the presence of additional heating components, adding to the complexity. Both machines were analysed independently and later compared as described below.

Documentation of the disassembly and reassembly of each washing machine

Each machine was disassembled and reassembled three times. Figure 2.1 shows the setup used to perform the analysis. The first and second disassembly and reassembly processes were video recorded with a wide-angle lens camera positioned to provide a top-down perspective. An operating area was marked on the floor to avoid stepping out of the shot while manipulating the products, which were placed on top of a moving plate to ease the process (Figure 2.1).

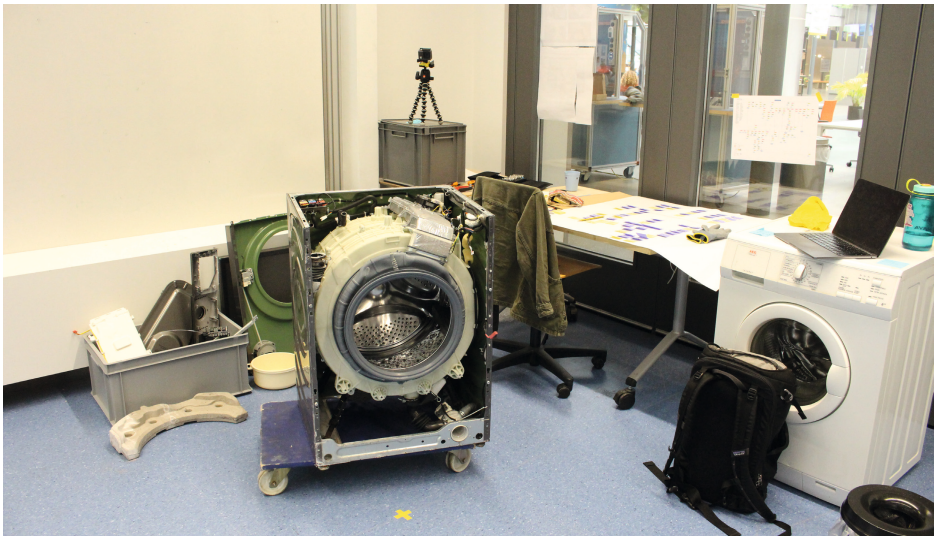


Figure 2.1. Experimental setup for the disassembly and reassembly of the washing machines.

During the disassembly process of each washing machine, all disassembly sequences and actions were documented in an adapted version of the Disassembly Map, developed by De Fazio et al. (2021). The Disassembly Map is a method for visually assessing the ease of disassembly of a product, indicating the set of necessary actions (sequences) required to reach a specific component. Video recordings were used to verify observations and derive the final disassembly maps of the washing machine and washer-dryer combo.

Figure 2.2 shows the adaptation made to the Disassembly Map for the purpose of this study. We simplified the visualization of tools to two shapes (hand and tool) instead of the three shapes in the original map (hand, spudger, screwdriver). We also reduced the number of colours used to represent force intensity from six to three, using a street-light system (green, yellow, red). These adaptations retain the capacity to represent disassembly actions and their characteristics, while reducing potential visual cluttering. This was done to improve readability in conjunction with repair safety mapping elements.

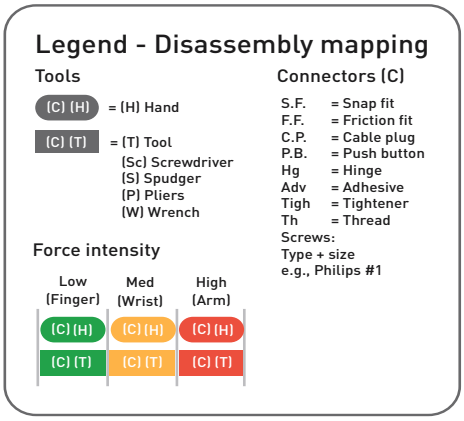


Figure 2.2. Disassembly mapping elements to indicate disassembly actions and sequences. Adapted from De Fazio et al. (2021) for the purpose of this study.

Identification and documentation of repair safety risks and risk-inducing design features, and architecture

During the disassembly and reassembly of the machines, we observed and documented potential repair safety risks and their associated design features and product architecture. In this study, design features refer to specific product characteristics that enable certain functions or qualities, while product architecture refers to the overall organization and interrelation of components. To structure the analysis, we first established an observation checklist (Table 2.1). This was created based on the definition of risks proposed by Bolaños Arriola et al. (2019), the repair

and industrial design experience of the researcher, and inspiration from publicly available washing machine repair guides (e.g., iFixit and YouTube).

Table 2.1. Observation checklist that includes examples of risk-inducing design features and architecture. The checklist was used to support the identification and documentation of repair risks.

Type of risk	Risks During Repair	Post repair Risks
Mechanical	- Features/architecture causing exposure to sharp edges or features in which body parts can be hit, or trapped. - Interaction with heavy components.	- Features/architecture leading to mechanical failure such as loose, or broken components.
Thermal	- Features/architecture causing exposure to heating systems, or to hot water. - Features/architecture leading to fire, such as punctured batteries.	- Features/architecture leading to overheating, fire, or malfunctioning of heating components, such as faulty connections.
Chemical	- Features/architecture causing exposure to hazardous substances, such as punctured batteries, gases, or fumes.	- Features/architecture leading to the release of hazardous substances, such as punctured components or faulty valves.
Electrical	- Features/architecture causing exposure to electrified components. - Features/architecture leading to short circuits, such as water leakage.	- Features/architecture leading to short circuits, or fire, such as faulty connections. - Features/architecture leading to water leakage.

We employed an Excel table to document our observations, and photographed all relevant design features and architecture. Table 2.2 shows the elements we considered to describe each potential risk in detail. This resulted in a list of risks for each washing machine. We then clustered the identified risks according to their similarities to develop a single summary of identified risks in both machines.

Table 2.2. Elements considered for the documentation and description of observed risks and risk-inducing design features and architecture.

Description of risk and related risk inducing design features and architecture	***Image of risk inducing design features / architecture***	***Related components***	***Risk type*** Mechanical, Electrical, Thermal, Chemical	***Disassembly / Reassembly***	***Risk during repair / Post repair risk***	***On person / on product***	***Aggravating factors yes/no*** (context, fixed installation, positioning, necessary help, sequences)	***Description of aggravating factors***

We analysed the documented disassembly and reassembly sequences to also identify any risks considering the product architecture, hypothetical behavioural factors, and contextual factors. These were documented and described under aggravating factors (Table 2.2). The following aspects were analysed:

- Differences in disassembly and reassembly sequences caused by the product architecture. If the disassembly sequence to get to a component differs from its reassembly sequence, it could lead to errors in the repair process, which could lead to risks.
- Potential shortcuts performed by the repairer. The potential of a repairer deviating from the intended disassembly sequence to reach a component. Shortcuts could lead to unintended exposure to risky components or to errors in the repair process.
- Contextual factors that could influence disassembly/reassembly sequences. Repairers may be forced to use alternative disassembly or reassembly sequences due to contextual restrictions, such as limited mobility due to the positioning or installation of the appliance.

2.2.2. Visualization of repair safety risks – Method development

To develop the repair risk visualization and assessment method, we used the adapted version of the disassembly map (Figure 2.2) (De Fazio et al., 2021) as a base to visually represent the entire product architecture. Repair safety risks were then presented as an additional layer to position over the disassembly map.

We created a set of mapping elements to represent the different identified repair safety risks. These were developed following our observations during the disassembly and reassembly of the washing machines, and expanding on what was previously proposed by Ingemarsdotter et al. (2021) and Bolaños et al. (2019), who performed disassembly analyses in blenders, coffee makers, radios, and washing machines, among others. The elements were developed iteratively, by visualizing all identified risks in the washing machines as an additional layer on their corresponding disassembly maps. We collaborated with design experts to gain input on the clarity of the mapping elements. The mapping elements were developed to indicate risks and their characteristics (Table 2.2), for instance, if they occur during the repair or post repair, their type, relevant components and potential aggravating factors.

2.2.3. Developing design recommendations – risk mitigation strategies

We developed a set of preliminary design recommendations for designers to address repair safety risks, focusing on the risks identified in the washing machines. To do this, we first created a summary that clustered the risks identified in both machines. We then developed design recommendations to address each risk cluster. These combine an element of ideation from the researchers' industrial design and

repair expertise, ideation from the findings obtained during the mapping of risks, inspiration from educational design projects involving repair safety, and observed risk-preventing design features in the washing machines.

Identifying risk-preventing design features
During the disassembly and reassembly of each washing machine, we observed and documented risk-preventing design features and architecture. To guide the analysis, we used a similar approach to the observation of risks and risk-inducing features and architecture. However, the observation checklist in Table 2.1 was applied in an opposite manner, for example, identifying features preventing exposure to sharp edges or preventing faulty connections that lead to electrical or mechanical malfunctions.

Again, we employed an Excel table to document our observations and photographed all risk-preventing design features and architecture. Table 2.3 shows the elements we considered to describe the prevented risk in detail. The observation of these features informed the identification of risk-mitigation strategies and the development of design recommendations.

Table 2.3. Elements considered for the documentation and description of observed prevented risks and their related design features and architecture.

Description of the prevented risk and risk-preventing design features and architecture	***Image of risk preventing design feature / architecture***	***Related components***	***Risk type*** Mechanical, Electrical, Thermal, Chemical	***Disassembly / Reassembly***	***Risk during repair /Post repair risk***	***On person / on product***

2.3. Results

The results are presented in three parts. The first part presents the risks identified during the analysis of the washing machines. The second part introduces the developed risk mapping elements and illustrates their application in visualizing the washing machine findings. The third part focuses on risk mitigation, presenting design recommendations derived from the analysis and mapping.

2.3.1. Identified repair safety risks and their related risk inducing design features.

We identified 44 repair risks and their associated design features and architecture in the washing machine, and 54 in the washer-dryer combo. Table 2.4 summarises and clusters these findings into 20 risk-inducing design features. The complete list for each machine is provided in Supplementary Material 2.1. We categorized the identified features to describe them according to the characteristics listed in Table 2.2.

Figures 2.3, 2.4, and 2.5 illustrate risk-inducing design features and clarify our terminology to describe risks and their characteristics. Figure 2.3 shows that after removing the back panel, the repairer is exposed to sharp edges, electrified parts, and moving components. We can observe what we define as risk zones, in this case, exposure to electrical risks from the motor and its cable connectors when the appliance is not disconnected from the electrical supply prior to the repair. What we denominate as aggravating factors are also observable, in this case originating in the product architecture: limited mobility and visibility for the motor disassembly, increasing the likelihood of injury or reassembly errors. Figure 2.4 shows a shallow, vulnerable connection, with minimum overlap between the tub outlet and its hose, which, despite using a reusable connector, can result in faulty reassembly or leakage. This is an example of what we denominate risk steps; if the reassembly of the hose is not done correctly it can lead to post repair risks. Architecture related risks are also observable, as the vulnerable connection sits above the pump, an electrified component, potentially leading to electrical risks. Figure 2.5 shows the disassembly of a heavy component that requires assistance from another person, which may not always be available, thereby increasing the risk of injury. We denominate this situations as an aggravating factor originating in both the product architecture and the context.

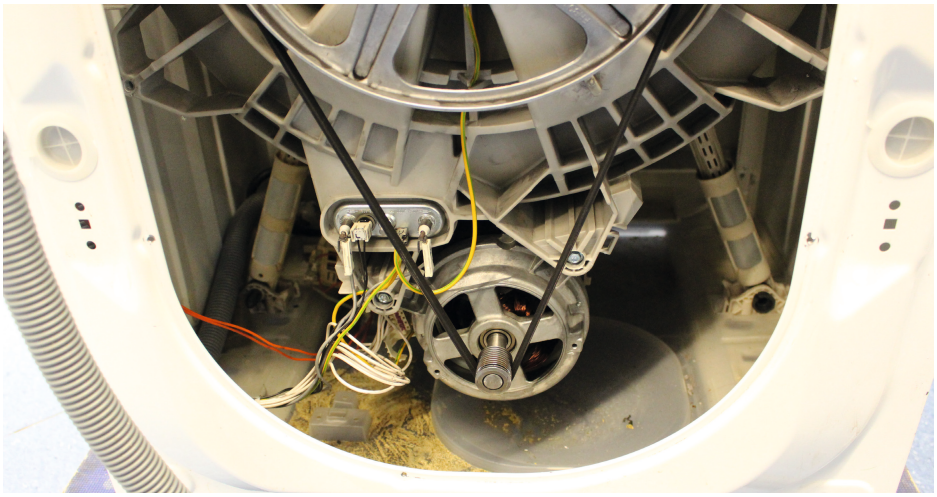


Figure 2.3. Back opening of the washing machine, showing a number of potential repair-related risks. Immediately after removing the back panel, the repairer is exposed to sharp edges, electrified parts, and moving components. Aggravating factors, such as mobility and visibility issues, to perform repairs that require the disassembly of the motor are also evident.



Figure 2.4. Shallow connection with minimum overlap (approx. 5mm) between the tub outlet and its corresponding hose. Shallow connections can be vulnerable or cause reassembly issues despite the reusable connector, potentially leading to leaks. In this case, a leak from the tub outlet hose could cause a short circuit since it is positioned directly on top of the pump.



Figure 2.5. Disassembly of the tub requires support from an additional repairer due to its weight and fixture type. The manipulation of heavy products and components can lead to injuries if the repairer does not have help available.

Table 2.4. Summary of risk-inducing design features and architecture identified in the washing machine and washer-dryer combo. For each identified risk inducing feature or architecture, we indicated the type of risk they generate, if the risk is related to specific components, if it affects a larger zone in the product architecture, whether it is generated in a disassembly or reassembly sequence, if there are aggravating factors present, and if these are related to differences in sequences. Risk types: electrical (E), mechanical (M), Thermal (T).

Description of risk-inducing design feature / architecture	Components	Risk type	During Post repair	Disassembly Reassembly	Agg. factors	Risk zones	Sequ.
R1. Exposure to non-insulated electrified components. Risk from remaining charge or the appliance remaining plugged into the electrical supply.	PCB, capacitor, heating element, inlet valve, motor, pump, top, back, and front panels.	E	During	Disassembly		*	
R2. Exposure to non-insulated cable plugs. Risk from remaining charge or the appliance remaining plugged.	PCB, capacitor, heating element, motor.	E	During	Disassembly		*	
R3. Water related components and hoses are located near high voltage components.	Outlet hose, tub, pump.	E	During Post	Disassembly Reassembly			
R4. Lack of information or affordances for the correct grounding of appliances.	Capacitor, motor, metal housing.	E	During Post	Reassembly			
R5. Lack of information or affordances for the correct reassembly of cable plugs.	Motor, pump, heating element, capacitor, PCB, lock, inlet valve.	E	Post	Reassembly			
R6. Lack of information or affordances for the correct routing and fixing of cables.	Cable harness, metal housing.	E	Post	Reassembly			

Table 2.4. *(Continued)*

Description of risk-inducing design feature / architecture	Components	Risk type	During Post repair	Disassembly Reassembly	Agg. factors	Risk zones	Sequ.
R7. Loss of mechanical integrity in electrical components and cable plugs, due to low quality or lack of information or affordances.	Capacitor, metal housing, power cable.	E	Post	Disassembly Reassembly			
R8. Differences between disassembly and reassembly sequences that can lead to errors in reassembly.	Rubber ring, concrete ring.	E	Post	Disassembly Reassembly	*		*
R9. Specialized tools required for reassembly that can lead to errors.	Rubber ring, spring.	E	Post	Reassembly			
R10. Lack of information or affordances for the correct reassembly of hoses and water related components.	Hoses, tub, inlet valve, soap module.	E	Post	Reassembly			
R11. Water related components with shallow connections that lead to incorrect reassembly and vulnerable connections.	Rubber ring, inlet hose (tub), outlet hose (tub).	E	Post	Reassembly			
R12. Limited mobility and visibility for disassembly and reassembly which can lead to errors.	Motor brushes, motor, dampers, tub, heating element, pump, inlet hose (tub), outlet hose (tub).	E, M, T	Post	Disassembly Reassembly	*		*

Table 2.4. *(Continued)*

Description of risk-inducing design feature / architecture	Components	Risk type	During Post repair	Disassembly Reassembly	Agg. factors	Risk zones	Sequ.
R13. Exposure to sharp edges and corners.	Front and back frame, back panel.	M	During	Disassembly Reassembly	*		
R14. Heavy products and/or components that require a lot of manipulation during disassembly and reassembly.	Entire machine, levelling elements, tub, motor, concrete ring.	M	During	Disassembly Reassembly	*		*
R15. Exposure to moving components.	Motor, drive wheel, tub.	M	During	Disassembly			
R16. Lack of information or affordances to prevent injury inducing disassembly actions or sequences.	Tub, dampers.	M	During	Disassembly			*
R17. Loss of mechanical integrity of mechanical related components and fixtures.	Concrete ring, damper holders.	M	Post	Disassembly Reassembly			
R18. Loaded components and disassembly actions that require high forces.	Screws, spring ring.	M	During	Disassembly Reassembly			
R19. Exposure to non-insulated hot components.	Heating element, motor.	T	During	Disassembly		*	
R20. High complexity that leads to incorrect reassembly.	Heating element.	T, E	Post	Reassembly			

2.3.2. Mapping repair risks on the disassembly maps of the washing machines

Figures 2.6 and 2.7 show the disassembly maps for each machine, outlining the product architecture and displaying all identified risks (Section 2.3.1, Supplementary Material 2.1). The risks are mapped as an additional layer on the disassembly map, using the mapping elements developed, to distinguish different risks from a design perspective. Below, we explain each of the mapping elements in detail, supporting the interpretation of the maps.

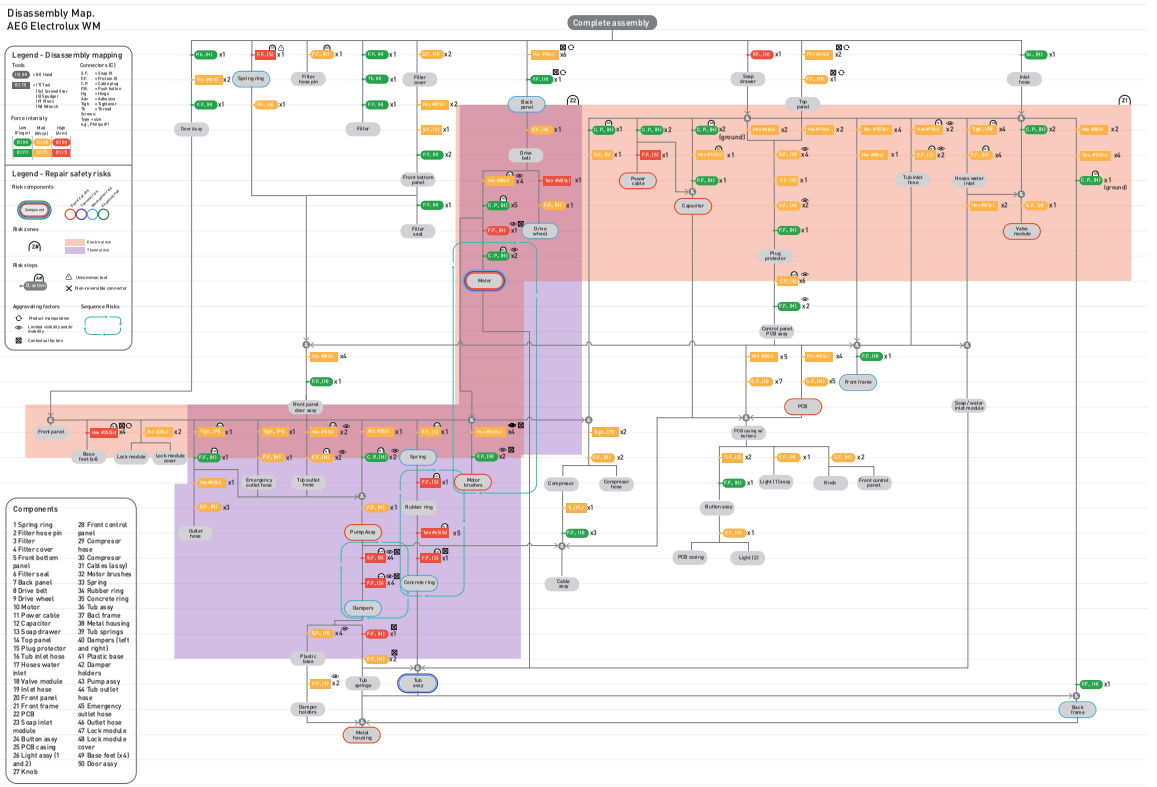


Figure 2.6. Disassembly map and visualization of risks of the washing machine. The risk mapping elements indicate the presence of thermal and electrical risk zones originating after the removal of panels. Thermal, electrical, and mechanical risks associated with components such as the capacitor, the motor, and the tub are highlighted. 26 risk steps indicate potential post repair risks due to reassembly issues. Sequence risks highlight differences between the disassembly and reassembly of the rubber ring, and potential shortcuts to reach the motor brushes. High-fidelity version available in Supplementary Material 2.2.

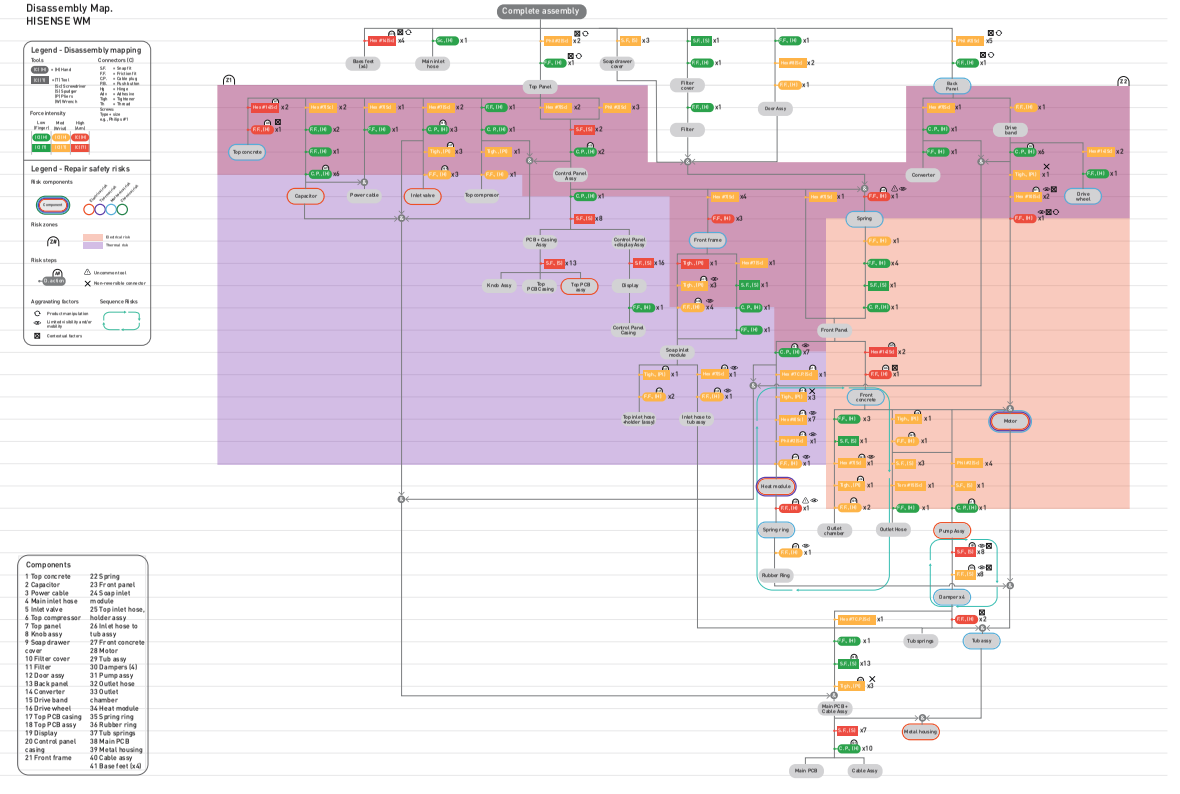


Figure 2.7. Disassembly map and visualization of risks of the washer-dryer combo. The risk mapping elements indicate the presence of thermal and electrical risk zones originating after the removal of panels. Thermal, electrical, and mechanical risks associated with components such as the capacitor, the motor, and the heating element are highlighted. 35 risk steps indicate potential post repair risks due to reassembly issues and several non-reusable connectors. Sequence risks highlight differences between the disassembly and reassembly of the rubber ring. High-fidelity version available in Supplementary Material 2.2.

Risk zones

We identified what we denominate risk zones during the disassembly of the washing machines. These constitute sets of disassembly sequences in which the repairer is exposed to risk. The objective of mapping risk zones is to denote high levels of risk in case precautions are not taken prior to the repair, such as unplugging a device, allowing the device to cool down, or emptying water systems. We identified risk zones relevant to electrical and thermal risks, that occur during repair. Risk zones are represented in the disassembly map by enclosing all disassembly actions for which the repairer is at risk (Figure 2.8). Thermal risks are represented in purple; electrical risks are represented in orange. Each risk zone is defined by an entry point and a limit boundary. An entry point constitutes the removal of a component after which the repairer is exposed to the risk (e.g., the removal of a housing component after which electrified components are exposed). The limit boundary or "end" of the risk zone is defined by the operation or set of operations after which the repairer is no longer exposed to the risk (e.g., the removal of power plugs from a PCB). A disassembly sequence and/or component can be a part of more than one risk zone simultaneously. To differentiate risk zones, we use colour and the notation Z1, Z2, Z3, etc.

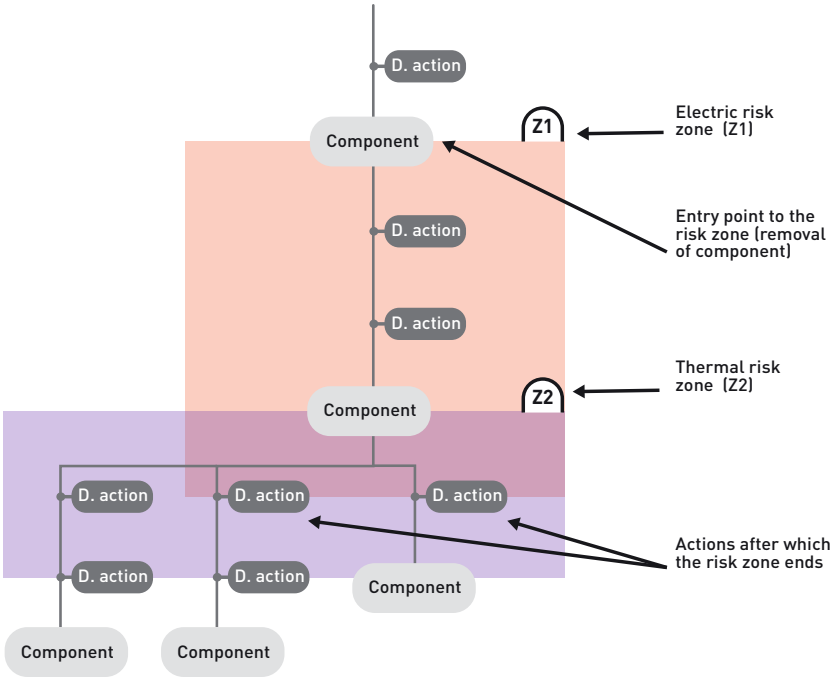


Figure 2.8. Visualization of two risk zones, Z1 electric risk zone, Z2 thermal risk zone. The coloured areas indicate the start and end of the risk zone, while enclosing all components and disassembly actions affected by it. The colours are given opacity to show any overlaps of the zones.

In the disassembly maps (Figures 2.6 and 2.7), we can observe that both machines present thermal (in purple) and electrical (in orange) risk zones. In both machines, repairers are exposed to potentially electrified and hot components immediately after disassembling the back or top panels. Removing one or several panels is necessary to be able to perform repairs on almost any other component, hence the importance of guaranteeing the removal of the electrical connection and the cool down of the products prior to repair. For the washer-dryer combo, the thermal risk zone is considerably larger than for the washing machine. This is due to the presence of a potentially hot motor and a heating element that lies deep in the disassembly sequence. The electrical risk zones in both machines are generated by a number of components (i.e., capacitor, motor, pump, etc.), all of which must be disconnected to "exit" the risk zone. The disassembly depth of some of these components results in an increase in the risk zone area.

Disassembly and reassembly risk steps

We identified the need to highlight disassembly and reassembly steps that lead to risk. We denominate these as risk steps, and annotate them in the disassembly map as A1, A2, A3, etc., attached to disassembly steps/actions (Figure 2.9). Specifically, we noted risk steps that can lead to post repair risks. According to our observations, post repair risks are commonly related to mistakes made during reassembly, or to damage caused to components during disassembly and/or reassembly. Examples include reconnecting cable plugs incorrectly, breaking fasteners, damaging a component, or reassembling connectors incorrectly. One risk step can be associated with multiple risks. Additionally, the penalizations for non-reversible connector and uncommon tool, as already indicated in the disassembly map (De Fazio et al., 2021), are considered to potentially lead to incorrect reassembly or damage during disassembly.

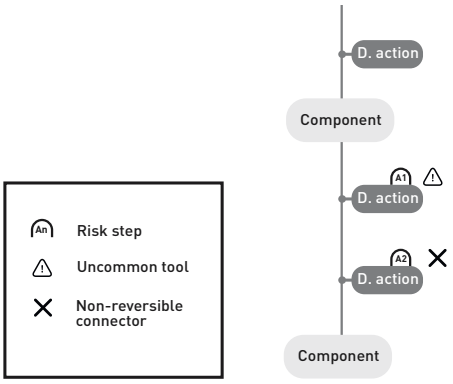


Figure 2.9. Visualization of risk steps in a disassembly sequence and the "non-reversible connector" and "uncommon tool" penalizations. The risk step indicators are numbered (i.e., A1, A2, A#) to differentiate and quantify them. Risk step indicators are always located in the top right corner of their relevant disassembly action.

A total of 26 risk steps were identified in the washing machine (Figure 2.6) and 35 in the washer–dryer combo (Figure 2.7), suggesting a number of post repair risks. In both machines, most risk steps stem from vulnerable hose connections and the lack of affordances to reconnect cable plugs correctly. A number of disassembly actions require high forces, which could result in injury or reduced mechanical integrity of components. The washer–dryer combo presents additional risks due to the heating element, which lacks reassembly affordances and involves a larger number of hoses and non-reversible connectors. For instance, zip-ties used in hose connections and cable harnesses. Finally, both machines require an uncommon tool for the correct reassembly of the rubber ring, a component that requires disassembly to access other parts.

Risk components

We identified that additional elements are necessary to link risks to their source. We define risk components as product components (e.g., heating element, PCB) that are sources of risk. Visualizing the associated risk types of a component provides design-specific insights concerning safety. Different types of risk can be indicated for a single risk component, as shown in Figure 2.10.

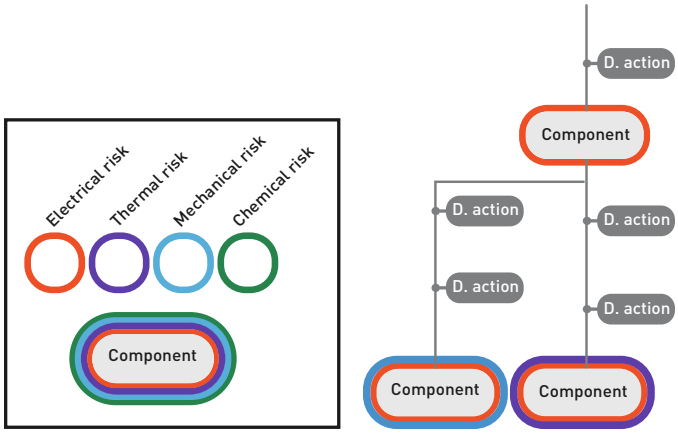


Figure 2.10. Visualization of risk components in a disassembly sequence. The top component has an associated electrical risk, while the two components at the bottom are associated with electrical and mechanical, and electrical and thermal risks, respectively.

Several risk components were highlighted in the disassembly maps (Figures 2.6 and 2.7). For the washing machine, the capacitor, motor, PCB, and pump all pose electrical hazards due to residual charge. In the washer–dryer combo, however, the main PCB was not marked as risky since it is insulated and does not require direct access for most repairs. Moving components (motor and drive wheel), panels with sharp corners, and heavy components (concrete ring and tub) have been marked as mechanical risks. These are either exposed after removing one or more panels

or must be disassembled to reach other parts, increasing risks. It is important to highlight that the disassembly depth of a component shown on the maps should not be confused with the proximity of touching. For example, the motor appears deep in the map sequence since several steps are required for its disassembly; however, in reality, repairers are physically exposed to it immediately after removing the back panel.

Sequence risks

We also identified the need to indicate potential risks in disassembly sequences (i.e., sets of steps required to reach a specific component). During the analysis of the washing machine, we observed that differences between disassembly and reassembly sequences can lead to risk due to errors. For example, in Figure 2.11, the disassembly of component A can be done without disassembling component B first. However, the correct reassembly of component A does require component B to be disassembled. Furthermore, we observed that the disassembly sequence represented in the disassembly map may not necessarily be the disassembly sequence conducted by the repairer. A repairer could choose a different disassembly sequence as a shortcut or due to contextual restrictions, which could lead to risks. Designers should then consider if alternative disassembly or reassembly sequences are possible and visualize those that could lead to risk. We denominate these as sequence risks, and they are represented in the disassembly maps as indicated in Figure 2.11.

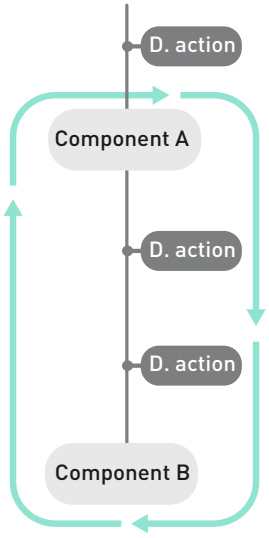


Figure 2.11. Visualization of sequence risks, i.e., differences between disassembly and reassembly sequences and/or potential changes in sequences due to contextual factors. The sequence risks are indicated by arrows that surround all components involved. The arrows are meant to indicate a potential "reverse" order or alteration to the sequence.

In both the washing machine and the washer-dryer the disassembly and reassembly of the rubber ring have been marked as sequence risks (Figures 2.6 and 2.7). The rubber ring can be disassembled without first removing the concrete ring. However, the correct reassembly of the rubber ring requires that the concrete ring be disassembled. The incorrect reassembly of the rubber ring could lead to leakage and electrical risks as a consequence. Similarly, the disassembly of the dampers poses a risk of injury if they are removed without first securing the tub. When all dampers are detached, the tension from the upper springs can cause the tub to spring suddenly upward. In the washing machine (Figure 2.6), the disassembly of the motor brushes was flagged as a sequence risk, since attempting to remove them without disassembling the entire motor can lead to incorrect reassembly, which could lead to electrical risks.

Aggravating factors

Finally, we observed the need to indicate additional sources or aggravators of risk (Figure 2.12). For example, if the repairer must work with limited space or visibility during disassembly or reassembly, this could lead to errors and risks. These aggravating factors may originate in the context (e.g., built-in installations) or stem from the product architecture (e.g., limited visibility of components).

De Fazio et al. (2021) proposed penalizations in the disassembly map that can be used to describe product characteristics that lead to, or aggravate, risk: limited visibility and manipulation. We propose to use both for risk mapping to represent what we denominate as aggravating factors that originate in the product design or architecture. We modified the original limited visibility penalization to also include limited mobility (i.e., lack of space to perform disassembly or reassembly actions correctly, or without incurring harm). We maintained the original manipulation penalization to describe cases where the product design forces the repairer to move the product (e.g., tilt, flip) in a specific way to access a component or perform an action.

We also identified aggravating factors originating in the context. For washing machines, these may result from fixed or built-in installations that restrict access to several components. Such factors can include additional mobility and/or visibility issues, the need for additional manipulation, or reliance on support from another person. To indicate these, we propose an additional penalization that we denominate contextual factors.

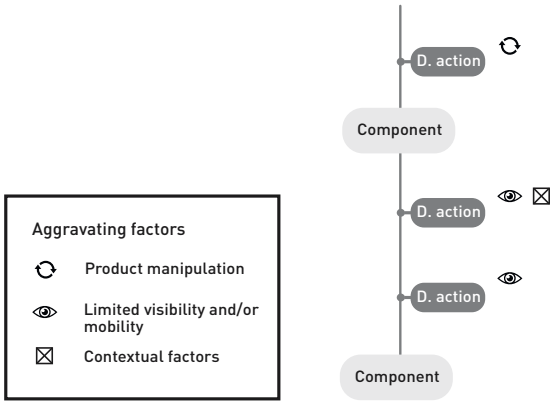


Figure 2.12. Visualization of aggravating factors. Product manipulation and limited visibility/mobility can originate in the product architecture and/or the context. Additional contextual factors can also be indicated, such as necessary help to perform a disassembly action.

Both disassembly maps show indicators of contextual aggravating factors (Figures 2.6 and 2.7). If installed in a way that blocks access to the back or top panels, the entire machine must be moved for repair, which is problematic since most disassembly sequences require removing these panels. Both machines show indicators of contextual factors for heavy components (e.g., tub, concrete ring) that likely require assistance to be handled safely. Aggravating factors stemming from the product design and architecture can also be observed in the maps, including limited space and visibility for the disassembly and reassembly of the motor, dampers, tub hoses, and heat module.

2.3.3. Mitigating repair safety risks – design recommendations

Based on the analysis and mapping (Figures 2.6 and 2.7), we developed design recommendations to address risks. The first set of recommendations indicates how designers can respond to the insights obtained from map: Risk zones can be eliminated by forcing precautionary actions before repair, or minimized by surfacing disassembly actions that remove the risk source. Alternatively, strategically maintaining disassembly sequences of specific components outside risk zones can prevent exposure. Risk steps can be mitigated by avoiding high-force actions, non-reusable connectors, and the need for specialized tools. Risks may also be prevented by avoiding sequence dependencies where the disassembly of high-risk components is necessary to reach others. Risk components can be sequenced strategically, either deeper to restrict access or earlier to eliminate risks quickly. Differences between disassembly and reassembly sequences should be avoided. Sequences can be defined and enforced by design to enhance safety. Aggravating factors can be mitigated by accounting for contextual conditions such as limited visibility or mobility, reducing the need for additional repairers, and minimizing un-

necessary manipulation. Finally, products should be designed to provide sufficient space and visibility for safe and correct disassembly and reassembly.

In addition to the recommendations above, which are based on the map observations, we developed a set of design recommendations by compiling several findings, including the identified risk-inducing features (Table 2.4), insights from the disassembly and reassembly, and the observation of risk-preventing features in the machines. Table 2.5 presents a set of strategies, practical recommendations to apply them, and the risk they are intended to mitigate.

We identified 16 risk-preventing design features and architecture in the washing machine, and 18 in the washer-dryer combo. The complete list for each machine is provided in Supplementary Material 2.1. Examples of these features include visual affordances that support the repairer in reassembling cable connectors correctly, deeper, more robust hose connections, and disassembly sequences that force the repairer to empty the water system before the disassembly of the bottom panel.

Table 2.5. Design recommendations for repair risk mitigation based on observations from washing machines and the mapping of risks.

Risk mitigation strategy	Design recommendations for risk mitigation	Related risk
A. Prevent repairers from coming into contact with electrified components.	1. Design components in a way that forces the power to be removed before disassembly. 2. Provide guidance for the repairer to remove power before disassembly. 3. Cover or insulate live components. 4. Provide warnings on risky components. 5. Position electrical risk–inducing components deeper in the disassembly sequence. 6. Facilitate access to frequently failing components without contact with risk–inducing parts. 7. Separate high-voltage PCBs from user-interface PCBs. 8. Reduce the need for manual testing. Or allow testing without disassembling. 9. Insulate cable plugs.	R1, R2.
B. Prevent electrical components from coming into contact with water.	1. Position high-voltage components and cable plugs away from water related parts. 2. Provide repairers with guidance to empty water systems before disassembly. 3. Design components and sequences to ensure water systems are emptied prior to access. 4. Ensure electrical components that may contact water are watertight.	R3.

Table 2.5. *(Continued)*

Risk mitigation strategy	Design recommendations for risk mitigation	Related risk
C. Ensure the correct and safe grounding of the appliance.	1. Provide indicators or guidance to ensure correct grounding. 2. Design components that ensure a correct grounding. 3. Design cable plugs, and electrical components for robustness, prevent loosening or loss of mechanical integrity. 4. Provide reusable, durable cable fasteners. 5. Avoid conducting materials for the product casing.	R4, R7.
D. Ensure the correct reassembly of electrical wiring.	1. Provide indicators or guidance to ensure correct connection of all electrical components. 2. Provide guidance for correct, cable routing. 3. Reduce wiring complexity and avoid visually cluttered layouts.	R5, R6, R20.
E. Ensure the correct, watertight reassembly of hoses and water related components.	1. Provide guidance for the repairer to follow safe disassembly and reassembly sequences. 2. Prevent differences in the order of disassembly and reassembly sequences. 3. Avoid non-reversible connectors. 4. Avoid the need for specialized tools, especially for reassembly. 5. Provide indicators to reconnect hoses and water related components correctly. 6. Ensure sufficient contact area in hose connections; avoid shallow connections. 7. Design water-related components for robustness to prevent loosening or loss of integrity.	R8, R9, R10, R11.
F. Provide sufficient visibility and mobility to disassemble and reassemble components safely and correctly.	1. Provide sufficient visibility and space to perform disassembly and reassembly actions. 2. Consider the context and accommodate potential mobility and visibility limitations.	R12.

Table 2.5. *(Continued)*

Risk mitigation strategy	Design recommendations for risk mitigation	Related risk
G. Prevent repairers from coming into contact with injury inducing components, or performing risky actions.	1. Avoid sharp edges on surfaces and components that may contact the repairer. 2. Design sequences that minimize product manipulation or handling of heavy components. 3. Provide configurations that aid component repositioning and reduce the need to carry heavy parts during reassembly. 4. Prevent the activation of moving components during repair. 5. Provide information or warnings in the product to indicate risk actions. 6. Cover, block, or isolate moving components. 7. Place mechanical risk–inducing components deeper in the disassembly sequence. 8. Enable access to frequently failing components without contact with risk–inducing parts. 9. Provide guidance for the repairer to follow safe disassembly and reassembly sequences.	R13, R14, R15, R16.
H. Ensure the correct reassembly of mechanical components.	1. Design for robustness to prevent mechanical components from loosening or losing integrity. 2. Provide guidance to prevent actions that damage components or their connectors.	R17.
I. Avoid disassembly actions that require high forces, or highly loaded components.	1. Provide warnings of high force actions or loaded components. 2. Provide fastening mechanisms that require less force to disassemble. 3. Use fasteners which tension can be adjusted.	R18.
J. Prevent repairers from coming into contact with potentially hot components	1. Design to ensure the repairer allows the appliance to cool before repair. 2. Provide guidance for the repairer to allow the appliance to cool before repair. 3. Cover or insulate hot components. 4. Provide warnings on risky components. 5. Move thermal risk-inducing components deeper into the disassembly sequence. 6. Facilitate access to frequently failing components without contact with risk–inducing parts. 7. Reduce the need for manual testing. Or allow testing without disassembling.	R19.

2.4. Discussion

The analysis of the washing machine and the washer-dryer combo demonstrates that repair safety risks are closely linked to product design. In both machines, repairers were exposed to electrical, mechanical, and thermal risks, particularly from heavy, moving, and exposed electrified or high temperature components. We also identified significant post repair risks arising from differences between disassembly and reassembly sequences and design features such as vulnerable electrical and water connections and the absence of reassembly indicators. The disassembly maps revealed not only these risks but also that many repair actions can be performed safely, and that most risks during repair can be mitigated through precautions that eliminate risk zones, such as unplugging the device, allowing it to cool, or emptying water systems before disassembly. In addition, we observed risk-preventing features and product architecture showing how relatively small interventions can reduce risks during and post repair; including insulating cable plugs, using reusable fasteners, providing visual reassembly guidance, and enforcing disassembly sequences. Our results highlight the role of designers in making products safe to repair, while providing a method to address repair safety in the design process.

Our design recommendations indicate that repair safety can be integrated into existing design-for-repair principles. Table 2.6 presents the design-for-repair features and principles proposed by Dangal et al. (2022) and illustrates how these principles can be adapted to better address safety based on our findings. While many principles apply both to repair-safety and repairability, such as connector removability and reusability, visibility, ease of handling, and guidance, our findings add specific safety considerations. Four design-for-repair principles are not related to safety and were therefore not addressed in this research (Table 2.6).

Table 2.6. Addition of repair safety considerations to existing design-for-repair features and principles (Dangal et al., 2022). The safety considerations are based on the design recommendations presented in Table 2.5.

Design features and principles empirically shown to drive repairability (Dangal et al., 2022)	**Relevance to repair safety**	**Addition to address repair safety risks**
Disassembly	X	Disassembly sequences to access (or prevent the access to) components can be defined and enforced by design to prevent risks.
Reassembly	X	Guaranteeing the correct reassembly of a product to its original configuration can prevent post repair risks.
Fastener removability and reusability	X	Preventing the damage of fasteners and connectors, and guaranteeing their reusability, can support correct reassembly, preventing post repair risks.
Fastener visibility	X	Fastener visibility, and the provision of visual cues, supports correct, safe disassembly and reassembly.
Modularity	X	Encapsulating risk zones, or risk components into modules can prevent contact with the repairer, reducing risks during repair.
Diagnosis	X	Facilitating diagnosis and testing without exposing the repairer to risk actions or risk inducing components.
Health and Safety	X	Minimize or eliminate safety risks by design. Increase confidence in repairers either through fail proof design features, or by providing guidelines and information.
Standard parts and interface		Not applicable
Information accessibility	X	Guidance on the repair process should emphasize potential risks during disassembly and provide information for a correct, safe reassembly.
Design simplicity and complexity	X	Product and component simplicity, and simplicity of disassembly and reassembly sequences can contribute to a correct, safe repair procedure.
Adaptability/ upgradability		Not applicable
Ease of handling	X	Potential risks from product manipulation should be considered, especially in the case of fixed product installations, and heavy products and components.

Table 2.6. *(Continued)*

Design features and principles empirically shown to drive repairability (Dangal et al., 2022)	**Relevance to repair safety**	**Addition to address repair safety risks**
Interchangeability	X	The mechanical integrity and correct reassembly of components should be guaranteed during their replacement to prevent post repair risks.
Robustness	X	Preventing the wear and breakage of components during disassembly and reassembly can prevent post repair risks due to failure.
Redundancy		Not applicable
Firmware reset		Not applicable

We argue that incorporating safety considerations into design-for-repair principles can enhance repair process safety and expand the range of repairs that non-professionals can perform. The proposed design recommendations may also address barriers faced by non-professional repairers, through increased repair confidence through risk reduction, improved ease of disassembly (Barros & Dimla, 2023), and improved product robustness (Dangal et al., 2021). However, the validity and effectiveness of the recommendations require further investigation across different scenarios to ensure that design-for-safe-repair aligns with the characteristics of the intended user group. For non-professional repairers, this entails understanding their existing knowledge, skills (Parajuly et al., 2024), access to repair information, and contextual constraints (beyond fixed installations). Prior studies show that self-reported repair experience significantly influences repair success among non-professionals and that access to repair information can guides repairers through safe procedures reducing risk, and improving the overall experience (Amend et al., 2022; Sandez et al., 2023). Future iterations of the method should explicitly consider these factors and further specify the competences and requirements for designing for non-professional repairers. Although this study focuses on washing machines, the proposed design recommendations are likely transferable to other complex household appliances. Nevertheless, additional research is needed to confirm their applicability across product groups with varying levels of complexity.

Our results show that while design interventions can improve repair safety, they may conflict with ease of disassembly, repairability, and product complexity. For example, positioning high-risk components later in the disassembly sequence reduces exposure but increases the number of steps required to access them. Such risk mitigating strategies may be suitable for components that do not require frequent repair or maintenance, whereas different approaches are needed for components that do, to avoid negative effects on ease of repair. Similarly, protective enclosures

around electrical or hot components can reduce risk but may require additional disassembly steps and components, introducing economic and sustainability trade-offs. Modularity could encapsulate risk zones or components, preventing exposure, but it may also increase costs, product complexity, and challenges related to fault diagnosis, and disassembly (Amend et al., 2022; Dangal et al., 2021; Pozo Arcos et al., 2021). Design decisions should therefore balance safety requirements with other product and sustainability requirements, while considering the intended repairers (professional versus non-professional). Further research is needed to assess how repair-safety interventions affect repairability, product complexity, and sustainability.

The repair risk mapping method proved effective for visualizing design related risks and provides a structured approach to anticipating hazards and identifying design interventions. However, several aspects of repair safety remain insufficiently captured. Risk steps could be differentiated more precisely, by distinguishing between lack of affordances, loss of mechanical integrity, and damage to vulnerable components. Risks related to component positioning are also not yet represented, such as the tub water outlet placed directly above the pump. In addition, the specific design features or product architecture causing the identified risks cannot yet be detailed. For instance, a vulnerable hose connection can be identified as a risk step, but its degree cannot be illustrated. Introducing a mechanical risk zone could highlight hazards from moving components if the appliance remains plugged in during repair, while a marker for heavy components could clarify risks related to product and component handling.

This study was limited to one washing machine and one washer-dryer and may not capture the full range of repair safety risks across product types. Broader testing across various products is necessary to determine whether the proposed mapping elements are sufficient or require expansion. Although the framework includes chemical risks, none were observed, indicating the need to assess chemical risks in other product groups and refine their representation. The method currently identifies risks without assigning probabilities, treating all risks as equally important. Integrating quantitative assessments that combine severity and occurrence (Ingemarsdotter et al., 2021) could provide a more comprehensive evaluation of repair safety. Further development should involve product designers to test the method in real cases and evaluate its usability and effectiveness.

2.5. Conclusion

This research explored how product design can reduce repair safety risks in non-professional repairs. We aimed to develop a method for identifying, assessing, and mitigating these risks from a product design perspective. To achieve this,

we analysed one washing machine and one washer-dryer combo, identifying risks during and post repair, as well as risk-inducing and safe design features and architecture. The analysis revealed a number of mechanical, electrical, and thermal risks, resulting from risk-inducing design features and architecture, including exposed components, vulnerable electrical and water connections, lack of reassembly guidance, and differences between disassembly and reassembly sequences. Based on these results, we developed a method for mapping repair safety risks as an additional layer to the disassembly map (De Fazio et al., 2021), visualizing risks across the product architecture. The repair-risk mapping method allows designers to systematically analyse and anticipate repair safety risks and identify relevant risk-inducing design features and architecture. A set of design recommendations derived from the analysis of the machines and risk mapping observations provides guidance for designers to address the identified risks. This work advances the field of design-for-repair by explicitly integrating repair safety into existing principles and providing a practical approach for incorporating safety into the design process.

Our findings suggest that design interventions, many of them relatively small, such as visual guidance, reusable connectors, robust connections, and enforced disassembly and reassembly sequences, can reduce risks and make several repairs accessible to non-professionals. This indicates that product design can play a critical role in expanding repair opportunities to a broader range of users while maintaining safety.

2.6. Appendices

Supplementary Material 2.1 - This document presents the complete set of identified risks, as well as the risk-inducing and risk-preventing design features and architecture observed in the washing machine and washer-dryer combo, supported by descriptions and images. It also includes an overview of the resulting design recommendations based on the insights derived from the analysis.

Supplementary Material 2.2 - This document provides a high-fidelity version of the disassembly maps of the washing machine and washer dryer combo.

These appendices are available in: https://data.4tu.nl/datasets/f8ee9ffd-c7cb-4287-8693-399ff93c802c

2.7. References

Alfieri, F., Cordella, M., & Sanfelix, J. (2019). Analysis and development of a scoring system for repair and upgrade of products : final report. Publications Office of the European Union.

Amend, C., Revellio, F., Tenner, I., & Schaltegger, S. (2022). The potential of modular product design on repair behavior and user experience – Evidence from the smartphone industry. Journal of Cleaner Production, 367, 132770. https://doi.org/10.1016/J.JCLEPRO.2022.132770

Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production, 69, 10–16. https://doi.org/10.1016/J.JCLEPRO.2014.01.028

Barros, M., & Dimla, E. (2023). Smartphone repairability indexes in practice: Linking repair scores to industrial design features. Journal of Industrial Ecology, 27(3), 923–936. https://doi.org/10.1111/JIEC.13398;-SUBPAGE:STRING:FULL

Bolaños Arriola, J., de Fazio, F., Balkenende, R., Bakker, C., & Flipsen, B. (2019). Safe by Design - Safe self-repairs (Vol. 2019, Number december). https://minienw.sitearchief.nl/?subsite=safebydesign#archive

Bracquené, E., Peeters, J., Alfieri, F., Sanfélix, J., Duflou, J., Dewulf, W., & Cordella, M. (2021). Analysis of evaluation systems for product repairability: A case study for washing machines. Journal of Cleaner Production, 281, 125122. https://doi.org/10.1016/J.JCLEPRO.2020.125122

Bracquene, E., Peeters, J. R., Burez, J., De Schepper, K., Duflou, J. R., & Dewulf, W. (2019). Repairability evaluation for energy related products. Procedia CIRP, 80, 536–541. https://doi.org/10.1016/J.PROCIR.2019.01.069

Brannon, I., & Seyfert, K. (2023). The Economic Downsides of "Right-to-Repair." https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/

Dangal, S., Balkenende, R., Faludi, J., Den Berge, V., & Arcos, P. (2021). Perceived Capabilities and Barriers for Do-It-Yourself Repair. Product Lifetimes and the Environment (PLATE). https://www.researchgate.net/publication/361074098

Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. Sustainability (Switzerland), 14(14). https://doi.org/10.3390/su14148634

De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. Journal of Cleaner Production, 320, 128552. https://doi.org/10.1016/J.JCLEPRO.2021.128552

European Commission. (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products. https://eur-lex.europa.eu/eli/dir/2009/125/oj

European Commission. (2023a). Delegated Regulation (EU) 2023/1669 of 16 June 2023 supplementing Regulation (EU) 2017/1369 of the European Parliament and of the Council with regard to the energy labelling of smartphones and slate tablets. https://eur-lex.europa.eu/eli/reg_del/2023/1669/oj/eng

European Commission. (2023b). Directive (EU) 2020/1828 of the European Parliament and the Council, on general product safety, amending Regulation (EU) No 1025/2012 of the European Parliament and of the Council and Directive (EU) 2020/1828 of the European Parliament and the Council, and repealing Directive 2001/95/EC of the European Parliament and of the Council and Council Directive 87/357/EEC.

European Commission. (2024a). Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828. http://data.europa.eu/eli/dir/2024/825/oj

European Commission. (2024b). Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401781

Ingemarsdotter, E., Stolk, M., & Balkenende, R. (2021). Design for Safe Repair in a Circular Economy. https://minienw.sitearchief.nl/?subsite=safebydesign#archive

Lee, T., & Wakefield-Rann, R. (2021). Conspicuous and inconspicuous repair: A framework for situating repair in relation to consumer practices and design research. Journal of Cleaner Production, 294, 126310. https://doi.org/10.1016/J.JCLEPRO.2021.126310

Ministères Aménagement du territoire Transition écologique. (2024). Indice de réparabilité. https://www.ecologie.gouv.fr/politiques-publiques/indice-reparabilite#information-and-documents-in-english-6

Parajuly, K., Green, J., Richter, J., Johnson, M., Rückschloss, J., Peeters, J., Kuehr, R., & Fitzpatrick, C. (2024). Product repair in a circular economy: Exploring public repair behavior from a systems perspective. Journal of Industrial Ecology, 28(1), 74–86. https://doi.org/10.1111/JIEC.13451

Pozo Arcos, B., Bakker, C., Flipsen, B., & Balkenende, R. (2020). Practices of fault diagnosis in household appliances: Insights for design. Journal of Cleaner Production, 265, 121812. https://doi.org/10.1016/J.JCLEPRO.2020.121812

Pozo Arcos, B., Dangal, S., Bakker, C., Faludi, J., & Balkenende, R. (2021). Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. Journal of Cleaner Production, 319, 128741. https://doi.org/10.1016/J.JCLEPRO.2021.128741

Right to Repair Europe. (2021). New Ecodesign regulations: 5 reasons Europe still doesn't have the Right to Repair. https://repair.eu/news/new-ecodesign-regulations-5-reasons-europe-still-doesnt-have-the-right-to-repair/

Right to Repair Europe. (2024a). Feedback on the Discussion Paper on Product Safety in the Circular Economy.

Right to Repair Europe. (2024b). The Current State of Right to Repair in the EU. https://repair.eu/resources/

Sandez, S., Pérez-Belis, V., Juan, P., & Bovea, M. D. (2023). Do users have the ability to self-repair non-complex electrical appliances? Design and development of a self-guided workshop with repair documentation in different formats. Sustainable Production and Consumption, 39, 244–256. https://doi.org/10.1016/J.SPC.2023.05.007

Spiliotopoulos, C., Alfieri, F., La Placa, M. G., Bracquene, E., Laps, E., Van Moeseke, T., Duflou, J., Dangal, S., Bolanos Arriola, J., Flipsen, B., Faludi, J., & Balkenende, R. (2022). Product Reparability Scoring System: specific application to Smartphones and Slate Tablets. Publications Office of the European Union. https://doi.org/doi:10.2760/340944

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. Journal of Cleaner Production, 288, 125488. https://doi.org/10.1016/J.JCLEPRO.2020.125488

van Oudheusden, A., Bolaños Arriola, J., Faludi, J., Flipsen, B., & Balkenende, R. (2023a). 3D Printing for Repair: An Approach for Enhancing Repair. Sustainability 2023, Vol. 15, Page 5168, 15(6), 5168. https://doi.org/10.3390/SU15065168

van Oudheusden, A., Buijserd, A., Doubrovski, Z., Flipsen, B., Faludi, J., & Balkenende, R. (2023b). Feasibility of On-demand Additive Manufacturing of Spare Parts. Product Lifetimes and the Environment (PLATE), 1129–1136.

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling, 135, 323–334. https://doi.org/10.1016/J.RESCONREC.2017.06.022



Chapter 3

Strategies for Dealing with Substances of Concern in Product Design
A review of five cases

This chapter was published as:

Bolaños Arriola, J., Aghaeian, S., Bakker, C., & Balkenende, R. (2024). Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases. Circular Economy and Sustainability, 1–20. https://doi.org/10.1007/S43615-024-00449-4/FIGURES/1

Abstract

Hazardous substances, or substances of concern (SoC), are present in numerous products and may be the source of significant risks to human health and the environment. In addition, the presence of SoC in products challenges the transition towards a circular economy. By implementing strategies such as reuse or recycling, SoC can be reintroduced in subsequent lifecycles, generating new forms of risk. Addressing SoC in the early stages of the product development process is necessary to mitigate the hazards and risks they may present throughout multiple lifecycles. Product designers hence need appropriate tools and methods to address SoC in products. However, we have observed that current research primarily focuses on the development of non-toxic chemical alternatives and approaches that mitigate the risks of SoC at a chemical and material level (i.e., substitution), lacking the necessary holistic approach to avoid trade-offs or unforeseen consequences. Available design specific methods, tools, and information to address SoC in products are extremely limited and have too a material focus. To address this, we investigated five cases to understand how SoC were dealt with across the product lifecycle and identify mitigation interventions used. We then analysed the interventions and classified them into five levels of influence, i.e., chemical, material, component, product, and system, and evaluated their respective implications for design, advantages, and drawbacks. Our analysis results in three groups of mitigation strategies that are specifically relevant to product design: Avoid, which entails any modification to the product that eliminates the SoC, Control, in which the SoC remains in use, but its emissions are prevented, and Reduce, which includes any modification that results in the reduction of the volume of the SoC or its emissions. Our findings establish the potential contribution of designers in the mitigation SoC in products and constitute a basis for the development of methods or guidelines to address SoC from a product design perspective.

3.1. Introduction

Hazardous substances, or substances of concern (SoC), are present in numerous products and may be the source of significant risks to human health and the environment. The presence of SoC in products also challenges the transition towards a circular economy (CE). By implementing strategies such as reuse or recycling, SoC can be reintroduced in subsequent lifecycles, generating new forms of risk. To fit the circular economy, products should not cause harm to human health or to the environment throughout their lifecycle, or subsequent lifecycles. This will require that consumer products are designed to be safely reused, repaired, refurbished, recycled, or reintroduced into nature, which is reflected in European legislation, about the transition to a clean circular economy (European Commission, 2019c, 2020a).

Examples of SoC in products include additives, such as phthalate-based plasticizers used in flexible plastic products (Bialecka-Florjańczyk & Florjańczyk, 2007; Luís et al., 2021), PFAS, used for their water and oil repellent properties in food packaging and textiles (Holmquist et al., 2016; Schaider et al., 2017), or lead, used in metal alloys and solder for electronics (Ogunseitan & Schoenung, 2012; Singh et al., 2019). The risks posed by SoC are increasingly worrying. In 2022, Europe produced 285 tons of chemicals of which over 60% were found to be hazardous to either the environment or health (Eurostat, 2022). Of the total number of chemicals put in the market, only a few have been well characterized for their hazards, and only a fraction of these is currently regulated to avoid or reduce their presence in specific applications, with many remaining in use (European Environment Agency, 2020b). Health hazards of SoC can include acute toxicity, carcinogenicity, mutagenicity, and reproductive toxicity, among others (United Nations, 2011). Additionally, SoC may have different effects on the environment depending on their characteristics, they may cause acute or chronic toxicity in environments and organisms, they may be persistent, bioaccumulative, and/or mobile (United Nations, 2011). Furthermore, Persson et al. (2022) recently stated that humanity has surpassed the safe operating space of the planetary boundary of novel entities and has a lower capacity to assess and monitor substances.

Substances are currently classified as hazardous based on known hazard types and severity, in accordance with the globally acknowledged hazard classification and labelling system for chemical substances and mixtures (United Nations, 2011). This classification is however solely based on known and reported effects, not considering substances that are in use but have not yet been identified as hazardous, or pollutants generated by products throughout their lifecycle (e.g., microplastics). In this research, we follow a broader classification based on the definition of the planetary boundary for chemical pollution (now known as novel entities proposed by Rockström et al. (Rockström et al., 2009; Steffen et al., 2015) “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". Such a definition is suitable from a CE perspective as it allows for the inclusion of a larger array of compounds of human origin (e.g., plastics), that not only account for substances that are present in the product, but also considers those used during production or generated during other stages of the lifecycle. Hence, our classification of SoC includes:

- SoC added to the composition of the product to achieve a permanent function, for instance additives such as phthalates that increase the flexibility of PVC products.
- SoC added during the production process to provide a temporary function, for instance textiles treated with formaldehyde during production to reduce creases.
- SoC generated by the product throughout Use or End of Life, for instance microplastics released from agricultural mulch films.

Microplastics are not usually considered 'SoC'. We included them here because of their ubiquitous presence in the environment (Bergmann et al., 2022; Muir et al., 2019; Sharma et al., 2021), and their ability to damage aquatic and terrestrial wildlife and cause respiratory problems and cardiovascular diseases in humans (Karbalaei et al., 2018).

The presence of SoC in products can usually be linked to a desired functionality or performance. In addition, the presence or absence of SoC in products can be linked to a number of trade-offs in relation to safety, sustainability, and performance. An example is the presence of flame retardants in upholstery products and other applications, where the potential benefits regarding fire safety need to be weighed against health and environmental risks due to the toxicity of the substance (Babrauskas et al., 2014). This indicates that to mitigate the risks of SoC in products while minimizing potential trade-offs, a holistic approach is required. Furthermore, SoC in products challenge the transition to the circular economy, not only due to the health and ecological risks they pose, but also for the limitations they put on circular strategies (Alaranta & Turunen, 2021; Barouta et al., 2022; Beekman et al., 2020; Bodar et al., 2018). The materials or components intended for reuse or recycling may contain hazardous substances that could impede their re-introduction or pose risks in new applications (Bodar et al., 2018; Leslie et al., 2016). Examples of this include contaminants deriving from recycled paper introduced in food packaging (Geueke et al., 2018; Vápenka et al., 2016), and toys containing contaminated recycled plastics derived from waste electrical and electronic equipment (WEEE) (Brandsma et al., 2022). Furthermore, legislations banning the use of these substances in new products has created barriers for recycling, increasing

the amount of incinerated plastic waste suspected to contain legacy hazardous substances (Fenwick et al., 2023; Wagner & Schlummer, 2020). In transitioning to a Circular Economy (CE), products must thus be designed either without substances of concern (SoC) or with measures in place to prevent exposure to their emissions throughout all stages of the product's life cycle.

We have observed that currently available research on how to deal with SoC in products is predominantly focused on the development of non-toxic chemicals and safe material alternatives (Bodar et al., 2018; Dumée, 2022; Keijer et al., 2019); from the chemical engineering, biotechnology, and nanomaterials perspective in particular, with approaches such as the Safe and Sustainable by Design framework (Caldeira et al., 2022; Mech et al., 2022; Sánchez Jiménez et al., 2022). Here, the presence of SoC in products is not explicitly dealt with from a product design perspective and no specific design guidelines, other than recommendations at a chemical or material level, are provided. Likewise, regulations regarding SoC in products also focus almost exclusively on interventions at a chemical and material level. The Circular Economy Action Plan requires, for example, the increase of recycled content in products while ensuring their performance and safety, and the development of methodologies that minimise the presence of hazardous substances in recycled materials (European Commission, 2020a). Meanwhile, the Ecodesign Directive indicates to refrain from using substances considered as hazardous, facilitate access to components containing hazardous substances (with a focus on recycling), restrict the presence of substances that inhibit circularity, and establish new information requirements that make it easier to track SoC, such as Digital Product Passports (European Commission, 2009a, 2022). Similarly, available literature and guidance for product designers regarding SoC, such as ecodesign and design for sustainability, provide recommendations at a material level, to identify if toxic materials are in use in a product, and to select "low impact" materials instead (Brezet & van Hemel, 1997; United Nations Environment Programme, 2009).

This "chemical" focus on dealing with SoC might limit the contribution of designers to material choices, which doesn't do justice to the integral nature of a product design process. Designers have the skills to adopt a broader approach, considering the lifecycle of the product, as well as relevant stakeholders and specific contextual aspects while meeting performance (functional) requirements. To the best of our knowledge, there is hardly any guidance that considers other than material focused strategies or provides a holistic approach to SoC, available for professional product designers to create safe products that have no negative effects on human and ecosystem health throughout their life cycle, including reuse and recycling. Our research objective is therefore to identify interventions used to mitigate the effects of SoC across the lifecycle of five example products containing SoC, as well as their implications for product design, their benefits, and their drawbacks. Through the

analysis of these cases, we aim to identify the contribution designers can offer in dealing with SoC in products and derive requirements for the future development of design methods and guidelines that enable designers to address SoC in products in a more systematic and comprehensive way. The research questions to address this research aim are: RQ 1. What kind of interventions have been used across the lifecycle of products to mitigate the risks posed by the SoC they contain? And RQ 2. What are the implications of these interventions in the discipline of product design?

In this paper we first present the process we followed to investigate the cases and analyse the mitigation interventions we identified. We then present the results obtained for the case of refrigerants in household refrigerators in detail (the rest of the cases can be consulted in Supplementary Information 3.1), and a table summarising all identified mitigation interventions. Finally, we discuss our results and their implications in design practice and design for the circular economy.

3.2. Methodology

In this section we first present our process and criteria for the selection of the cases. We then present the process we followed to perform the literature review to research each case of products containing SoC and identify mitigation interventions. Finally, we present the series of steps we took to analyse the identified mitigation interventions to understand and describe their implications to the discipline of product design.

3.2.1. Selection of cases

We investigated five cases of products containing SoC to understand how and why SoC were used in products and to identify mitigation interventions and their implications for product design. An original selection of eleven cases relevant to the European society was done during a study performed by the Dutch Ministry of Infrastructure and Water Management (Subramanian & Guinée, 2021). They considered the significance or impact of SoC by accounting the annual tonnage used in the EU and the type of hazard. We selected five cases out of the eleven based on the following criteria:

- Variety in type of products and applications/fields (electronics, textiles, etc.).
- Variety in the nature of the SoC, considering the above-mentioned classification of SoC.
- Relevance to the field of product design based on the variety of release mechanisms across the product lifecycle and thus potential for mitigation interventions beyond substitution of materials or chemicals.

Table 3.1 presents the selected five cases with background information about their regulatory status and function of the SoC in the product.

Table 3.1. Selected cases of products containing substances of concern

Case	Background – Current regulatory status	Specific rationale for selection
Case 1 - Household refrigerators containing refrigerant gases	Current common refrigerants (e.g., HFC 134a) are not banned but regulated by: Regulation (EU) (No 517/2014), on fluorinated greenhouse gases, (European Commission, 2014). Directive 2008/68/EC, on the inland transport of dangerous goods, (European Commission, 2008a). Regulation (EC) No 1272/2008, on classification, labelling and packaging of substances and mixtures (European Commission, 2008c).	The case is interesting for its long history of interventions, and because the use of refrigerants is heavily regulated.
Case 2 – Charging cables containing DEHP (Bis(2-ethylhexyl) phthalate) as plasticizer	Banned in the EU since 2021 by: Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (European Commission, 2018).	The case is interesting due to the ban of DEHP in products.
Case 3 – PVC flooring containing DEHP (Bis(2-ethylhexyl) phthalate) as plasticizer	Banned in the EU since 2021 by: Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (European Commission, 2018).	The case offers opportunities for comparison with Case 2 to observe interventions to mitigate the same SoC in 2 different applications.
Case 4 – Emission of microplastics from agricultural mulch films	Not currently banned or regulated.	Microplastics are emitted throughout the use and EoL of the product, allowing the observation of interventions in these stages.
Case 5 - Synthetic textiles, such as outdoor garments, containing PFAS for water and oil repellency	Several PFAS groups (e.g., PFOS, and PFOA) are restricted and regulated by: Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (European Commission, 2018). Regulation (EU) 2019/ 1021 on persistent organic pollutants (European Commission, 2019b). A number of PFAS remain unrestricted and not regulated.	The case is interesting due to discussions on the essentiality of PFAS and the ban on specific types, where alternatives can be observed.

3.2.2. Literature review of cases

We performed a literature review on each of the selected cases. The main databases used for the literature review were Google Scholar and Scopus, as well as the chemical databases ECHA's C&L inventory, SIN List, and Pub Chem. Additionally, the search engine Google was used to investigate relevant regulations. Considering only documents in English, we used a combination of Boolean functions "AND" and "OR" and keywords, including Hazards, Effects, Risk Assessment, Life Cycle Assessment, Emissions, Exposure, Regulation, Waste management, Production, Manufacturing, Function, Risk Management, Alternatives, Risk Management Strategies, Disadvantages, Name of the substance (i.e., DEHP, Bis(2-ethylhexyl) phthalate, HFC 134a, etc.), Name of the substance group (i.e., phthalates, PFAS, fluorinated gases, etc.), Name of product (i.e., charging cable, cable, PVC flooring, mulch film, etc.), and Product category (i.e., flooring products, electronics, agricultural plastics, cooling equipment, etc.).

We retrieved a total of 6,548 documents from this search. Through the screening of titles, abstracts, and scan reading, we eliminated irrelevant documents and duplicates. The remainder of 426 documents was considered for information regarding the human health and environmental effects of the product-substance combination, the emission and exposure scenarios of the product-substance combination, mitigation interventions applied to manage the effects of the SoC. In addition to the database search, we used a snowballing technique to identify relevant articles that may not have appeared in the initial search results by reviewing the reference lists of relevant articles.

After reviewing each SoC, to understand their nature, applications, regulatory status, and potential hazards to human health and the environment, we investigated each product-substance combination in more detail. The focus of this review was to understand the function of the substance in the product and establish the most concerning emission and exposure scenarios across the lifecycle, considering the emissions of the substance, exposure to the substance, the mechanisms through which the SoC is released (e.g., volatilization, leaching, migration), and the inputs that could aggravate the release mechanisms (e.g., UV light, chemicals, temperature). In our analysis, we considered the most concerning emission and exposure scenarios to be those that were specifically or repeatedly mentioned in literature or reports as having the greatest effects on human health and/or the environment. Finally, we investigated and listed the mitigation interventions used or proposed to address the SoC in the product.

3.2.3. Analysis of the interventions to deal with SoC in products

Using the results of the literature review, we identified mitigation interventions for each of the cases. We then analysed each intervention through the following steps:

- Identify potential benefits of the intervention. We collected literature that described: a) positive effects on the reduction of emissions, b) no perceived trade-offs related to performance, sustainability, or safety.
- Identify potential drawbacks or trade-offs of the intervention. We collected literature that described: a) limited or no effects on the reduction of emissions, b) perceived trade-offs related to performance, sustainability, or safety. If this information was not available, we noted the uncertainty of the potential negative effects of the intervention.
- Analyse and describe how the intervention impacted the design of the product. This analysis was based on own observations and discussions with design experts within our research group.
- Classify the intervention based on their effects at a chemical, material, component, product, or system level.
- Finally, an inductive analysis of the mitigation interventions to identify patterns was done, which resulted in the identification of three overall strategies.

3.3. Results

In this section, we first provide the results obtained for one of the cases: household refrigerators containing refrigerant gases. The other four cases were analysed in the same way and are presented in Supplementary Information 3.1. The results of all cases are then summarised and clustered, resulting in three major groups of mitigation strategies that can be followed by designers.

3.3.1. Case 1 - Dealing with refrigerant gases in household refrigerators

Refrigerant gases are used in household refrigerators as part of the cooling system and as a blowing agent for insulating foam. Prior to the enactment of the Montreal Protocol in 1987 (UN Environment, n.d.) and the regulations concerning substances that deplete the ozone layer (European Commission, 2009b), the most commonly used substances for refrigerants and blowing agents in cooling equipment were chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), recognized as ozone depleting substances (ODS) (Ardente et al., 2015; European Environment Agency, 2020a). Regulatory actions led to the replacement of these refrigerants with hydrofluorocarbons (HFCs), which, while not depleting the ozone layer, are greenhouse gases with a high global warming potential (GWP) (Ardente et al., 2015; European Environment Agency, 2020a). Among HFCs, HFC 134a (also known as 1,1,1,2-tetrafluoroethane), stands as the most used type (European Environment Agency, 2020a; Velders et al., 2015). When utilized within the cooling system, HFC 134a circulates through the components of the hermetically sealed refrigerating unit (Ardente et al., 2015; McCulloch, 2009). When used as a foaming agent, HFC 134a remains contained within the cells of the polyurethane foam that constitutes the insulation walls of the refrigerator (Ardente et al., 2015; McCulloch, 2009).

Despite being considered non-toxic and non-flammable under typical temperature and pressure conditions and posing no substantial human health risks under normal exposure conditions (except for overexposure) (Tsai, 2005; World Health Organization, 1998), its elevated GWP makes HFC 134a a significant contributor to radiative forcing and, consequently, climate change (Graziosi et al., 2017; Velders et al., 2015). For this reason, the identification, containment, use, transportation, recovery, and destruction of fluorinated gases are subject to regulation in Europe, (European Commission, 2008a, 2008c, 2014), as well as the waste management of cooling equipment (European Commission, 2012). Nonetheless, the literature we examined indicates that emissions of gases like HFC 134a still occur due to leaks in uncontrolled environments, during filling of hermetically sealed cooling units, insulation foam manufacturing, refrigerator use, repairs, and improper treatment and disposal (Ardente et al., 2015; Coste et al., 2020; Keri, 2019; Koronaki et al., 2012; McCulloch, 2009). HFC 134a is primarily released into the atmosphere, where it remains with an atmospheric lifetime of about 12 years (Harby, 2017). Emissions into wastewater and water bodies are expected to volatilize while accumulation in organisms or soil is not expected (World Health Organization, 1998). Exposure scenarios are normally of low or no concern (World Health Organization, 1998). In case of spillage, it is recommended to wear personal and respiratory protection (World Health Organization, 1998). Overexposure via inhalation can cause central nervous system depression and cardiac sensitization (Tsai, 2005).

The goal of this case was to examine the interventions that have been developed or were considered for managing refrigerant gases in domestic refrigerators at different levels (Table 3.2). For conciseness, we focused on identifying mitigation interventions related to currently prevalent refrigerants like HFC 134a and their associated risks. Table 3.2 shows the potential benefits and drawbacks for each of the identified interventions, as well as their implications for the design of the refrigerator and associated systems (e.g., recovery systems). The interventions are classified to observe their level of influence: Chemical refers to changes or substitution of additives or individual substances, Material refers to substitution of a material type or substantial changes in the composition of a material, Component refers to interventions that influence individual parts of the product, Product refers to interventions that influence the design, features, or functionality of an entire product, System addresses changes in the product's context.

Table 3.2. Identified mitigation interventions for dealing with refrigerant gases (HFC 134a) in household refrigerators. Levels of intervention are indicated as follows: ***Chemical, Material, Component, Product, System.***

Identified intervention	Potential benefits	Potential drawbacks	Implications for product design (authors' interpretation)
Substitution of HFC 134a as a refrigerant with inert gases, CO2, and hydrocarbons, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	- Decreased global warming potential and lower atmospheric lifetimes, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	- No substance fulfills all criteria: no Ozone Depleting Potential (ODP), low GWP, non-flammable, non-toxic, and highly energy-efficient, (European Commission, n.d.; Velders et al., 2015). - CO2's higher operating pressures make it unsuitable for household applications, (Vuppaladadiyam et al., 2022). - Some alternative refrigerants have a lower energy efficiency, potentially increasing indirect environmental impact, (Velders et al., 2015).	- The refrigerator and its cooling system need to be redesigned to address potential drawbacks or effects of substitution (e.g., flammability, performance, higher costs, higher operating pressures). - The product design needs to be adapted together with new recycling and manufacturing systems to account for the flammability of the new substance.
Substitution of HFC 134a as a blowing agent with HFOs, inert gases, and hydrocarbons, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	- Decreased global warming potential and lower atmospheric lifetimes, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	- Higher production costs and changes in the production methods, (Coste et al., 2020). - Risk of explosion and high flammability for the use phase and recycling processes, (Coste et al., 2020). - No substance fulfills all criteria: no Ozone Depleting Potential (ODP), low GWP, non-flammable, non-toxic, and highly energy-efficient, (European Commission, n.d.; Velders et al., 2015).	- The refrigerator and its insulation system need to be redesigned to address potential drawbacks or effects of substitution (e.g., higher costs, flammability). - The product design needs to be adapted together with new recycling and manufacturing systems to account for the flammability of the new substance.
Hermetic cooling units, (McCulloch, 2009).	- When functioning correctly, hermetic systems can entirely prevent refrigerant emissions from the cooling system, (McCulloch, 2009; McCulloch et al., 2006).	- Leakage may result from faulty or loose components, such as joints, (McCulloch, 2009). - Servicing the system, which may require puncturing for recharging or releasing refrigerant, can lead to leakage (McCulloch, 2009). - Damage during use or transportation is a potential source of leakage, (Keri, 2019; McCulloch, 2009).	- Hermetic systems require redesign to prevent emissions throughout the product's lifecycle, accounting for various processes and stakeholders (use, servicing, recycling, etc.).
Leakage detection systems, (Tassou & Grace, 2005).	- Prompt detection and warning can result in immediate response, (Tassou & Grace, 2005).	- Not currently applied to household refrigerators, only applied in professional refrigerating equipment, (Tassou & Grace, 2005).	- The design of the product needs to be adapted to allocate new components.

Table 3.2. *(Continued)*

Identified intervention	Potential benefits	Potential drawbacks	Implications for product design (authors' interpretation)
Controlled recovery, and collection of refrigerant gases, (European Commission, 2012).	- Refrigerants are collected to be recycled or destroyed, avoiding emissions of improper disposal, (Ardente et al., 2015; European Commission, 2012; Keri, 2019).	- Emissions resulting from the extraction process, due to puncture, faulty components, or operations, (Ardente et al., 2015; Koronaki et al., 2012; McCulloch, 2009). - Emissions resulting from the cooling system breakage during transportation or handling, (Keri, 2019).	- The product needs redesign associated with the development of new recycling systems and transportation protocols.
Collection of blowing agents at end-of-life, (Ardente et al., 2015; Keri, 2019).	- Blowing agents are collected during the shredding process in a controlled environment to then be recycled or destroyed, avoiding emissions of improper disposal, (Ardente et al., 2015; European Commission, 2012; Keri, 2019).	- The process can only be performed by specialized treatment plants due to explosion risk, (Ardente et al., 2015; European Commission, 2012; Keri, 2019).	- The product needs redesign associated with the development of new recycling and recovery systems.
Addition of a valve for extraction and recharge of refrigerants, (Ardente et al., 2015).	- The puncturing of the hermetic system is no longer necessary, avoiding leakage during servicing and recovery processes, (Ardente et al., 2015).	- The cooling system is hermetic by regulation, (European Commission, 2014). - The valve could increase risks of leakage during the use phase if users misuse it, (Ardente et al., 2015).	- The valve requires redesign considering the different processes and actors of each stage of the lifecycle of the refrigerator to prevent emissions or new risks.
Strengthening or protecting the components of the cooling system, (Ardente et al., 2015; Keri, 2019).	- Prevention of leakage caused by breakage during transportation and handling, (Ardente et al., 2015; Keri, 2019).	- No documented drawbacks were found for this intervention.	- The refrigerator might need redesign to counteract potential drawbacks (e.g., increased costs, reduced disassemblability).
Reducing the volume of refrigerant gas in the cooling system, (Ardente et al., 2015).	- Lower refrigerant emissions, (Ardente et al., 2015; McCulloch, 2009).	- Reduction is constrained since the refrigerant volume influences the energy efficiency of the appliance, (Ardente et al., 2015). - Reduced energy efficiency could lead to an increased indirect environmental impact, (Velders et al., 2015).	- The refrigerator and its cooling system need redesign to avoid loss of performance.

3.3.2. Summary of identified interventions in the five cases

Table 3.3 shows a summary of all identified interventions in the five different cases, classified into their effects on a chemical, material, component, product, and system level. We performed an inductive analysis of the interventions to identify patterns. We observed that interventions could be classified into two groups, those that focused on eliminating the SoC, and those that maintained the SoC in use but focused on managing their effects. Furthermore, when the SoC remains in use, we found two visible differences on the effects (benefits) of the interventions, with some aiming to prevent emissions altogether, and others only focused on reducing emissions of the SoC in a particular stage. From this analysis we then identified three main strategy groups relevant to product design: Avoid, Control, and Reduce, which we describe further in Table 3.4. These strategy groups are also used as ordering principle in Table 3.3.

Table 3.3. Summary of identified mitigation interventions in all five cases classified into strategy groups according to the authors' interpretation. The levels of intervention are indicated as follows: *Chemical*, *Material*, *Component*, *Product*, *System*.

Case/ Strategy group	Avoid. Any action that eliminated the SoC from the product or avoided its use.	Control. Any action that prevented exposure and emissions of the SoC.	Reduce. Any action that reduced the volume of the SoC in the product or reduced exposure or emissions of the SoC.
1) Household refrigerators containing refrigerant gases	· Substitution of HFC 134a as a refrigerant with inert gases, CO2, and hydrocarbons, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	· Hermetic cooling units, (McCulloch, 2009).	· Reducing the volume of refrigerant gas in the cooling system, (Ardente et al., 2015).
	· Substitution of HFC 134a as a blowing agent with HFOs, inert gases, and hydrocarbons, (Coste et al., 2020; Vuppaladadiyam et al., 2022).	· Leakage detection systems, (Tassou & Grace, 2005).	
		· Addition of a valve for extraction and recharge of refrigerants, (Ardente et al., 2015).	
		· Strengthening or protecting the components of the cooling system, (Ardente et al., 2015; Keri, 2019).	
		· Infrastructure for controlled recovery, and collection of refrigerant gases, (European Commission, 2012).	
		· Infrastructure for the collection of blowing agents, (Ardente et al., 2015; Keri, 2019).	
2) Charging cables containing DEHP (Bis(2-ethylhexyl) phthalate)	· Substitution of DEHP by another phthalate-based plasticizer (e.g., DINP and DIDP), (Brutus et al., 2013).	· Infrastructure for controlled recovery (European Commission, 2012).	· Increasing the useful life of cables through repair and durable design, to reduce accumulation at EoL (European Commission, 2019).

Table 3.3. *(Continued)*

Case/ Strategy group	Avoid. Any action that eliminated the SoC from the product or avoided its use.	Control. Any action that prevented exposure and emissions of the SoC.	Reduce. Any action that reduced the volume of the SoC in the product or reduced exposure or emissions of the SoC.
	· Substitution of DEHP by a non- phthalate-based plasticizer (e.g., DEHT, Dioctyl Adipate, biobased alternatives), (Brutus et al., 2013).		
	· Substitution of the cable material (e.g., PE, PP, PUR, PS, rubber), (Danish Environmental Protection Agency, 1996).		
3) PVC flooring containing DEHP (Bis(2-ethylhexyl) phthalate)	· Substitution of DEHP by another phthalate-based plasticizer (e.g., DINP and DIDP), (Brutus et al., 2013).	· Preventing emissions with layered materials, (Jeon et al., 2016; Kashyap & Agarwal, 2018).	· Increasing the useful life of flooring products by supporting product selection based on user requirements (level of comfort, acoustic properties, etc.), preventing early disposal and reducing accumulation at EoL, (Günther & Langowski, 1997).
	· Substitution of DEHP by a non- phthalate-based plasticizer, (e.g., DINCH), (Grossman, 2008; Tarkett, n.d.-a, n.d.-b).	· Infrastructure for controlled recovery for controlled landfill and incineration of flooring waste, (Miliute-Plepiene et al., 2021).	· Inform the user to reduce emissions and exposure: Improving indoor air quality, (Bialecka-Florjańczyk & Florjańczyk, 2007; European Commission, 2008b; Kashyap & Agarwal, 2018). E.g., avoiding high temperatures and humid environments near PVC flooring, and cleaning contaminated dust, (Clausen et al., 2011; Jeon et al., 2016; Kashyap & Agarwal, 2018).
	· Substitution of the material (e.g., PE, PP, PUR, PS, rubber), (Danish Environmental Protection Agency, 1996).	· Infrastructure for recovery and recycling, (Günther & Langowski, 1997; Miliute-Plepiene et al., 2021).	· Increasing the useful life of flooring products through maintenance and repair, to reduce accumulation at EoL, (Günther & Langowski, 1997).

Table 3.3. *(Continued)*

Case/ Strategy group	Avoid. Any action that eliminated the SoC from the product or avoided its use.	Control. Any action that prevented exposure and emissions of the SoC.	Reduce. Any action that reduced the volume of the SoC in the product or reduced exposure or emissions of the SoC.
4) Emission of microplastics from agricultural mulch films	· Substitution of LDPE films for photodegradable and biodegradable materials, (Kasirajan & Ngouajio, 2012; Shah & Wu, 2020).	· Automated mulch recovery systems, (Huang et al., 2020; Meng et al., 2020; Shah & Wu, 2020).	· Reduce mechanical degradation through reduced use of machinery or increase of film thickness, (Meng et al., 2020).
	· Substitution of LDPE films for paper mulch, (Shah & Wu, 2020).	· Infrastructure for recovery and recycling of used agricultural mulch films, (Madrid et al., 2022; Sorema, n.d.).	
	· Substitution of material for biobased alternatives (e.g., straw, woodchips, living mulches), (Hoidal, 2021).		
5) Synthetic textiles, such as outdoor garments, containing PFAS	· Substitution of long carbon chain PFAS with those with shorter carbon chains, (Whiting et al., 2020).	· No control interventions for PFAS were found.	· Increasing the useful life of textile products through repair, reuse, and recycling, to reduce accumulation at EoL, (Ellen MacArthur Foundation, 2017; Patagonia, n.d.-b, n.d.-a).
	· Substitution of PFAS with non-fluorinated substances or materials (e.g., polyurethanes, dendrimers, silicones, hydrocarbons, and paraffin), (Hill et al., 2017).		· Reduce PFAS emissions from washing by providing washing instructions to users, (Whiting et al., 2020).
	· Delivering waterproof function with non-chemical techniques (e.g., weaving and fiber control), (Park et al., 2015; Whiting et al., 2020).		
	· Phasing out PFAS by re-evaluating functional requirements, (Cousins et al., 2019; NRDC, 2021; Schellenberger et al., 2019).		

Table 3.3 shows each of the cases has interventions at different levels. On the vertical axis, we find that most interventions clustered under Avoid happen at a chemical or material level, with a couple of exemptions where the substance is dealt with at a product level by delivering a function with non-chemical techniques. Under Control we find all interventions found at a component level, focused on preventing leakage, and several system level interventions focused on controlled recovery. Under Reduce we find a single intervention at a chemical level, focused on reducing the overall volume of the substance, as well as several interventions at a product level to increase the useful lifetime through mechanisms such as maintenance, durability, and repair, to prevent the accumulation of the substance at EoL. System level interventions under Reduce focus on providing information to the user to minimize emissions in different stages of the lifecycle. Table 3.4 presents each of the identified strategy groups and describes its characteristics as observed from the cases.

Table 3.4. Definition of the identified strategy groups to deal with SoC in products (authors' interpretation)

Strategy groups	Definition and characteristics
Avoid	Any action or modification to the product that eliminates the SoC. Including any form of chemical/material substitution.
Control	Any action or modification to the product or the systems surrounding it that results in: 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.
Reduce	Any action or modification to the product or the systems surrounding it that results in: a) A significant reduction of the volume of the SoC in the product. b) A reduction of emissions of the SoC in any stage of the lifecycle. c) A reduction of exposure of the SoC in any stage of the lifecycle.

Figure 3.1 presents the strategy groups in a hierarchy that prioritizes Avoid over Control and Reduce, and examples for each of the strategy types.

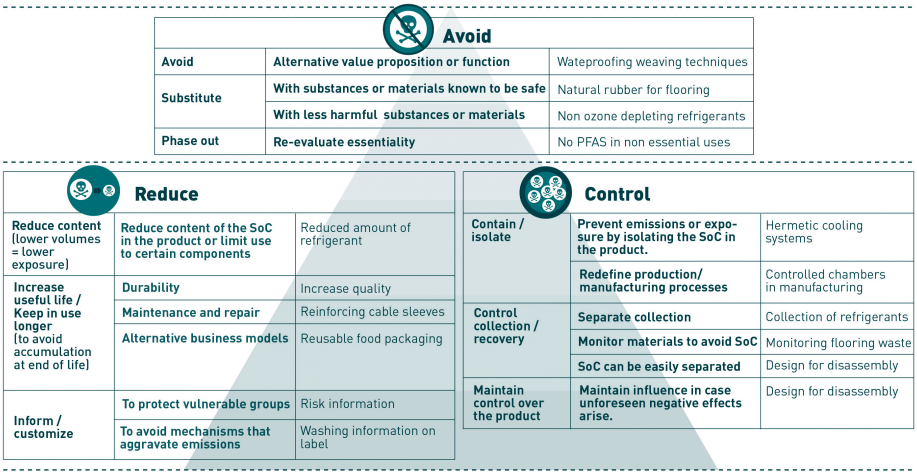


Figure 3.1. Hierarchy and examples of the identified strategy groups to deal with SoC in products (authors' interpretation)

3.4. Discussion

In this section we first discuss observed characteristics, advantages and disadvantages of the strategy groups we identified (Avoid, Control, and Reduce). We then compare our findings with existing literature and approaches to deal with SoC. Furthermore, we discuss observed challenges of dealing with SoC and their potential relation to the field of design. Finally, we provide recommendations for future research, focusing on the development of methods to deal with SoC in products that are targeted at designers.

3.4.1. Potential contribution of design compared to a material/chemical approach

The inventory of interventions shows that SoC in products can not only be addressed at a chemical or material level, but also at a component, product, and system level. However, we observed that available research and guidelines to deal with SoC are mainly focused at the chemical and material levels. We have identified mitigation interventions that often have implicit consequences on product design, and from our analysis derived three main strategies with the goal of supporting designers in making intentional design decisions at a material, product, and context level to mitigate SoC in products.

We described Avoid strategies as any action or modification to the product that removes the SoC. Avoid strategies have a hazard approach, which focuses on the elimination of harmful substances rather than dealing with potential risks caused by the substances in later stages. Substitution was a recurrent intervention, for

instance the substitution of the SoC with safer or safe substances, or the use of alternative materials that don't contain SoC. Substitution could however lead to drawbacks, such as new health risks and environmental impacts, or trade-offs such as loss of performance and increased costs. An example was the case of DEHP in cables, where the alternative materials (non-phthalate-based plasticizers like PE and PP) led to reduced cable durability. The increased flammability of substitute refrigerants with lower GWP was another example. In both examples, substitution with alternative materials or substances impacted the design of the products. Although these interventions occur at a chemical or material level, we can observe the potential contribution of designers in facilitating their implementation through interventions at a product level. However, it is important to note that substitution is not always a viable solution, for some SoC no safe alternatives have been yet identified, which requires addressing it through interventions other than at a chemical or material level. A second Avoid approach was the elimination of the SoC by delivering the function of the product in a different way, or by eliminating non-essential applications. In the case of PFAS in synthetic textiles, we observed the development of a new weaving technique to generate waterproof fabrics without the use of chemicals (Park et al., 2015; Whiting et al., 2020). This solution, however, also came with trade-offs such as stiff fabrics, that will need to be addressed in the design of the product. Avoid strategies suggest that designers can deal with SoC at a product and/or system level by delivering alternative value propositions.

Control strategies include any modification to the product, or its related systems, that prevents exposure to the SoC or prevents its emissions. Control strategies have the potential to prevent emissions and exposure when a SoC remains in use (because it is deemed essential for a certain application or no substitutes are available), or when substitute substances cannot be deemed safe. To eliminate risks completely, Control strategies should prevent any form of leakage throughout the entire product lifecycle. The case of refrigerants, for example, required the redesign of both the fridge (hermetic systems, extraction valves, etc.) and its recycling system (controlled recovery and extraction of the refrigerant). And in the case of PVC flooring, use-phase emissions of DEHP were controlled by an additional layer of an alternative material over the plasticized PVC layer. Control strategies were most often associated with end-of-life drawbacks. For instance, the presence of SoC in materials often limited their recyclability, because of the risk of reintroducing contaminants into the value chain. From the results we can observe Control strategies are very visibly linked to component and system level interventions, which from a design perspective will require knowledge of the specific context of use and EoL.

Under the category of Reduce, we classified interventions that decreased the overall volume of the SoC in the product, and those that lowered SoC emissions or exposure at various stages of the lifecycle. Although Reduce strategies contributed to re-

ducing the effects of SoC in specific stages of the lifecycle, making a product safer, they usually didn't eliminate all risks for the product to be deemed safe. Approaches at a product level to extend the useful life were common under this category, due to their potential systemic effects of reducing the accumulation of SoC during EoL. For example, increasing the useful life of textiles containing PFAS through (design for) repair, or preventing early replacement of PVC floor tiles. However, keeping products containing SoC in use for longer had the potential trade-off of aggravating emissions or prolonging exposure during the use phase. For example, prolonging the life of textiles containing PFAS, could increase emissions from laundering and potential replenishing of the waterproof treatment. However, we also found system level interventions under Reduce focused on the provision of information to users to minimize emissions during the use phase. An additional Reduce approach was the reduction of the overall volume of a SoC in a product. This strategy may require design modifications to counter associated performance reduction. We observed this in the case of refrigerators, where reducing the volume of the refrigerant gas had a direct effect on the performance of the product.

3.4.2. Comparison of strategy groups to existing chemical approaches

We identified Avoid, Control, and Reduce as strategies to manage SoC in products from the analysis of the cases. The Chemicals Strategy for Sustainability of the European Commission (European Commission, 2020b) proposes a framework, the Toxic-free hierarchy for chemicals management, which prioritizes interventions that eliminate SoC (i.e., use of safe and sustainable chemicals) over those that address risks, focusing on preventive measures over reactive ones (i.e., minimizing exposure, providing full information on chemicals, eliminating SoC from waste, and remediation). Similar approaches are proposed in the Inherently Safer Design Approach for chemical process safety (Hendershot, 2012), and the Twelve principles of Green Chemistry and Green Engineering (Anastas & Warner, 1998; Anastas & Zimmerman, 2003). We consider a similar recommendation should be given to designers; prioritizing Avoid strategies over Reduce or Control. These approaches, however, have a chemical focus, while our strategies also consider interventions at a product and component level, as well as behaviour around the product and infrastructure (System level).

Dealing with SoC in design was challenging and had, at times, far-ranging consequences. The main learnings from the cases were the following:

3.4.3. Combination of mitigation strategies

In the cases we reviewed, interventions were regularly combined at different levels (chemical, material, component, product, context). The case of refrigerants, for instance, showed a combination of Avoid, Control, and Reduce strategies, where ozone-depleting refrigerants were substituted by less hazardous substances, in

a smaller volume, the product was designed to prevent leakage, and systems throughout the lifecycle of the product were designed to control emissions during production, transportation, and EoL. Combining strategies seems most effective when the SoC is substituted by a safer (but not safe) alternative, or when the safety of the alternative substance remains inconclusive. In this way, Control and Reduce strategies can generate additional safety barriers. This requires an understanding of the context and stakeholders surrounding the specific application of SoC, which is within the boundaries of design practice.

3.4.4. Dealing with trade-offs

All identified interventions presented drawbacks and/or trade-offs; these included the generation of new environmental or health risks, changes in product performance, or increased product costs. An example in the cases was the substitution of DEHP for DINP, a substance with a similar risk profile. Another example is the resulting increase in costs, necessary changes in manufacturing processes, and energy intensive processing, from the substitution of PVC plasticized with DEHP for materials that do not require plasticizers to be flexible, such as PUR, or rubber in flooring products. The prediction of these unintended (negative) side-effects is very difficult. When developing solutions for dealing with SoC, it is important to consider a holistic approach that considers the full product lifecycle, the product's functional requirements, its context, and the relevant users and stakeholders. Designers typically count with the skills to acquire such an integrated approach, which can increase the chance that potential drawbacks, trade-offs, and unintended side-effects are identified in the early stages of the design process, when changes are still relatively easy and cost-effective. Designers can contribute to dealing with trade-offs in performance, sustainability, and safety at a material, component, product, and system level.

3.4.5. Dealing with SoC in a circular economy

Professional designers should consider the potential fate of products, components, and materials as they design for reuse, refurbishing, remanufacturing, and recycling. Designing for subsequent lifecycles is challenging, at a material/chemical level, the selection of non-toxic alternatives (which is the existing recommendation) should be prioritized. However, safe substitution is not always possible or known. Uncertainty about the safety of a chemical or material is never recommended, especially if the materials (or components) will be entering new loops. When the safety of a material is uncertain, for example, when using recycled materials, Control strategies could be implemented to mitigate potential risks. Furthermore, we should increase efforts to improve the availability and transparency of information on material composition throughout the lifecycles of products, for example, through digital product passports.

3.4.6. Impact on the design process and need for expertise

The implications for design of dealing with SoC could vary from negligible to substantial. Substituting one chemical for another with identical properties has hardly any impact on the design of the product. But when considering how to deliver the same functional value without using the SoC (e.g., delivering waterproof properties with new weaving techniques; or using wireless charging to avoid the use of cables), the implications could be considerable, requiring fundamental design innovations at different levels (material, component, product, context). Such design innovations may take time but can lead to socially and economically preferred outcomes. Furthermore, the mitigation of SoC in products can theoretically also be done through an incremental approach. Control and Reduce strategies could be applied when a SoC remains in use, while a combination of strategies can be suitable when the safety of a "new" substance is uncertain.

Designers, engineers, and R&D staff don't usually have the necessary expertise to make adequate judgements on the toxicological and regulatory status of substances of concern, and potential replacements. Working with experts that can provide the necessary information in a digestible format is vital. This is particularly important considering the potential levels of uncertainty and lack of information when dealing with complex products. Collaboration with stakeholders throughout the supply chain is recommended. Nevertheless, such experts are not always available to practicing designers and engineers, which is why developing a method or a set of guidelines for dealing with SoC might be helpful, to raise awareness and give initial guidance to design practitioners.

For the future development of a design method or guidelines, we recommend considering the following aspects and topics for future research:

- A structured analysis considering all the stages of the product lifecycle when assessing the effects of SoC to identify relevant action points and provide effective strategies.
- Guidance to identify promising mitigation strategies according to identified action points.
- An assessment of the proposed solutions to measure their effectiveness and prevent unintended consequences. This study mentioned drawbacks and benefits qualitatively, based on existing literature. Quantitative methods such as Life Cycle Assessment and Risk Assessment could help give a better idea of the risks and unintended consequences of alternative solutions.
- Guidance to address trade-offs and drawbacks, considering new forms of environmental impact, increased costs, performance losses, and new risks, amongst others.

- Further explore the effects of the combination of strategy groups and strategies at different levels (material, product, system, etc.) to deal with trade-offs.
- Guidance to address uncertainty and possible limitations and fluctuations in data availability.
- Further investigation of the proposed strategy groups to understand if they sufficiently cover the possible interventions towards SoC from a design perspective and develop comprehensive guidance on how to apply them.

The investigation of the cases was limited to the available information in the literature. In some instances, generic information about a substance, or group of substances, was used to build the case when information on the specific substance or product-substance combination was not available. For instance, considering PFAS as a cluster and not as a specific substance. Information availability was not only limited in relation to known hazards or risks of substances, but also regarding material compositions, the behavior of SoC throughout the lifecycle of products, and the potential effects of identified alternatives. This challenge will be similar for product designers dealing with SoC, which calls for an active learning approach, as well as an anticipatory, preventive approach to known and potential SoC.

3.5. Conclusion

Dealing with SoC in products as part of a CE is a complex task, that requires a systemic approach. Designers have the skills to follow such an approach, considering the subsequent lifecycles of the product, relevant stakeholders, and specific contextual aspects, while meeting performance (functional) requirements. This could potentially minimize rebounds and trade-offs and maximize safety. However, current approaches and guidelines to deal with SoC have a chemical/material focus and no guidelines are available specifically for product designers to address SoC at other levels, often limiting their contribution to material selection. In this study we investigated five cases of products containing SoC to understand how the substance behaved across their lifecycle and to identify mitigation interventions used to deal with the associated risks. We classified the identified interventions into five levels of influence, i.e., chemical, material, component, product, and system, and evaluated their respective implications for design, advantages, and drawbacks. The inventory of interventions shows that SoC in products are not only addressed at a chemical or material level, but also at a component, product, and system level. Our analysis on this inventory of interventions resulted in three groups of mitigation strategies that are specifically relevant to product design: Avoid, Control, and Reduce. These strategies serve as a foundation for the future development of methods and tools that support designers in making intentional design decisions at all levels and address SoC in products in a more systematic and comprehensive way.

3.6. Appendices

Supplementary Information 3.1- This document presents the investigation of Cases 2-5. This appendix is available in: https://data.4tu.nl/datasets/f8ee9ffd-c7cb-4287-8693-399ff93c802c



3.7. References

Alaranta, J., & Turunen, T. (2021). How to Reach a Safe Circular Economy?—Perspectives on Reconciling the Waste, Product and Chemicals Regulation. Journal of Environmental Law, 33(1), 113–136. https://doi.org/10.1093/JEL/EQAA016

Anastas, P. T., & Warner, J. C. (1998). Green Chemistry: Theory and Practice. Oxford University Press.

Anastas, P. T., & Zimmerman, J. B. (2003). Design Through the 12 Principles of Green Engineering. Environmental Science & Technology, 37(5), 94A-101A. https://doi.org/10.1021/ES032373G

Ardente, F., Calero Pastor, M., Mathieux, F., & Talens Peiró, L. (2015). Analysis of end-of-life treatments of commercial refrigerating appliances: Bridging product and waste policies. Resources, Conservation and Recycling, 101, 42–52. https://doi.org/10.1016/J.RESCONREC.2015.05.005

Babrauskas, V., Fuoco, R., & Blum, A. (2014). Flame Retardant Additives in Polymers: When do the Fire Safety Benefits Outweigh the Toxicity Risks? In Polymer Green Flame Retardants (pp. 87–118). Elsevier. https://doi.org/10.1016/B978-0-444-53808-6.00003-2

Barouta, D., Alassali, A., Picuno, C., Bruno, M., Syranidou, E., Fiore, S., & Kuchta, K. (2022). E-plastics in a circular economy: A comprehensive regulatory review. Journal of Cleaner Production, 355, 131711. https://doi.org/10.1016/J.JCLEPRO.2022.131711

Beekman, M., Bakker, J. B. C., van Leeuwen, L., Waaijers-van der Loop, S., Zijp, M., & Verhoeven, J. (2020). Coping with Substances of Concern in a Circular Economy.

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G. W., Provencher, J. F., Rochman, C. M., van Sebille, E., & Tekman, M. B. (2022). Plastic pollution in the Arctic. Nature Reviews Earth & Environment 2022 3:5, 3(5), 323–337. https://doi.org/10.1038/s43017-022-00279-8

Bialecka-Florjańczyk, E., & Florjańczyk, Z. (2007). Solubility of Plasticizers, Polymers and Environmental Pollution. Thermodynamics, Solubility and Environmental Issues, 397–408. https://doi.org/10.1016/B978-044452707-3/50024-0

Bodar, C., Spijker, J., Lijzen, J., Waaijers-van der Loop, S., Luit, R., Heugens, E., Janssen, M., Wassenaar, P., & Traas, T. (2018). Risk management of hazardous substances in a circular economy. Journal of Environmental Management, 212, 108–114. https://doi.org/10.1016/J.JENVMAN.2018.02.014

Brandsma, S. H., Leonards, P. E. G., Koekkoek, J. C., Samsonek, J., & Puype, F. (2022). Migration of hazardous contaminants from WEEE contaminated polymeric toy material by mouthing. Chemosphere, 294, 133774. https://doi.org/10.1016/J.CHEMOSPHERE.2022.133774

Brezet, H., & van Hemel, C. (1997). Ecodesign : a promising approach to sustainable production and consumption. United Nations Environment Programme, Industry and Environment, Cleaner Production.

Brutus, J., Calero, J., Corden, C., Esparrago, J., & Mackay, C. (2013). Analysis of alternatives for a group of phthalates (Issue December, p. 134). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.rivm.nl/sites/default/files/2018-11/Analysis%20of%20alternatives%20for%20a%20group%20of%20phthalates%20-%20AMEC%20final%20report.pdf

Caldeira, C., Farcal, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Ameli, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials. https://doi.org/10.2760/487955

Clausen, A., Liu, Z., Kofoed-Sørensen, V., Little, J., & Wolkoff, P. (2011). Influence of Temperature on the Emission of Di-(2-ethylhexyl)phthalate (DEHP) from PVC Flooring in the Emission Cell FLEC. https://doi.org/10.1021/es2035625

Coste, G., Negrell, C., & Caillol, S. (2020). From gas release to foam synthesis, the second breath of blowing agents. European Polymer Journal, 140, 110029. https://doi.org/10.1016/J.EURPOLYMJ.2020.110029

Cousins, I. T., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C. A., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z., & Dewitt, J. C. (2019). The concept of essential use for determining when uses of PFASs can be phased out. Environmental Science: Processes & Impacts, 21(11), 1803–1815. https://doi.org/10.1039/C9EM00163H

Danish Environmental Protection Agency. (1996). Optimization of PVC-free materials in cables,. https://www2.mst.dk/udgiv/Publications/1999/87-7909-561-5/html/helepubl_eng.htm#6.1

Dumée, L. F. (2022). Circular materials—An essay on challenges with current manufacturing and recycling strategies as well as on the potential of life cycle integrated designs. Circular Economy and Sustainability: Volume 2: Environmental Engineering, 359–372. https://doi.org/10.1016/B978-0-12-821664-4.00008-X

Ellen MacArthur Foundation. (2017). A new textiles economy: Redesigning fashion's future. https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future

European Commission. (n.d.). Climate-friendly alternatives to HFCs. Retrieved July 6, 2022, from https://ec.europa.eu/clima/eu-action/fluorinated-greenhouse-gases/climate-friendly-alternatives-hfcs_en

European Commission. (2008a). Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0068&from=EN#d1e32-59-1

European Commission. (2008b). Priority List European Union Risk Assessment Report bis(2-ethylhexyl)phthalate (DEHP). https://doi.org/10.2788/80862

European Commission. (2008c). 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. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R1272

European Commission. (2009a). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0125

European Commission. (2009b). Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009R1005

European Commission. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02012L0019-20180704&from=EN

European Commission. (2014). Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0517&rid=1

European Commission. (2018). Regulation (EC) No 1907/2006 Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). 219–219. https://doi.org/10.4324/9781315270326-156

European Commission. (2019a). Impact Assessment Study on Common Chargers of Portable Devices (Issue December). https://circabc.europa.eu/ui/group/43315f45-aaa7-44dc-9405-a86f639003fe/library/d0737bf2-7738-4073-9ba0-1eb681e893eb/details

European Commission. (2019b). Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32019R1021

European Commission. (2019c). The European Green Deal. https://doi.org/10.1017/CBO9781107415324.004

European Commission. (2020a). A new Circular Economy Action Plan For a Cleaner and More Competitive Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN

European Commission. (2020b). Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN

European Commission. (2022). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT On making sustainable products the norm. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0140&qid=1649112555090

European Environment Agency. (2020a). Fluorinated greenhouse gases 2020 (Issue 15). https://doi.org/10.2800/08599

European Environment Agency. (2020b). The European environment-state and outlook 2020. https://doi.org/10.2800/96749

Eurostat. (2022). Chemicals production and consumption statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Chemicals_production_and_consumption_statistics#Effective_changes_in_the_production_of_chemicals_hazardous_to_health

Fenwick, C., Mayers, K., Lee, J., & Murphy, R. (2023). Recycling plastics from e-waste: Implications for effective eco-design. Journal of Industrial Ecology, 27(5), 1370–1388. https://doi.org/10.1111/JIEC.13409

Geueke, B., Groh, K., & Muncke, J. (2018). Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. Journal of Cleaner Production, 193, 491–505. https://doi.org/10.1016/J.JCLEPRO.2018.05.005

Graziosi, F., Arduini, J., Furlani, F., Giostra, U., Cristofanelli, P., Fang, X., Hermanssen, O., Lunder, C., Maenhout, G., O'Doherty, S., Reimann, S., Schmidbauer, N., Vollmer, M. K., Young, D., & Maione, M. (2017). European emissions of the powerful greenhouse gases hydrofluorocarbons inferred from atmospheric measurements and their comparison with annual national reports to UNFCCC. Atmospheric Environment, 158, 85–97. https://doi.org/10.1016/J.ATMOSENV.2017.03.029

Grossman, R. F. (2008). Handbook of Vinyl Formulation . https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/reader.action?docID=469476&ppg=3

Günther, A., & Langowski, H.-C. (1997). LCA Case Studies - Life Cycle Assessment Study on Resilient Floor Coverings. The International Journal of Life Cycle Assessment.

Harby, K. (2017). Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: An updated overview. Renewable and Sustainable Energy Reviews, 73, 1247–1264. https://doi.org/10.1016/J.RSER.2017.02.039

Hendershot, D. C. (2012). Inherently Safer Design: The Fundamentals. Chemical Engineering Progress, 108(1), 40.

Hill, P. J., Taylor, M., Goswami, P., & Blackburn, R. S. (2017). Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance. Chemosphere, 181, 500–507. https://doi.org/10.1016/J.CHEMOSPHERE.2017.04.122

Hoidal, N. (2021). Exploring alternatives to plastic mulch. In University of Minnesota Extension 20. https://blog-fruit-vegetable-ipm.extension.umn.edu/2021/01/exploring-alternatives-to-plastic-mulch.html

Holmquist, H., Schellenberger, S., van der Veen, I., Peters, G. M., Leonards, P. E. G., & Cousins, I. T. (2016). Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing. Environment International, 91, 251–264. https://doi.org/10.1016/J.ENVINT.2016.02.035

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution, 260, 114096. https://doi.org/10.1016/J.ENVPOL.2020.114096

Jeon, S., Kim, K. T., & Choi, K. (2016). Migration of DEHP and DINP into dust from PVC flooring products at different surface temperature. Science of The Total Environment, 547, 441–446. https://doi.org/10.1016/J.SCITOTENV.2015.12.135

Karbalaei, S., Hanachi, P., Walker, T. R., & Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. Environmental Science and Pollution Research, 25(36), 36046–36063. https://doi.org/10.1007/S11356-018-3508-7/FIGURES/2

Kashyap, D., & Agarwal, T. (2018). Concentration and factors affecting the distribution of phthalates in the air and dust: A global scenario. Science of the Total Environment, 635, 817–827. https://doi.org/10.1016/j.scitotenv.2018.04.158

Kasirajan, S., & Ngouajio, M. (2012). Polyethylene and biodegradable mulches for agricultural applications: a review. Agronomy for Sustainable Development 2012 32:2, 32(2), 501–529. https://doi.org/10.1007/S13593-011-0068-3

Keijer, T., Bakker, V., & Slootweg, J. C. (2019). Circular chemistry to enable a circular economy. Nature Chemistry 2019 11:3, 11(3), 190–195. https://doi.org/10.1038/s41557-019-0226-9

Keri, C. (2019). Recycling cooling and freezing appliances. Waste Electrical and Electronic Equipment (WEEE) Handbook, 357–370. https://doi.org/10.1016/B978-0-08-102158-3.00013-6

Koronaki, I. P., Cowan, D., Maidment, G., Beerman, K., Schreurs, M., Kaar, K., Chaer, I., Gontarz, G., Christodoulaki, R. I., & Cazauran, X. (2012). Refrigerant emissions and leakage prevention across Europe – Results from the RealSkillsEurope project. Energy, 45(1), 71–80. https://doi.org/10.1016/J.ENERGY.2012.05.040

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., de Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy — weeding out the toxics first. Environment International, 94, 230–234. https://doi.org/10.1016/J.ENVINT.2016.05.012

Luís, C., Algarra, M., Câmara, J. S., & Perestrelo, R. (2021). Comprehensive insight from phthalates occurrence: from health outcomes to emerging analytical approaches. In Toxics (Vol. 9, Issue 7). https://doi.org/10.3390/toxics9070157

Madrid, B., Wortman, S., Hayes, D. G., DeBruyn, J. M., Miles, C., Flury, M., Marsh, T. L., Galinato, S. P., Englund, K., Agehara, S., & DeVetter, L. W. (2022). End-of-Life Management Options for Agricultural Mulch Films in the United States—A Review. Frontiers in Sustainable Food Systems, 0, 282. https://doi.org/10.3389/FSUFS.2022.921496

McCulloch, A. (2009). Evidence for improvements in containment of fluorinated hydrocarbons during use: an analysis of reported European emissions. Environmental Science & Policy, 12(2), 149–156. https://doi.org/10.1016/J.ENVSCI.2008.12.003

McCulloch, A., Midgley, P. M., & Lindley, A. A. (2006). Recent changes in the production and global atmospheric emissions of chlorodifluoromethane (HCFC-22). Atmospheric Environment, 40(5), 936–942. https://doi.org/10.1016/J.ATMOSENV.2005.10.015

Mech, A., Gottardo, S., Amenta, V., Amodio, A., Belz, S., Bøwadt, S., Drbohlavová, J., Farcal, L., Jantunen, P., Małyska, A., Rasmussen, K., Riego Sintes, J., & Rauscher, H. (2022). Safe- and sustainable-by-design: The case of Smart Nanomaterials. A perspective based on a European workshop. Regulatory Toxicology and Pharmacology, 128, 105093. https://doi.org/10.1016/J.YRTPH.2021.105093

Meng, F., Fan, T., Yang, X., Riksen, M., Xu, M., & Geissen, V. (2020). Effects of plastic mulching on the accumulation and distribution of macro and micro plastics in soils of two farming systems in Northwest China. PeerJ, 8. https://doi.org/10.7717/PEERJ.10375/SUPP-2

Miliute-Plepiene, J., Fråne, A., & Almasi, A. M. (2021). Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries. In Cleaner Engineering and Technology (Vol. 4, p. 100246). Elsevier. https://doi.org/10.1016/j.clet.2021.100246

Muir, D., Bossi, R., Carlsson, P., Evans, M., De Silva, A., Halsall, C., Rauert, C., Herzke, D., Hung, H., Letcher, R., Rigét, F., & Roos, A. (2019). Levels and trends of poly- and perfluoroalkyl substances in the Arctic environment – An update. Emerging Contaminants, 5, 240–271. https://doi.org/10.1016/J.EMCON.2019.06.002

NRDC. (2021). A review of PFAS as a chemical class in the textile sector.

Ogunseitan, O. A., & Schoenung, J. M. (2012). Human health and ecotoxicological considerations in materials selection for sustainable product development. MRS Bulletin, 37(4), 356–363. https://doi.org/10.1557/MRS.2012.8/TABLES/4

Park, S., Kim, J., & Park, C. H. (2015). Superhydrophobic textiles: Review of theoretical definitions, fabrication and functional evaluation. Journal of Engineered Fibers and Fabrics, 10(4). https://doi.org/10.1177/155892501501000401

Patagonia. (n.d.-a). Repairs - Patagonia. Retrieved August 23, 2022, from https://eu.patagonia.com/nl/en/repairs.html

Patagonia. (n.d.-b). Worn Wear - Used Patagonia Clothing & Gear. Retrieved August 18, 2022, from https://wornwear.patagonia.com/

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environmental Science and Technology, 56(3), 1510–1521. https://doi.org/10.1021/ACS.EST.1C04158/ASSET/IMAGES/LARGE/ES1C04158_0002.JPEG

Rockström, J., Steffen, W. L., Noone, K., Persson, Å., Stuart, F., Iii, C., Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C. A., Hughes, T., … Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Planetary Boundaries: Exploring the Safe Operating Space for Humanity Space for Humanity Citation Details Citation Details.

Sánchez Jiménez, A., Puelles, R., Perez-Fernandez, M., Barruetabeña, L., Jacobsen, N. R., Suarez-Merino, B., Micheletti, C., Manier, N., Salieri, B., Hischier, R., Tsekovska, R., Handzhiyski, Y., Bouillard, J., Oudart, Y., Galea, K. S., Kelly, S., Shandilya, N., Goede, H., Gomez-Cordon, J., … Llopis, I. R. (2022). Safe(r) by design guidelines for the nanotechnology industry. NanoImpact, 25, 100385. https://doi.org/10.1016/J.IMPACT.2022.100385

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., Lunderberg, D. M., Lang, J. R., & Peaslee, G. F. (2017). Fluorinated Compounds in U.S. Fast Food Packaging. Environ. Sci. Technol. Lett. https://doi.org/10.1021/acs.estlett.6b00435

Schellenberger, S., Hill, P. J., Levenstam, O., Gillgard, P., Cousins, I. T., Taylor, M., & Blackburn, R. S. (2019). Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. Journal of Cleaner Production, 217, 134–143. https://doi.org/10.1016/J.JCLEPRO.2019.01.160

Shah, F., & Wu, W. (2020). Use of plastic mulch in agriculture and strategies to mitigate the associated environmental concerns. Advances in Agronomy, 164, 231–287. https://doi.org/10.1016/BS.AGRON.2020.06.005

Sharma, S., Basu, S., Shetti, N. P., Nadagouda, M. N., & Aminabhavi, T. M. (2021). Microplastics in the environment: Occurrence, perils, and eradication. Chemical Engineering Journal, 408, 127317. https://doi.org/10.1016/J.CEJ.2020.127317

Singh, N., Duan, H., Ogunseitan, O. A., Li, J., & Tang, Y. (2019). Toxicity trends in E-Waste: A comparative analysis of metals in discarded mobile phones. Journal of Hazardous Materials, 380, 120898. https://doi.org/10.1016/J.JHAZMAT.2019.120898

Sorema. (n.d.). Agricultural film recycling. Retrieved July 10, 2022, from http://sorema.it/en_US/applications/plastic-film-recycling/agricultural-film-recycling/

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223). https://doi.org/10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF

Subramanian, V., & Guinée, J. B. (2021). Selection of product-chemical substance combinations for illustrating a variety of Safe by Design approaches. https://www.safe-by-design-nl.nl/documenten/onderzoek+documenten/default.aspx

Tarkett. (n.d.-a). Environmental product declaration. Retrieved June 12, 2022, from https://media.tarkett-image.com/docs/EPD_Premium_Plus.pdf

Tarkett. (n.d.-b). Material Health Declaration. Retrieved June 12, 2022, from https://media.tarkett-image.com/docs/MHS_Acczent.pdf

Tassou, S. A., & Grace, I. N. (2005). Fault diagnosis and refrigerant leak detection in vapour compression refrigeration systems. International Journal of Refrigeration, 28(5), 680–688. https://doi.org/10.1016/J.IJREFRIG.2004.12.007

Tsai, W. T. (2005). An overview of environmental hazards and exposure risk of hydrofluorocarbons (HFCs). Chemosphere, 61(11), 1539–1547. https://doi.org/10.1016/J.CHEMOSPHERE.2005.03.084

UN Environment. (n.d.). About Montreal Protocol. Retrieved June 23, 2022, from https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

United Nations. (2011). Globally harmonized system of classification and labelling of chemicals (GHS). United Nations.

United Nations Environment Programme. (2009). Design for Sustainability: A Step-by-Step Approach. United Nations Environment Programme (UNEP). https://wedocs.unep.org/xmlui/handle/20.500.11822/8742

Vápenka, L., Vavrouš, A., Votavová, L., Kejlová, K., Dobiáš, J., & Sosnovcová, J. (2016). Contaminants in the paper-based food packaging materials used in the Czech Republic. Journal of Food and Nutrition Research, 55(4), 361–373.

Velders, G. J. M., Fahey, D. W., Daniel, J. S., Andersen, S. O., & McFarland, M. (2015). Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmospheric Environment, 123, 200–209. https://doi.org/10.1016/J.ATMOSENV.2015.10.071

Vuppaladadiyam, A. K., Antunes, E., Vuppaladadiyam, S. S. V., Baig, Z. T., Subiantoro, A., Lei, G., Leu, S. Y., Sarmah, A. K., & Duan, H. (2022). Progress in the development and use of refrigerants and unintended environmental consequences. Science of The Total Environment, 823, 153670. https://doi.org/10.1016/J.SCITOTENV.2022.153670

Wagner, S., & Schlummer, M. (2020). Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. Resources, Conservation and Recycling, 158, 104800. https://doi.org/10.1016/J.RESCONREC.2020.104800

Whiting, R., Nicole, L., Keyte, I., Kreibig, J., Crookes, M., Gebbink, W., Potrykus, A., & Schopel, M. (2020). The use of PFAS and fluorine-free alternatives in textile, upholstery, carpets, leather and apparel. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote= World Health Organization, G. (1998). 1,1,1,2 Tetrafluoroethane - Concise International Chemical Assessment Document.

World Health Organization, (1998). 1,1,1,2 Tetrafluoroethane - Concise International Chemical Assessment Document.



Chapter 4

Safe and circular Design A design method for dealing with substances of concern in products

This chapter was published as:

Bolaños Arriola, J., Subramanian, V., Bakker, C., & Balkenende, R. (2023). Safe and Circular Design – A design method for dealing with substances of concern in products. In K. Niinimäki & K. Cura (Eds.), 5th PLATE Conference Proceedings 2023. https://kth.divaportal.org/smash/get/diva2:1795825/FULLTEXT01.pdf

Abstract

The transition to a circular economy (CE) is challenged by the presence of hazardous substances, also known as substances of concern (SoC), in products. SoC are used in various applications such as electronics, textiles, and toys, and can cause harmful effects on human health and the environment. The topic of SoC in products has been predominantly studied in the fields of chemical engineering and material sciences to develop alternative chemicals and materials. However, methods to safely deal with SoC from the product design perspective are currently limited. This paper aims to address this issue and presents a first version of a Safe and Circular by Design Method. This method supports designers when (re)developing products containing SoC by mitigating or managing the associated risks, resulting in products that last and are safe for the circular economy. The method is based on the results obtained in a previous study on five historical cases of product-substance combinations (IenW, 2022), which identified and classified design strategies to deal with SoC in products. The method involves guiding designers through a comprehensive analysis of the product-SoC combination and its context, considering all stages of the lifecycle(s). The results of the analysis help designers identify action points, informing their decision when selecting and developing mitigation strategies. The method also recommends a list of possible strategies to deal with the SoC. The selected strategies can be qualitatively assessed by the designer to identify their benefits, drawbacks, and trade-offs.

4.1. Introduction

Any product that potentially harms health or the environment throughout its lifecycle, including multiple use cycles and end-of-life treatments, does not meet the circular economy (CE) principles. To increase the useful life of products, it is imperative that they can be used and reused safely (Alaranta & Turunen, 2021; Bodar et al., 2018).

SoC are present in a variety of consumer products, often without designers and users being aware. Although some SoC are currently regulated to avoid or reduce their presence in specific applications, many others remain in use due to the characteristics or functionality they provide to products. A common example of SoC in products is the use of PFAS (per- and polyfluoroalkyl substances) in food packaging and textiles for their water and oil repellency properties (Holmquist et al., 2016; Schaider et al., 2017). PFAS are ubiquitous and persistent contaminants with a variety of exposure paths, which accumulate in body tissues of humans and animals causing long-term exposure (Krafft & Riess, 2015; OECD, 2013). Some of their known health effects include liver damage, reproductive damage, and thyroid disease (Dickman & Aga, 2022; OECD, 2013). Nevertheless, PFAS continue to be in use in many applications, where safer alternatives do not yet meet similar repellency requirements (Cousins et al., 2019; Hill et al., 2017; Schellenberger et al., 2019). Another example is the use of fluorinated gases as refrigerants and foam blowing agents in cooling equipment (Koronaki et al., 2012; Vuppaladadiyam et al., 2022). Although no significant human health risks are expected from exposure to these gases (except for accidental overexposure), some types of fluorinated gases have ozone depleting properties or may have a high global warming potential (Graziosi et al., 2017; Tsai, 2005; Velders et al., 2015; Vuppaladadiyam et al., 2022). These gases may be released into the environment throughout the lifecycle of refrigerators, generating concerning emissions during the use or during inappropriate treatment and disposal (Ardente et al., 2015; Keri, 2019; McCulloch, 2009).

An informed and better management of SoC in the early stages of the product development process can reduce the hazards and risks posed by SoC. However, awareness, information, and methods for designers to safely deal with SoC in products are currently limited. Our research found that scientific publications concerning safety in a circular economy and the use of SoC in products, predominantly focus on risk management and the development of non-toxic chemicals and material alternatives (E.g., Bodar et al., 2018; Dumée, 2022; Keijer et al., 2019); from the chemical engineering and nanomaterials perspective in particular (E.g., Mech et al., 2022; Sánchez Jiménez et al., 2022) . Other scientific publications center on risk assessment and other methods to measure and analyse the effects of exposure and emissions of SoC (E.g., Harder et al., 2015; Subramanian et al., 2023;

Undas et al., 2023). Furthermore, a large number of studies describe cases where SoC represent risks to health and the environment or limitations to the CE, such as: contaminants and plastic recycling (E.g., Brandsma et al., 2022; Leslie et al., 2016) or food packaging materials (E.g., Geueke et al., 2018), amongst others. To the best of our knowledge, no scientific studies address the presence of SoC in products from the product design perspective or provide guidelines for product designers. This paper aims to address this issue, describing the development of a method for designers to deal with SoC in products to mitigate or manage health and environmental risks and make them fit the CE. For this paper, we will be using the classification of SoC shown in Table 4.1.

Table 4.1. Classification of SoC in products, from (IenW, 2022).

A) SoC present in the product – intentionally added to their composition (e.g., additives such as phthalates in flexible PVC)
B) SoC unintentionally generated by the product – byproducts generated throughout the lifecycle (e.g., microplastics released from synthetic textiles)
C) SoC used or added temporarily to the material or product for additional functions but not intended to be present in the end product (e.g., formaldehyde added to textiles during manufacturing to reduce creases, which can remain if not washed before wear)

4.2. Method

The Safe and Circular Design method was developed based on a previous study (IenW, 2022), which identified design relevant strategies to deal with SoC in products from five historical cases, as well as approaches to deal with SoC from the industry and other fields, such as green chemistry. The five cases were analysed through a lifecycle approach, using literature research, Risk Assessment (RA), and Life Cycle Assessment (LCA). These steps were translated into a theoretical first version of a method. Table 4.2 shows the approach for each of the elements that constitute the Safe and Circular Design Method.

Table 4.2. Approach and development of the elements of the method.

Safe and Circular by Design Method elements	Approach
1. Analysis of the product-substance combination and emission-exposure scenarios.	The SoC were analysed through a literature review (including grey literature) to identify their hazards and characteristics and describe where in the lifecycle of the product emissions and exposure occur.
2. Prioritization of emission-exposure scenarios	A qualitative assessment based on the findings of the literature review was done to define emission-exposure scenarios of most concern. Screening RA was used to prioritize the scenarios whenever data was available.
3. Strategy selection – List of possible design strategies	Design relevant strategies were investigated for each case using literature review. The identified strategies were classified into three categories: **Avoid / Eliminate** - Any action that avoids the use of the SoC. **Reduce** – Any action that results in the reduction of the content of the SoC or a reduction of its emissions. **Control / Prevent** – Any action that prevents or controls exposure and emissions of the SoC.
4. Assessment of strategies	The identified strategies were qualitatively assessed by listing benefits, drawbacks, and potential trade-offs found in literature. Screening RA and LCA were used to assess the effects of the strategies if data was available.

4.3. Results

The Safe and Circular Design Method supports designers in dealing with SoC in products; its scope considers the mitigation of SoC through design solutions in the product, as well as related services, or systems. We recommend adopting an iterative approach, until a useful level of detail is obtained (e.g., a feasible strategy to eliminate the substance is identified, or a strategy to reduce emissions is proven effective). The results obtained from the method can be used to steer the development process and facilitate the communication of designers with experts and suppliers. The method is displayed in the form of fillable templates that guide designers through the process and facilitate the collection, analysis, and visualization of information (Figures 4.2 to 4.8). Additionally, the method suggests potential sources for the requested information on all the steps of the process. Figure 4.1 gives an overview of the steps of the method. First, the designer identifies and analyses SoC and their hazards (Step 1). The designer then identifies where in lifecycle of the product emissions and exposure occur, and which of these scenarios are most concerning (Step 2). The results of this analysis inform the designer's decision when selecting or generating strategies that mitigate the effects of the

SoC (Step 3). Finally, the designer assesses alternative strategies, guided by a set of recommendations to qualitatively measure their effects and performance (Step 4).

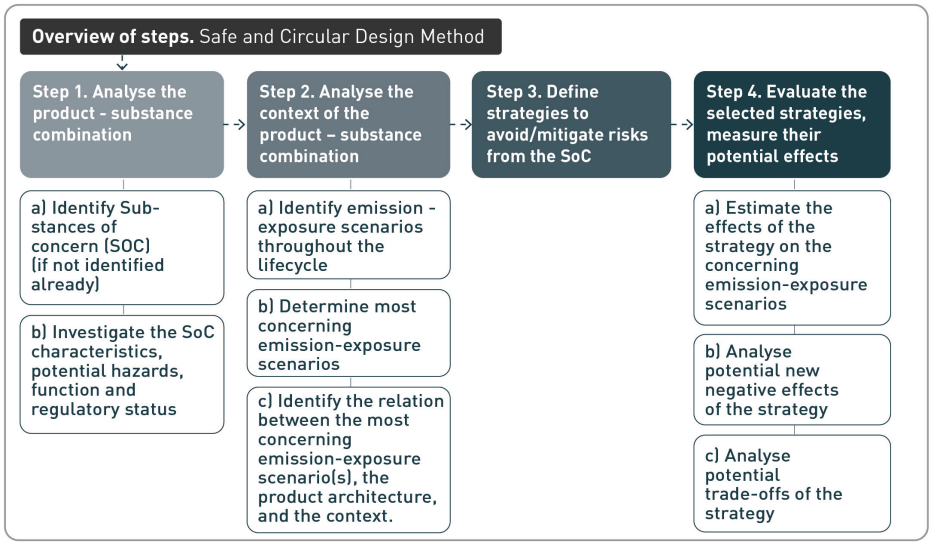


Figure 4.1. Overview of steps - Safe and Circular Design Method

Step 1 - Analysis of the product-substance combination

a) In cases where the presence of SoC in a product is unknown, the method provides guidance to the designer to identify them. Figure 4.2 shows the template for this step. The method considers the classification of SoC proposed in Table 4.1.

b) Once identified, the designer investigates the nature, characteristics, potential hazards, intended function, and regulatory status of each SoC. The method provides a set of questions the designer can follow in the investigation. Figure 4.3 shows the template for this step with example answers of a case, DEHP (a phthalate-based plasticizer) in vinyl flooring (for illustration purposes).

Step 1. Analyse the product - substance combination

Step 1a Identify SoC (if not identified already)

Analyse your product for each type of SoC following the recommended actions

Type of SoC	Present in the product – intentionally added	Generated by the product – by-products 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
Recommended actions	- Obtain a full material declaration of the product and consider all material compositions.	- Briefly reflect on the lifecycle stages of the product. List any substances or by-products the product might generate or release that were not intentionally added to its composition.	- Reflect about the production and manufacturing processes of the product. Identify and list any substances that may be added or used during this processes but are not intended to remain in its composition.
	- Screen the list and search if the materials and substances are marked as SoC in: ECHA information about chemicals and materials [1], SIN list [2], Material Wise [3], or other resources.		

Figure 4.2. Step 1a - Identify SoC. 1(European Chemicals Agency, n.d.), 2(ChemSec, n.d.), 3(Chem Forward, n.d.)

Step 1. Analyse the product - substance combination

Step 1b Investigate the SoC

Fill in the information to each question on the table, use literature research and the recommendations for possible sources.

Question	Possible sources	Answers
1. What is the SoC? Name(s), type of substance?	ECHA information about chemicals [1], SIN List [2], Material Wise [3]	DEHP or di(2- ethylhexyl) phthalate is a plasticizer. Plasticizers are additives used in plastics to make them flexible.
2. What is the function of the substance in the product?	ECHA Guidance on Information Requirements and Chemical Safety Assessment, Chapter R.12, descriptor list for chemical products category and technical functions [4]	DEHP is used in vinyl flooring to increase, flexibility, dimensional stability, wear resistance, stain resistance, acoustic dampening, and comfort.
3. What kind of hazards does it have on health and the environment?	ECHA information about chemicals [1], SIN List [2], Material Wise [3], scientific studies on health and environmental hazards of the substance	Eendocrine disruption, deformities in the reproductive system, increased risk of premature birth, and cancer. Bioaccumulative and ubiquitous environmental contaminants.
4. How is the substance currently regulated/banned?	ECHA information about chemicals [1], SIN List [2], Material Wise [3]	Banned in the EU since 2021 by the REACH regulation.
5. How much substance is in the product? (If possible and available)	Material declarations from suppliers. Books and manuals on common material compositions.	Varies on the composition of the product depending on the flexibility requirements.

Figure 4.3. Step 1b - Investigate the SoC. Example answers of the case of DEHP in vinyl flooring. 1(European Chemicals Agency, n.d.), 2(ChemSec, n.d.), 3(Chem Forward, n.d.), 4(European Chemicals Agency, 2014)

Step 2 – Analysis of the context of the product-substance combination

a) The designer identifies emission and exposure scenarios for each stage of the lifecycle. In this step the choice of lifecycle stages includes three different end of life pathways (recycling, landfill, and incineration), circular strategies (reuse, recycling, repair, refurbishing, etc.), transportation, collection, and separate production phases, one for materials/chemicals and one for the product manufacturing/assembly. This allows the illustration of a variety of cases. Figure 4.4 shows the template for this step with example information for the case of DEHP in vinyl flooring (for illustration purposes).

b) The designer qualitatively analyses the emission-exposure scenarios to prioritize those with concerning emission levels and important environmental and health risks. This is done based on the results of Step 2a, or on additional data obtained from further literature research. The severity of the scenario can be indicated for each of the stages of the lifecycle. Uncertainty can be indicated for those stages where information was unavailable or inconclusive. This is relevant to mark and communicate knowledge gaps. Figure 4.5 shows the template for this step, with the most concerning emissions-exposure scenarios of the case of DEHP in vinyl flooring.

c) The designer analyses the relationship between the most concerning emission and exposure scenarios, the architecture of the product, and the context of the product-substance combination. This step is meant to support the designer in identifying design opportunities to eliminate/mitigate the effects of the SoC. Figure 4.6 shows the template for this step with example information of a case, DEHP in vinyl flooring.

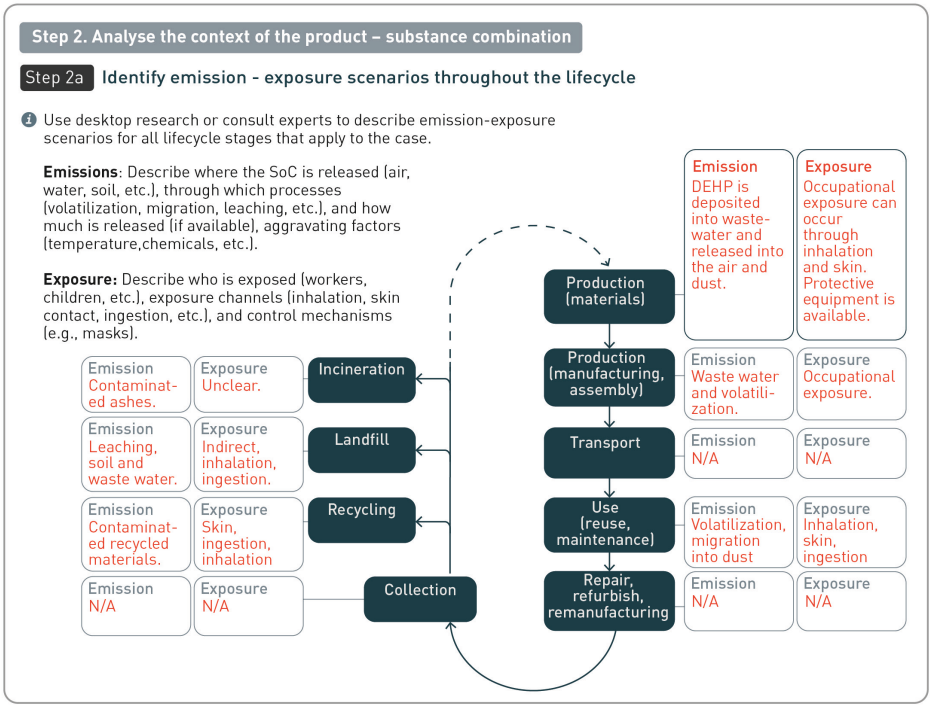


Figure 4.4. Step 2a – Identify emission-exposure scenarios per lifecycle stage. Example answers for the case of DEHP in vinyl flooring.

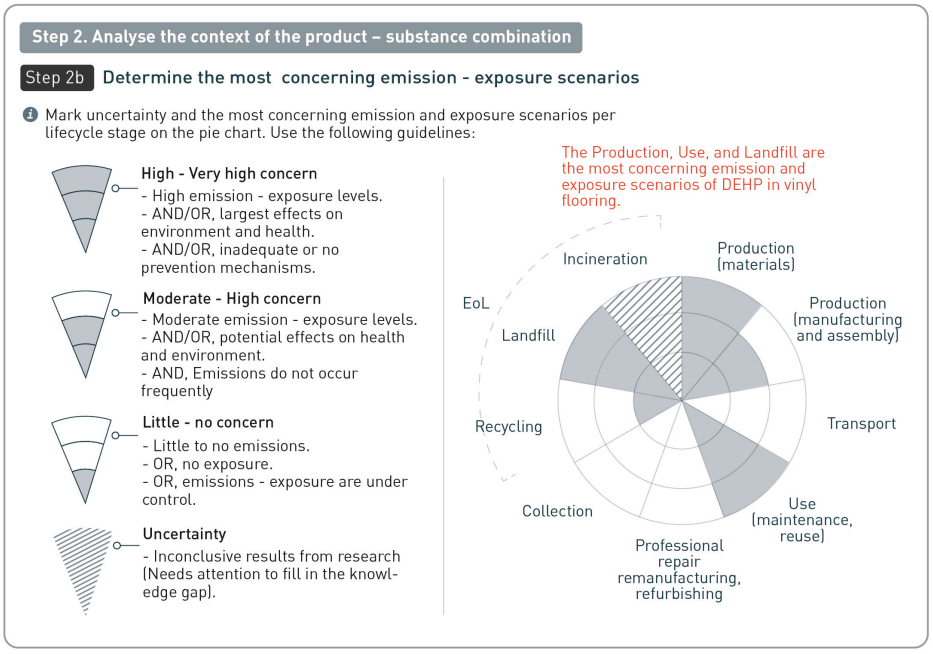


Figure 4.5. Step 2b, Prioritize emission and exposure scenarios. Example answer of the case of DEHP in vinyl flooring.

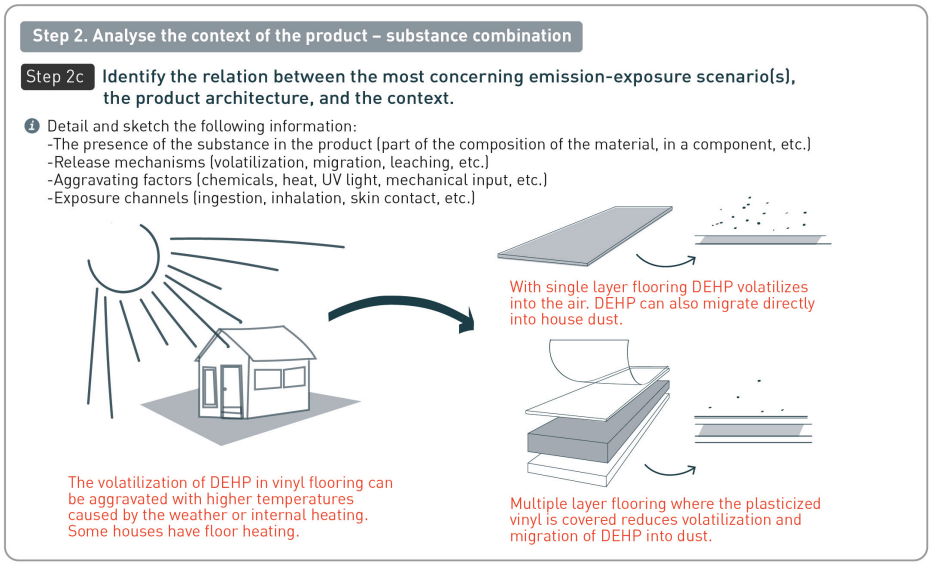


Figure 4.6. Step 2c, Identify the relation between concerning emission exposure scenarios, the product architecture, and the context. Example answer of the case of DEHP in vinyl flooring.

Step 3 - Selection of strategies

The method provides a list of possible design strategies for the designer to consider. The method prioritizes strategies to Avoid/Eliminate the use of the substance over Reduce or Prevent/Control strategies (Figure 4.7).

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

a) If possible avoid or eliminate the substance of concern
b) Target emission – exposure scenarios with the largest effects.
c) Target the identified release mechanisms and exposure channels
d) Develop the selected strategy further to be assessed

Avoid /Eliminate	
Avoid	Alternative value proposition or function
Substitute	Less harmful material
	Less harmful additive or substance
Phase out	Re-evaluate essentiality

Reduce	
Reduce content	Reduce content of the SoC
Increase useful life / Keep in use longer	Durability
	Maintenance and care
	Repair
	Refurbish
	Remanufacture
	Alternative business models
Inform / customize	To avoid emissions
	To avoid exposure
Redefine production/ manufacturing processes	

Control/Prevent	
Contain / isolate	Prevent emissions
	Prevent exposure
Control collection / recovery	Separate collection
	Monitor materials to avoid SoC

Figure 4.7. Step 3, List of possible design strategies to deal with SoC in products.

Step 4 - Evaluate the selected strategies

a) The designer qualitatively estimates if the selected strategy(ies) reduces, maintains, or increases the level of concern of the identified concerning emission-exposure scenarios. This way the designer can observe improvements and further attention points.
b) The designer reflects on the potential negative effects the strategy may have across the lifecycle(s) of the product (e.g., new or increased environmental impacts, new or increased risks).
c) The designer reflects on the potential trade-offs of the strategy, which can include reduced performance, and increased manufacturing costs amongst other.

Figure 4.8 shows the template for Step 4 with example information of the evaluation of a strategy to reduce emissions of DEHP from vinyl flooring.

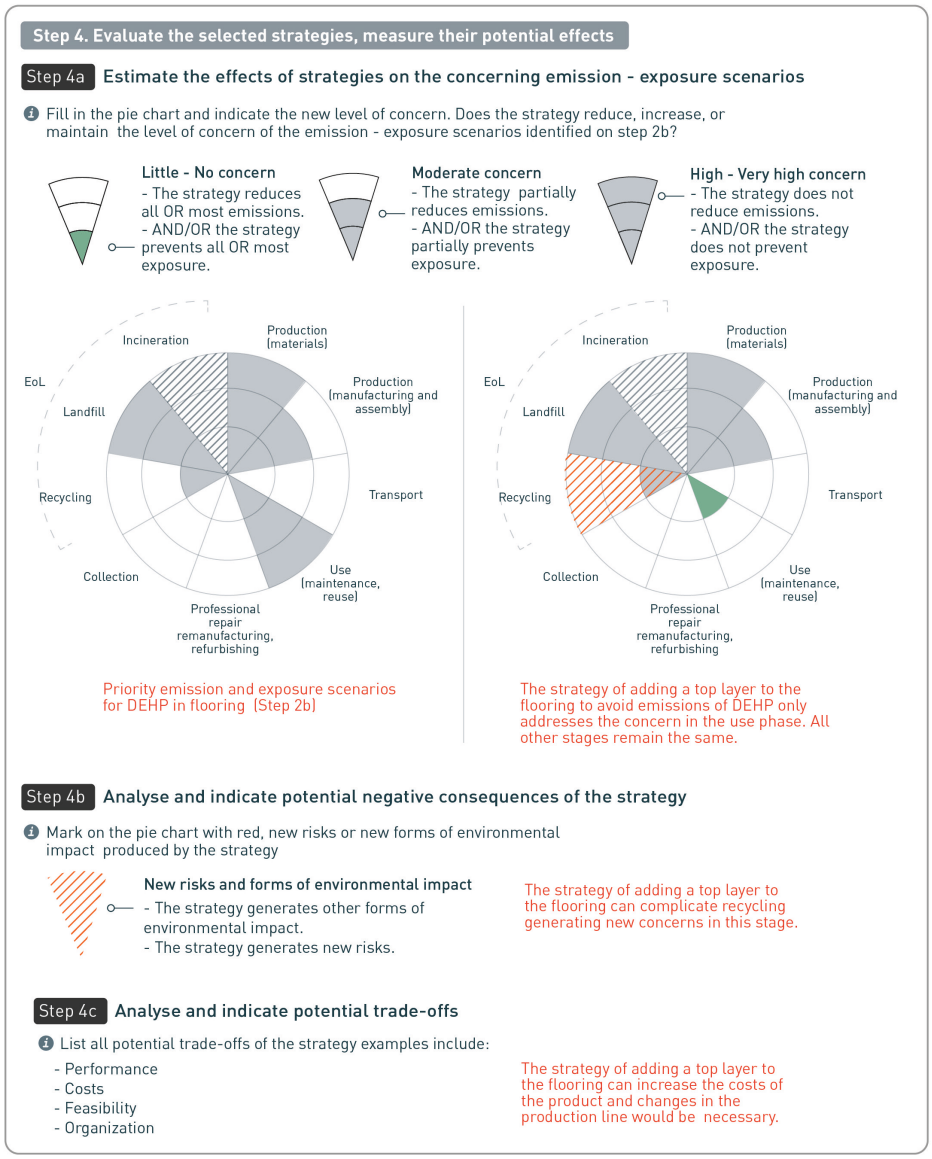


Figure 4.8. Step 4, Evaluation of selected design strategies. Example answer of the case of DEHP in vinyl flooring.

4.4. Discussion and Conclusion

This study aimed to develop a method to address the presence of SoC in products from the product design perspective. The result is a first iteration of the Safe and Circular Design Method, which was developed based on the analysis of five historical cases of product-substance combinations where design-relevant strategies to mitigate the effects of SoC were identified (IenW, 2022).

Currently, the presence of SoC in products is mainly addressed from a chemicals and materials perspective, by both the industry and regulatory bodies. Due to this, strategies are often limited to substitution, which may cause unintended, often unknown consequences, such as: similar or new risks, new forms of environmental impact, or trade-offs, including performance loss or increased costs. Furthermore, in some cases, alternatives that meet equal functional requirements do not yet exist or are technically impossible, which causes the hazardous substance to remain in use. By approaching SoC in this manner, potential negative effects throughout the lifecycle(s) of products can be overlooked, and alternative strategies become limited.

Although possible design strategies were derived from the investigation of the case studies, we have no indication that these were carried out by manufacturers intentionally through a design perspective. Additionally, we found a few successful examples where the importance of following a systemic (holistic) approach is evident, such as the case of refrigerants in cooling equipment, where substitution with less harmful gases has been combined with hermetic systems in the product, collection systems, and recycling processes that prevent emissions. We have therefore developed a process through which designers can partake in the mitigation of risks caused by SoC through a systemic approach which makes possible trade-offs and unintended side effects visible. By using this method, designers can consider multiple layers (product-substance combination, its context, users, lifecycle), and a larger variety of strategies.

Since the current version of the method was derived theoretically from the investigation of the five cases, it will need to be tested by design practitioners to evaluate its usability, workflow, and performance. We have identified several aspects to be considered in next iterations of the method. First, we observed challenges when collecting the necessary data for the analysis of the product-substance combination, its emission and exposure scenarios, and effects of potential strategies. Following iterations of the method will have to provide designers with insights on how to source data and how to deal with uncertainty. Additionally, the method is currently largely based on qualitative analysis, which can lead to uncertainty in establishing priority emission and exposure scenarios and determining the effects

of alternative strategies. While qualitative analysis provides a first estimation, the integration of quantitative methods such as Risk Assessment and Life Cycle Assessment will deliver more accurate results. However, these require large amounts of data and may not be a part of the skills of a designer, highlighting the importance of collaboration with environmental scientists. Furthermore, future developments should explicitly address how to deal with trade-offs, newfound risks, and environmental impacts of new strategies. Similarly, ethical considerations, such as balancing performance losses with safety concerns and environmental impacts, need to be specifically addressed. Finally, the method was originally intended to be applied in early stages of the development process. However, it now appears to be more suitable for redesign assignments. Therefore, the integration of this method as part of the development process of new products needs to be further considered.

4.5. References

Alaranta, J., & Turunen, T. (2021). How to Reach a Safe Circular Economy?—Perspectives on Reconciling the Waste, Product and Chemicals Regulation. Journal of Environmental Law, 33(1), 113–136. https://doi.org/10.1093/JEL/EQAA016

Ardente, F., Calero Pastor, M., Mathieux, F., & Talens Peiró, L. (2015). Analysis of end-of-life treatments of commercial refrigerating appliances: Bridging product and waste policies. Resources, Conservation and Recycling, 101, 42–52. https://doi.org/10.1016/J.RESCONREC.2015.05.005

Bodar, C., Spijker, J., Lijzen, J., Waaijers-van der Loop, S., Luit, R., Heugens, E., Janssen, M., Wassenaar, P., & Traas, T. (2018). Risk management of hazardous substances in a circular economy. Journal of Environmental Management, 212, 108–114. https://doi.org/10.1016/J.JENVMAN.2018.02.014

Brandsma, S. H., Leonards, P. E. G., Koekkoek, J. C., Samsonek, J., & Puype, F. (2022). Migration of hazardous contaminants from WEEE contaminated polymeric toy material by mouthing. Chemosphere, 294, 133774. https://doi.org/10.1016/J.CHEMOSPHERE.2022.133774

Chem Forward. (n.d.). MaterialWise – A pathway to better chemistry. Retrieved September 14, 2022, from https://www.materialwise.org/

ChemSec. (n.d.). SIN List. Retrieved September 14, 2022, from https://sinlist.chemsec.org/

Cousins, I. T., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C. A., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z., & Dewitt, J. C. (2019). The concept of essential use for determining when uses of PFASs can be phased out. Environmental Science: Processes & Impacts, 21(11), 1803–1815. https://doi.org/10.1039/C9EM00163H

Dickman, R. A., & Aga, D. S. (2022). A review of recent studies on toxicity, sequestration, and degradation of per- and polyfluoroalkyl substances (PFAS). Journal of Hazardous Materials, 436, 129120. https://doi.org/10.1016/J.JHAZMAT.2022.129120

Dumée, L. F. (2022). Circular materials—An essay on challenges with current manufacturing and recycling strategies as well as on the potential of life cycle integrated designs. Circular Economy and Sustainability: Volume 2: Environmental Engineering, 359–372. https://doi.org/10.1016/B978-0-12-821664-4.00008-X

European Chemicals Agency, (n.d.). Information on Chemicals. Retrieved September 14, 2022, from https://echa.europa.eu/information-on-chemicals

European Chemicals Agency, (2014). Guidance on information requirements and chemical safety assessment Chapter R11 : PBT/vPvB assessment (Issue 2, pp. 1–119). http://echa.europa.eu/documents/10162/13559/mb_63_2013_consultation_procedure_for_gui

Geueke, B., Groh, K., & Muncke, J. (2018). Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. Journal of Cleaner Production, 193, 491–505. https://doi.org/10.1016/J.JCLEPRO.2018.05.005

Graziosi, F., Arduini, J., Furlani, F., Giostra, U., Cristofanelli, P., Fang, X., Hermanssen, O., Lunder, C., Maenhout, G., O'Doherty, S., Reimann, S., Schmidbauer, N., Vollmer, M. K., Young, D., & Maione, M. (2017). European emissions of the powerful greenhouse gases hydrofluorocarbons inferred from atmospheric measurements and their comparison with annual national reports to UNFCCC. Atmospheric Environment, 158, 85–97. https://doi.org/10.1016/J.ATMOSENV.2017.03.029

Harder, R., Holmquist, H., Molander, S., Svanström, M., & Peters, G. M. (2015). Review of Environmental Assessment Case Studies Blending Elements of Risk Assessment and Life Cycle Assessment. Environmental Science and Technology, 49(22), 13083–13093. https://doi.org/10.1021/ACS.EST.5B03302/ASSET/IMAGES/LARGE/ES-2015-03302Y_0002.JPEG

Hill, P. J., Taylor, M., Goswami, P., & Blackburn, R. S. (2017). Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance. Chemosphere, 181, 500–507. https://doi.org/10.1016/J.CHEMOSPHERE.2017.04.122

Holmquist, H., Schellenberger, S., van der Veen, I., Peters, G. M., Leonards, P. E. G., & Cousins, I. T. (2016). Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing. Environment International, 91, 251–264. https://doi.org/10.1016/J.ENVINT.2016.02.035

IenW. (2022). Safe by Design-A design approach for dealing with hazardous substances in products. https://www.rijksoverheid.nl/documenten/rapporten/2022/12/22/safe-by-design

Keijer, T., Bakker, V., & Slootweg, J. C. (2019). Circular chemistry to enable a circular economy. Nature Chemistry 2019 11:3, 11(3), 190–195. https://doi.org/10.1038/s41557-019-0226-9

Keri, C. (2019). Recycling cooling and freezing appliances. Waste Electrical and Electronic Equipment (WEEE) Handbook, 357–370. https://doi.org/10.1016/B978-0-08-102158-3.00013-6

Koronaki, I. P., Cowan, D., Maidment, G., Beerman, K., Schreurs, M., Kaar, K., Chaer, I., Gontarz, G., Christodoulaki, R. I., & Cazauran, X. (2012). Refrigerant emissions and leakage prevention across Europe – Results from the RealSkillsEurope project. Energy, 45(1), 71–80. https://doi.org/10.1016/J.ENERGY.2012.05.040

Krafft, M. P., & Riess, J. G. (2015). Per- and polyfluorinated substances (PFASs): Environmental challenges. Current Opinion in Colloid and Interface Science, 20(3), 192–212. https://doi.org/10.1016/J.COCIS.2015.07.004

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., de Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy — weeding out the toxics first. Environment International, 94, 230–234. https://doi.org/10.1016/J.ENVINT.2016.05.012

McCulloch, A. (2009). Evidence for improvements in containment of fluorinated hydrocarbons during use: an analysis of reported European emissions. Environmental Science & Policy, 12(2), 149–156. https://doi.org/10.1016/J.ENVSCI.2008.12.003

Mech, A., Gottardo, S., Amenta, V., Amodio, A., Belz, S., Bøwadt, S., Drbohlavová, J., Farcal, L., Jantunen, P., Małyska, A., Rasmussen, K., Riego Sintes, J., & Rauscher, H. (2022). Safe- and sustainable-by-design: The case of Smart Nanomaterials. A perspective based on a European workshop. Regulatory Toxicology and Pharmacology, 128, 105093. https://doi.org/10.1016/J.YRTPH.2021.105093

OECD. (2013). PER- AND POLYFLUORINATED OECD / UNEP Global PFC Group Synthesis paper on per- and polyfluorinated chemicals (PFCs). Environment, Health and Safety, Environment Directorate, OECD., 1–60.

Sánchez Jiménez, A., Puelles, R., Perez-Fernandez, M., Barruetabeña, L., Jacobsen, N. R., Suarez-Merino, B., Micheletti, C., Manier, N., Salieri, B., Hischier, R., Tsekovska, R., Handzhiyski, Y., Bouillard, J., Oudart, Y., Galea, K. S., Kelly, S., Shandilya, N., Goede, H., Gomez-Cordon, J., … Llopis, I. R. (2022). Safe(r) by design guidelines for the nanotechnology industry. NanoImpact, 25, 100385. https://doi.org/10.1016/J.IMPACT.2022.100385

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., Lunderberg, D. M., Lang, J. R., & Peaslee, G. F. (2017). Fluorinated Compounds in U.S. Fast Food Packaging. https://doi.org/10.1021/acs.estlett.6b00435

Schellenberger, S., Hill, P. J., Levenstam, O., Gillgard, P., Cousins, I. T., Taylor, M., & Blackburn, R. S. (2019). Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. Journal of Cleaner Production, 217, 134–143. https://doi.org/10.1016/J.JCLEPRO.2019.01.160

Subramanian, V., Peijnenburg, W. J. G. M., Vijver, M. G., Blanco, C. F., Cucurachi, S., & Guinée, J. B. (2023). Approaches to implement safe by design in early product design through combining risk assessment and Life Cycle Assessment. Chemosphere, 311, 137080. https://doi.org/10.1016/J.CHEMOSPHERE.2022.137080

Tsai, W. T. (2005). An overview of environmental hazards and exposure risk of hydrofluorocarbons (HFCs). Chemosphere, 61(11), 1539–1547. https://doi.org/10.1016/J.CHEMOSPHERE.2005.03.084

Undas, A. K., Groenen, M., Peters, R. J. B., & van Leeuwen, S. P. J. (2023). Safety of recycled plastics and textiles: Review on the detection, identification and safety assessment of contaminants. Chemosphere, 312, 137175. https://doi.org/10.1016/J.CHEMOSPHERE.2022.137175

Velders, G. J. M., Fahey, D. W., Daniel, J. S., Andersen, S. O., & McFarland, M. (2015). Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. Atmospheric Environment, 123, 200–209. https://doi.org/10.1016/J.ATMOSENV.2015.10.071

Vuppaladadiyam, A. K., Antunes, E., Vuppaladadiyam, S. S. V., Baig, Z. T., Subiantoro, A., Lei, G., Leu, S. Y., Sarmah, A. K., & Duan, H. (2022). Progress in the development and use of refrigerants and unintended environmental consequences. Science of The Total Environment, 823, 153670. https://doi.org/10.1016/J.SCITOTENV.2022.153670



Chapter 5

Safe and sustainable by design Co-creating a design method for dealing with harmful substances in product design

This chapter was submitted as:

Bolaños Arriola, J., Weber, M., Aghaeian, S., Bakker, C., & Balkenende, R. Safe and sustainable by design: co-creating a design method for dealing with harmful substances in product design. Circular Economy and Sustainability.

Abstract

Hazardous substances in everyday products pose significant risks to human health and the environment, hindering the transition to a circular economy. There is an urgent need for safer, more sustainable design practices that address these risks. Although designers play a relevant role in achieving this, existing guidance on mitigating hazardous substances is limited, predominantly material-focused, and often lacks a design perspective. This paper presents the co-creation of the Design for Substance Safety and Sustainability (DSSS) Method, initially developed from theoretical insights. Using Method Content Theory to structure co-creation sessions with professional designers, we ensured that the revised DSSS Method covers the essential elements of a high-quality design method and aligns with the realities of professional practice. Through the sessions, we identified procedural and functional requirements, contextual factors influencing the method's successful application, and actionable insights to refine the method framework. The resulting DSSS Method provides a systematic, lifecycle-oriented approach to mitigating SoC risks across product lifecycles. It integrates tools for assessing and addressing SoC risks, iterative validation mechanisms, and strategies to prevent trade-offs. The DSSS Method fills a resource gap, providing a practical framework that integrates into professional design processes. It supports informed decision-making toward safer, more sustainable products.

5.1. Introduction

Everyday products, from the clothes we wear to the devices we use, often hide a concerning reality: the presence of hazardous substances that threaten both our health and the environment. Headlines frequently surface about the troubling impacts of these substances, how they linger in the environment, accumulate in our bodies, and disrupt our health and ecosystems (Hosea & Salvidge, 2024a, 2024b; Main, 2024; Perkins, 2024). These substances, also known as Substances of Concern (SoC), threaten our well-being and challenge the transition to a sustainable, circular economy. The well-being of people and the environment depends on access to safe, sustainable products for everyday use. Designers play a pivotal role in shaping the products we rely on daily. Yet, creating safe and sustainable products becomes more complex when SoC are embedded in the materials and functions of those designs. Designers require guidance to avoid harmful substances in their designs or prevent the risks they can generate. This article introduces a new method, the Design for Substance Safety and Sustainability (DSSS) Method, to support designers in addressing SoC.

SoC can escape during a product's lifecycle, posing risks such as carcinogenicity, endocrine disruption, and reproductive toxicity (United Nations, 2011). Many of these substances are also resistant to degradation, leading to their accumulation in organisms and the environment and amplifying their effects (United Nations, 2011). For example, PFAS (Per- and polyfluoroalkyl substances), a group of chemicals used to make textiles water and stain-resistant, are linked to cancer (Hill et al., 2017; NRDC, 2021; Straková et al., 2022). Similarly, BPA (Bisphenol A), a common ingredient in high-performance plastics, has been shown to interfere with hormonal functions (Hahladakis et al., 2023; Usman & Ahmad, 2016). These examples illustrate the challenge of balancing high-performance product design with safety and sustainability. The presence of SoC also undermines efforts to advance circular design strategies like reuse, repair, and recycling (Alaranta & Turunen, 2021; Barouta et al., 2022; Beekman et al., 2020; Bodar et al., 2018). Contamination from SoC can make recycling unsafe or reintroduce contaminated products, materials, and components into subsequent lifecycles, creating new risks (Bodar et al., 2018; Brandsma et al., 2022; Leslie et al., 2016).

Addressing these challenges requires a holistic perspective that considers the entire product lifecycle, broader systems, and the balance between performance and sustainability, as seen in sustainable design practices (Ceschin & Gaziulusoy, 2016). While the importance of designing non-toxic, safe products is well recognized, the existing literature offers little guidance for designers to achieve this. A literature search revealed no design methods specifically tailored to addressing SoC risks in products within a circular economy. Consultations with designers,

design experts, and grey literature identified several resources currently used in practice (Section 5.2.1), but these remain fragmented. We observed the need for a comprehensive framework that integrates existing resources into design processes, adapts them for design practice, and creates new design-specific resources where necessary. Furthermore, current efforts primarily emphasize substitution, focus predominantly on chemicals, and give limited attention to lifecycle, circularity, and broader design considerations. While Regulatory initiatives, such as the European Chemicals Strategy for Sustainability (European Commission, 2020), the Ecodesign for Sustainable Products Regulation (European Commission, 2024), and the Safe and Sustainable by Design approach, (Apel et al., 2024) are increasingly addressing SoC in products, these prioritize the development of safe chemicals and materials, and do not provide support to address SoC from a product design perspective.

Based on these observations, we aimed to develop a method that enables designers to comprehensively address SoC in products, using a holistic approach that considers the entire product lifecycle and subsequent lifecycles. We initially developed a first version of the Design for Substance Safety and Sustainability (DSSS) Method based on theoretical insights from a previous study (Bolaños Arriola et al., 2024) (Section 5.2.2). However, in this paper, we refine and expand the first version of the DSSS Method to ensure it aligns with the realities of design practice, integrating Method Content Theory (Cash et al., 2023; Daalhuizen & Cash, 2021) and a co-creation approach involving design professionals. Co-creation provides insights into the needs of intended users and incorporates their input for further development (de Koning et al., 2016; Mattelmäki & Sleeswijk Visser, 2011; van Dam et al., 2021). The research aim of this paper is as follows: To co-create a Design for Substance Safety and Sustainability (DSSS) Method with and for design professionals. In this paper, we first provide background on existing tools and introduce the first version of the DSSS Method. Next, we describe the process for further developing the DSSS Method, explaining how Method Content Theory and co-creation were integrated and applied. Finally, we present and discuss our findings, including a list of requirements, a framework for the revised method, and implications for future development.

5.2. Background

5.2.1. Existing resources that address SoC

After consulting designers, design experts, and grey literature, we identified several resources designers currently apply in practice, and publications that address SoC in product design to some extent, including:

Design guides and guidelines. These resources provide guidance on eliminating harmful substances and materials in products. Examples include:

- The Circular Design Guide from the Ellen MacArthur Foundation provides a set of methods and guidelines for safe and circular material choices and product redesign (Ellen Macarthur Foundation, 2016).
- Literature on Ecodesign and Design for Sustainability (Brezet & van Hemel, 1997; United Nations Environment Programme, 2009) recommends identifying the use of toxic materials in products and substituting them with "low impact" materials.

Overviews of materials and chemicals. These resources provide relevant information about the properties and hazards of materials and substances. Examples include:

- Restricted Substances Lists (RSLs), for instance, regulatory lists such as REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) (European Commission, 2018), as well as company-specific RSLs that limit the use of unwanted substances across the supply chain (TÜVRheinland, 2024).
- Material Safety Data Sheets, which contain information provided by suppliers summarizing material properties and hazards, with content and format specified under REACH (European Commission, 2018).
- LCA databases and chemical inventories, such as Ecoinvent (Ecoinvent, n.d.), IDEMAT (Vogtländer, n.d.), ECHA's chemical information (ECHA, n.d.), and the SIN List (Chemsec, n.d.), provide data on chemicals, materials, processes, and associated human health and ecotoxicity impacts.

Assessment methods and certificates. These resources support designers in evaluating material alternatives. Designers can conduct assessments or rely on certified institutions to verify the safety of materials or products. Examples include:

- Product and material standards and certificates, for instance, Cradle to Cradle (Bakker et al., 2010; Cradle to Cradle Products Innovation Institute, n.d.), and Bluesign (Bluesign, n.d.), both of which consider material safety in their assessments.
- Alternative assessment methods, for example, Faludi et al. (2016) propose a scoring method to assess chemical and material alternatives based on functionality and hazard.

Current design guidelines prioritize healthy material choices but neglect interventions at the component, product, or system levels. Certifications and alternative assessment methods are similarly focused on substitution. Substitution is, however, often not feasible; alternatives may be unavailable, or their safety may be uncertain. Trade-offs and broader effects of material choices are rarely addressed, and the integration of these guides and guidelines into the overall design process is

unclear. Chemical databases and life cycle inventories are technically demanding and may not contain the necessary information to understand substance behaviour throughout product lifecycles. While they help identify chemicals to avoid, they offer little guidance on alternatives or mitigation strategies. Although relevant, these resources constrain the scope of design interventions and present a fragmented approach toward SoC in design. A comprehensive approach towards SoC from a product design perspective is necessary to integrate existing practices and resources into the design process.

5.2.2. A first version of a method for dealing with SoC in products

The initial version of the Design for Substance Safety and Sustainability (DSSS) Method is based on the analysis of five products containing SoC, where risk mitigation strategies have been applied (Bolaños Arriola et al., 2024). This analysis yielded a set of design strategies that served as the basis for the first version of the DSSS Method, along with fundamental concepts of risk assessment (RA) and life cycle assessment (LCA). Figure 5.1 presents the identified design strategies, and Figure 5.2 presents an overview of the steps of the first version of the DSSS Method. A detailed explanation of the method, and fillable templates for designers to follow the process are available in Supplementary Material 5A.

We identified three groups of design strategies: Avoid, which includes any modification to the product that eliminates the SoC (e.g., substitution), Control, in which the SoC remains in use, but its emissions are prevented (e.g., controlled recovery), and Reduce, which includes any modification that decreases the volume or emissions of SoC across the product lifecycle.

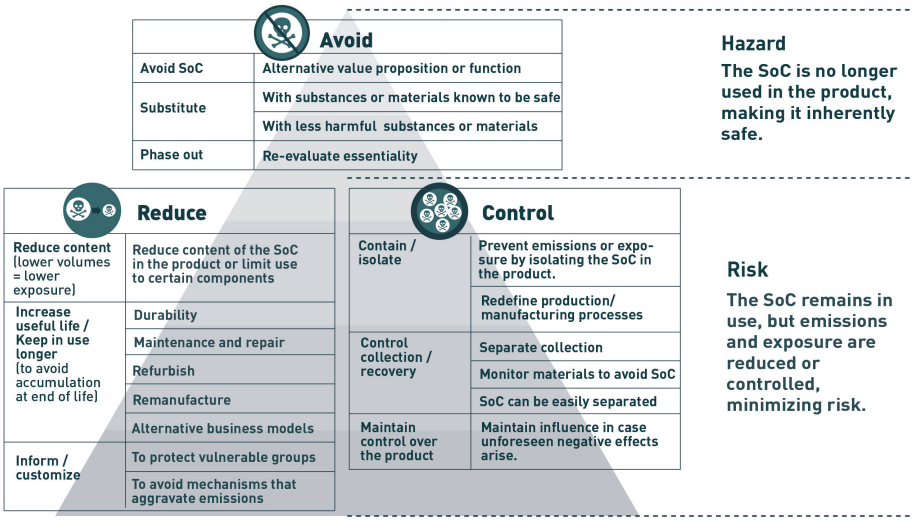


Figure 5.1. Design Strategies to deal with SoC in products (Bolaños Arriola et al., 2024). The three strategy types (Avoid, Reduce, Control) are arranged in a triangle to indicate the prioritization of strategies that eliminate the use of the SoC (Avoid) over those that keep the SoC in use but mitigate its effects (Reduce, Control). Each strategy group depicts several sub-strategies.

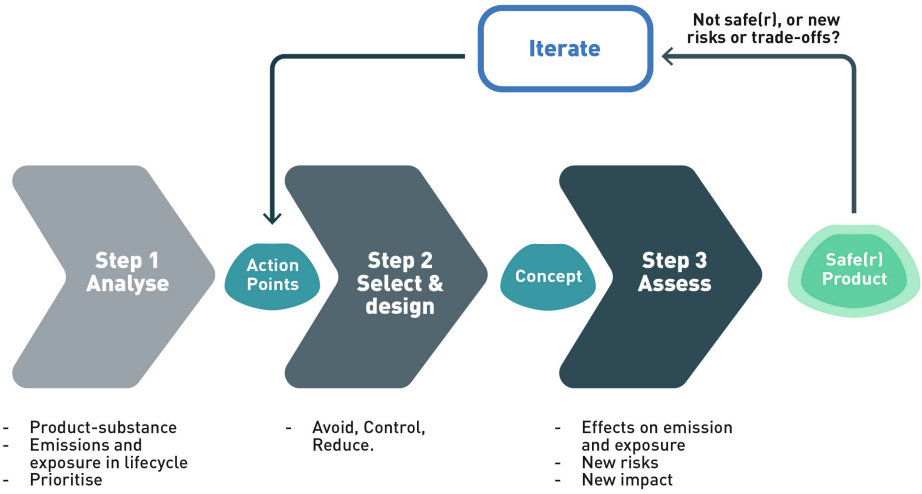


Figure 5.2. Overview of steps of the 1st version of the DSSS Method.

The method consists of three steps (Figure 5.2). Before Step 1, the designer receives guidance on screening the product to identify potential SoC, if not identified yet.

- Step 1 guides an investigation of the SoC characteristics and a qualitative analysis of potential risks to health or the environment throughout the product's lifecycle and subsequent lifecycles. After Step 1, designers can define action points for risk mitigation.
- Step 2 provides a list of possible design strategies to mitigate the SoC, which designers can choose from to develop alternatives and new concepts (Figure 5.1).
- Step 3 guides the assessment of alternatives or new designs to measure their effectiveness in addressing the identified risks and to identify new, unforeseen consequences or outcomes. The results of this assessment can then inform new iterations.

The first iteration of the DSSS Method combines several of the resources in Section 5.2.1 within a single framework. However, this version does not integrate into a design workflow, lacks tools for a comprehensive assessment of SoC risks, and relies on existing resources in their current form. Many may first need adaptation before designers can effectively apply them. We therefore see a need for co-creation with design professionals to further develop the DSSS Method and its resources.

5.3. Method

Our research set-up for developing a new version of the DSSS Method used Method Content Theory (Cash et al., 2023; Daalhuizen & Cash, 2021) to inform co-creation sessions with professionals. By using Method Content Theory, we considered all essential elements of a design method. Method Content Theory guided both the structure of the co-creation sessions and the analysis of the resulting data. By involving professional designers in the co-creation, we could gather insights from real-world practice and obtain detailed input on the initial version of the DSSS Method. Figure 5.3 shows an overview of the research setup.

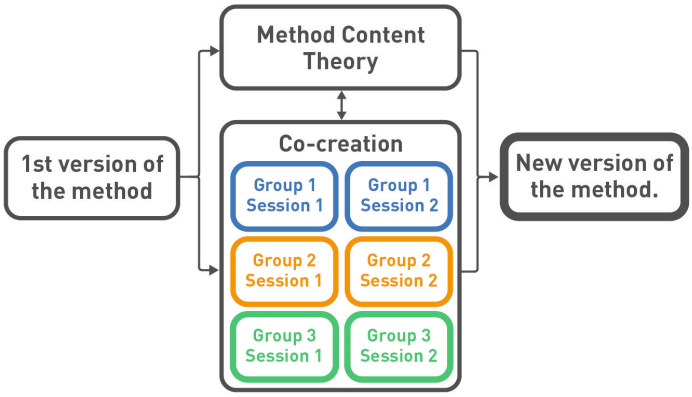


Figure 5.3. Research set-up for the co-creation of a new version of the DSSS Method

5.3.1. Using Method Content Theory to inform the co-creation of a new version of the DSSS Method

To structure our co-creation sessions and analysis of the results, we pre-formulated codes (Table 5.1), following Daalhuizen & Cash, Method Content Theory (MCT) (2021, 2023). Their theory establishes all the essential components of a high-quality design method. Method Content Theory can be used to assess the efficacy and effectiveness of existing design methods. The authors also suggest it can be used as a checklist for method development. Their assessment framework is the first to lay a foundation for good practice in design method development and reporting. In this study, we use their assessment framework for this purpose.

Method Content Theory considers the following five elements, and four sub-elements of Method Framing (Cash et al., 2023; Daalhuizen & Cash, 2021):

- **Method goal:** What the use of the method aims to achieve and its scope.
- **Method rationale:** The relevance of the goal of the method in a specific context. Daalhuizen (2021) establishes that the method rationale contains information that helps measure progress towards reaching the method goal, 'how to evaluate if you have succeeded, when to end'.
- **Method procedure:** The prescribed set of activities to reach the goal, their order, and instructions to complete them.
- **Method mindset:** Necessary values, principles, and beliefs to use and interpret the method as intended.
- **Method framing:** Information that frames the use of the method within the appropriate context.
    - o **Context:** prescribed context of use of the method, when, where, and how the method is applied. E.g., type of project, intended audience, product category.

- **Pre-requisites:** resources or knowledge necessary for the use of the method and to meet the method goal.
- **Positioning in the design process:** where in the design process to apply and integrate the method.
- **Task:** type of tasks prescribed to apply the method. E.g., calculations, visualisation, etc.

The codes in Table 5.1 served to analyse and translate the observations from the co-creation sessions into insights to develop the new method. First, we proposed an initial list of topics to address during the co-creation sessions. We then compared this list with the elements addressed in Method Content Theory to ensure completeness and avoid any omissions. The result is a list of 11 topics used to structure the discussions and activities of the co-creation sessions and later used as codes to structure the analysis of the collected data. Table 5.1 shows the relationship between Method Content Theory and each code/topic. Most codes do not have a one-to-one relation to the elements of Method Content Theory. Instead, several codes address multiple Method Content Theory elements simultaneously. Nevertheless, all elements of Method Content Theory are addressed, increasing the likelihood that the new DSSS Method will adhere to the quality standard established by the theory. Code C2 for example, addresses the barriers of dealing with SoC, which provides information on several elements: Method Context (e.g., stakeholders and project types), Method Mindset (e.g., the designer's scope and perceived opportunities), Pre-requisites (e.g., required tools to address a specific problem), and Method Rationale (e.g., the adaptation of the method to contextual elements to meet the Method Goal). Meanwhile, codes like C9 and C10 focused on direct feedback on the method's clarity, completeness, and delivery, and linked to Method Content Theory elements such as Method Procedure and Method Framing. Code C11, additional observations, was added to the list for any aspects not covered by other codes.

Table 5.1. List of codes/topics and their relation to elements of Method Content Theory.

Codes/Topics	Elements of Method Content Theory							
					Method Framing			
	Method Goal	Method Rationale	Method Procedure	Method Mindset	Context	Pre-requisites	Positioning in design process	Task
C1. Perceived role and responsibilities of designers regarding SoC in products.		*		*	*			
C2. Perceived barriers for designers when dealing with SoC in products.		*		*	*	*		
C3. Perceived necessary resources and knowledge for designers to deal with SoC in products.			*		*	*		
C4. Situations in which the DSSS method could be applied by designers in professional practice, and desired characteristics and functions of the method.	*				*			*
C5. Integration of the DSSS method in the design process.			*				*	
C6. Main and intermediate goals of the DSSS method.	*		*					
C7. Overlooked content and contextual elements in the DSSS method.					*	*		
C8. Completeness and logic of the steps proposed for the DSSS method, and suggestions for improvement.	*		*					*
C9.1 Perception of the delivery/ proposed use of the DSSS method. C9.2 Suggestions to the delivery of the DSSS method to improve its integration to the design process and become attractive to designers.			*		*		*	
C10.1 Perception and clarity of the proposed information artifacts (elements used to display and manipulate information). C10.2 Suggestions to improve the information artifacts.			*					*
C11. Additional observations and information provided by participants.	*	*	*	*	*	*	*	*

We used co-creation, as it establishes an active form of sharing, allowing us to understand user needs better and build a closer connection to their experiences (de Koning et al., 2016; van Dam et al., 2021). Co-creation also provides an opportunity to obtain diverse ideas and perspectives on how to approach certain problems or tasks (Sleeswijk Visser et al., 2005). Through co-creation, we aimed to understand designers' perspectives on addressing SoC in products and to gather insights from their use of the initial method.

We conducted six co-creation sessions with three groups of professional designers. The participants had 3 to 10 years of experience and worked at well-established design agencies in the Netherlands. In total, eight professional designers took part: Group 1 included two participants from Agency A, while Groups 2 and 3 each consisted of three participants from Agency B. Previous experience with SoC, circular economy, or sustainability was not a consideration in selecting participants or their agencies, and no screening was carried out on this basis. All participants signed an informed consent form, and the co-creation sessions were conducted in accordance with the protocols of the Delft University of Technology's human research ethics. We followed well-established procedures for defining and conducting the co-creation sessions (de Koning, 2023; Sanders & Stappers, 2012). Table 5.2 shows the activities conducted during each session and the rationale behind them. These activities were created to address the pre-defined codes (Table 5.1). The sessions were tested in a pilot conducted with a group of two researchers with professional experience in design. We adjusted the sessions accordingly prior to our appointments with the professional designers. The sessions were facilitated by two researchers, one facilitator and one note-taker. The note-taker used a log with the pre-defined codes (Table 5.1) for observations. A complete description of the session planning and their corresponding materials (fillable templates) can be consulted in Supplementary Material 5B.

Table 5.2. Co-creation sessions' activities and justification.

	Activity	Justification
Session 1	a) Discussion on design methods used in current practice, their pros and cons.	- Sensitize the participants to the topic of design methods.
	b) Discussion on known cases of SoC in products (in daily life and practice).	- Sensitize the participants to the topic of SoC, their presence in products, and potential effects in a circular economy.
	c) Ideation and discussion on the contribution of designers in mitigating SoC in products and potential barriers. We provided templates for the ideation.	- Understand what the participants perceive is the role and scope of designers in dealing with SoC, and the barriers they expect to encounter.
	d) Ideation of a process to deal with SoC in products. Designers were given a hypothetical case (waterproof jacket containing PFAS) to use as reference to develop the process. We provided a template to formulate the process.	- Allow designers to propose their own set of steps to approach the SoC in the product, define the necessary resources, and establish a goal.
	e) Discuss the proposed process.	- Clarify the proposed process and gain further insights on their rationale for the steps/actions, process, and goal.
Session 2	a) Pre-read of the method (1st version) and explanation of the steps by the facilitator.	- Familiarize participants with the first version of the method and present the steps.
	b) Use the first version of the method to solve a hypothetical case (fast-food packaging containing PFAS). We provided templates to follow and document the process.	- Observe how participants interact with the first version of the method and understand if the method is clear, and the steps achieve the expected results. Have the designers interact with each of the steps to be able to provide feedback.
	c) Discuss the process and provide feedback to make the method applicable to professional practice.	- Collect feedback on the existing method and ideas to modify and improve it.

5.3.2. Analysis of the results and development of a new version of the DSSS Method

After the co-creation sessions, we collected several forms of data for analysis, including transcripts of the recorded sessions, digitized versions of templates completed by participants, and a logbook kept by a researcher serving as a note-taker during the sessions (using the codes from Table 5.1).

We analysed the data through the following steps:

1. The session facilitator played back the recordings and filled the same logbook (containing the codes in Table 5.1) as the note-taker did during the sessions. We compared the resulting logs for verification, updated the code list, and removed redundant or irrelevant codes. Table 5.1 shows the final version of the codes.
2. We generated transcripts of the audio recordings of the sessions using Microsoft Word's transcription feature. We then manually revised, corrected, and anonymized all transcripts. The complete transcript of all sessions is available on 4TU.Research Data repository (Bolaños Arriola, 2025).
3. We used a deductive approach to analyse the transcripts, applying the predefined codes (Table 5.1) to participants' quotes. This resulted in a collection of quotes for each code. For this coding exercise, we used the Atlas.ti software.
4. We analysed the templates completed by the participants, including their proposed process and method use, and compared the results with the quotes in the transcript for verification.
5. After the codes were applied, we conducted a second coding exercise to identify subcodes within each code cluster. This resulted in sets of sub-coded quotes, per code cluster. This exercise was also done using the Atlas.ti software. All coding exercises were performed separately by two researchers to later compare and validate results. A complete set of the sub-coded quotes can be consulted in Supplementary Material 5C.
6. Finally, we synthesized the quotes under each sub-code by analysing and grouping them according to their similarities. These were subsequently reinterpreted into recommendations and requests from the participants. Using these insights, we reformulated the quote sets into requirements for developing the new version of the method. The detailed analysis and translation of the quotes are provided in Supplementary Material 5D.

To develop the framework for the new version of the DSSS Method, we used the Double Diamond diagram (Design Council, n.d.) to depict the design process. The double diamond was chosen as our base due to its simplicity in representing the design process. Nevertheless, it effectively illustrates both the divergent and convergent phases of design, as well as the non-linear, iterative nature of the process—key requirements for the DSSS Method. In this diagram, we mapped and defined steps and workflows based on the identified requirements, building on the original method while adapting it to insights from the co-creation sessions. Finally, we mapped the identified resources (e.g., data, guidance, assessment tools) for each step. The structuring and visualization of these elements also involved a creative process.

5.4. Results

We present the results of this study in three sections. Section 5.4.1 presents the analysis results, summarised into requirements and suggestions provided by the participants. In Section 5.4.2, we present the interpretation of those requirements and suggestions into a framework. Section 5.4.3 presents contextual factors that may influence the successful application of the method, based on participants' remarks. For reference, Supplementary Material 5C includes the full set of results from the coding exercise, with all quotes organized by code and sub-code. Supplementary Material 5D includes a summary of insights from the coding exercise and their translation into requirements.

5.4.1. List of requirements and suggestions for a method to deal with SoC

Table 5.3 presents the identified requirements for developing a new version of the DSSS Method, including structural requirements and the desired functions. Table 5.4 presents participants' suggestions for resources and approaches to deliver the method, which could help address some of the identified requirements. These include specific methodological characteristics and the necessary resources, both qualitative and quantitative, that the designers mentioned or ideated during the sessions. Each requirement and suggestion in the tables is linked to the corresponding code from which it was derived.

The requirements and suggestions were drawn from insights gained during the co-creation sessions. We prioritized those that were most frequently mentioned by participants, without excluding conflicting requirements or assessing their feasibility. During the step where participants could present their own processes for addressing SoC, they provided insights into what they deemed necessary, including desired functions and resources. They also outlined how they would incorporate this topic into their usual design process, providing a structure detailing the necessary steps, the stages requiring resources, and the relevant stakeholders for each stage. When participants tested the initial version of the method, they gave specific feedback on the process structure. At this stage, they also identified potential limitations in completing the method and suggested resources to address them. We observed similarities across the three groups in establishing a process, but notable differences in their approaches to SoC. For instance, some favoured a data-driven approach, while others preferred an iterative approach that gradually reduces uncertainty. Figure 5.4 shows an example of results from the co-creation sessions, illustrating how the designers in Group 3 presented their own process for addressing SoC in products, using the case study of a waterproof jacket containing PFAS. The designers outlined the steps they would follow, the necessary resources, the stakeholders involved, and the intermediate and overall goals. The resources

provided to designers to complete this step are available and further explained in Supplementary Material 5B.

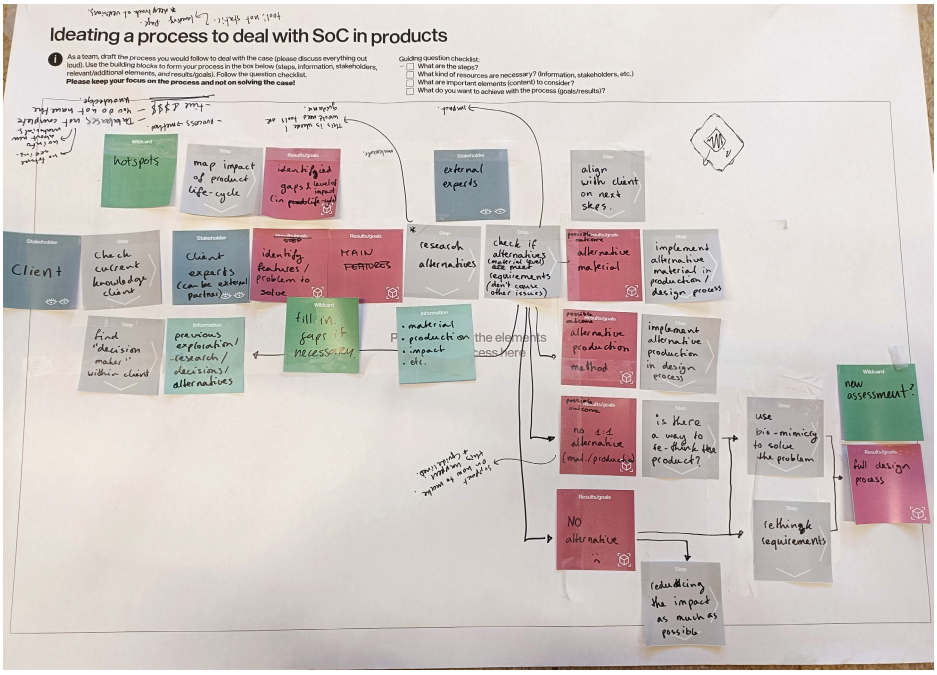


Figure 5.4. Process to deal with SoC presented by Group 3 during the first co-creation session. The methods proposed by the two other groups are available in Supplementary Material 5E.

Table 5.3. Derived requirements for a method to deal with SoC in products. Each requirement is linked to the code or codes from which it was derived.

Method requirement (Note: Numbering does not reflect relevance)	**Corresponding codes**
(R1) Facilitate communication with stakeholders by visualizing (and summarizing) results and insights (Including assessment results, problem definition, dealing with trade-offs).	C1, C4, C9.2
(R2) The method, tools, and resources to deal with SoC should integrate into the (larger) design process.	C2, C5, C9.1
(R3) Dealing with SoC in different types of tasks (design, redesign) should be considered. The method should describe different entry points and relevant tools.	C4, C5
(R4) The topic of SoC should be integrated as early as possible in the design process.	C5, C11
(R5) Dealing with SoC should be considered as an iterative process.	C5, C10.2, 11

Table 5.3. *(Continued)*

Method requirement (Note: Numbering does not reflect relevance)	Corresponding codes
(R6) The goal of the method should be to eliminate SoC entirely whenever possible, or otherwise to minimize risks when they remain in use.	C6
(R7) Intermediate goals or milestones should be established to help designers keep track of their progress and ensure a step has been completed.	C6, C8, C11
(R8) A step to identify safe alternatives or eliminate the SoC entirely should be added prior to the evaluation of the concerning scenarios as a shortcut to avoid unnecessary analysis time.	C8
(R9) The method should allow the documentation and update of information throughout the process.	C9.2
(R10) Guidance dealing with trade-offs and ethical dilemmas (e.g., loss of performance, new forms of risk, increased or new forms of environmental impact) should be provided.	C1, C2
(R11) Guidance finding relevant information about the SoC and resources is necessary.	C1, C2, C3, C4
(R12) Strategies to mitigate SoC at different levels (product, system, component, material, and substance), and guidance to select them should be provided.	C1, C3, C10.1, C11
(R13) Guidance involving stakeholders in different stages of the development process (to help identify SoC, to identify risks in the lifecycle, for decision making, to assess concepts) is necessary.	C2, C3, C7, C8
(R14) The method should provide guidance to deal with uncertainty.	C2
(R15) Tools or guidance to assess and identify risks throughout the lifecycle of products are necessary.	C2, C3
(R16) Tools or guidance to assess and compare concepts and/or alternatives are necessary.	C3
(R17) Guidance to increase the interest of clients in dealing with SoC should be provided, highlighting benefits, and addressing limitations.	C2, C11
(R18) Guidance to formulate requirements according to analysis results is necessary.	C3, C8, C10.1
(R19) The method should consider all possible users during the assessment of risks throughout the lifecycle of the product.	C7
(R20) Designers require guidance selecting the relevant EoL strategy to analyse when assessing the risks throughout the lifecycle. Avoiding the reinsertion of SoC in subsequent lifecycles.	C7, C10.1
(R21) All information gaps must be highlighted as concerning and further guidance to deal with the lack of data should be provided.	C10.2
(R22) Guidelines for the assessment of risks in the lifecycle and the assessment of concepts should be clearly stated and avoid the use of gut feeling.	C10.1

Table 5.4. Suggestions from participants to address method requirements. Each suggestion is linked to the code or codes from which it was derived.

Suggestion *(Note: Numbering does not reflect relevance)*	**Addressed requirement**	**Corresponding codes**
Method suggestions		
(S1) Use fillable elements/templates for documentation.	R1, R9	C9.2
(S2) Display the method as an automated version using available software (e.g., excel).	R1, R9	C9.2
(S3) Integrate summary checklists for guidance.	R7. R9	C9.2
Qualitative resources		
(S4) Include guidance to find relevant information about the SoC for example, guiding questions, suggested resources (e.g., databases, reports, regulations, etc.), guidelines to navigate resources, and explanation of basic concepts.	R11	C1, C2, C3, C4
(S5) Include guidance to deal with uncertainty on the safety of substances. For example, guidelines to implement the precautionary principle.	R14	C2
(S6) Include and describe basic elements of RA to qualitatively assess products and alternatives.	R15, R16	C2, C3
(S7) A database that relates functional properties to potential SoC (rules of thumb) (e.g., flexible or soft materials may contain plasticizers) to support designers in identifying and preventing the use of SoC during the design phase.	R3, R16	C3
(S8) A database or access to examples of the application of potential alternatives to SoC for validation and for dealing with uncertainty.	R14	C2, C7
(S9) Prescribe the use of prototypes for concept assessment and dealing with uncertainty.	R14	C7
(S10) Consider the evaluation of the essentiality of the SoC in the product as a starting point of ideation.	R12	C7
(S11) Consider the core functionalities of the product and SoC as a starting point for ideation.	R12	C7
(S12) Prescribe the use of less radical interventions as an entry point to deal with SoC. Providing guidance to formulate roadmaps into more radical interventions.	R17	C11
(Semi-)quantitative resources		
(S13) Semiquantitative assessment tool to identify risks and most concerning stages in the lifecycle.	R15	C3, C10.2
(S14) Semiquantitative assessment tool to evaluate and compare concepts.	R16	C3, C8, C10.2
(S15) A database on available alternatives with scores on their safety.	R16	C3
(S16) Quantitative methods such as LCA and RA can be done by external experts to validate concepts.	R15, R16	C3

5.4.2. The DSSS Method - A framework to support designers in dealing with SoC in products

Based on the identified requirements (Table 5.3) and several suggested resources (Table 5.4), a new version of the DSSS Method is presented. The new version is displayed as a framework in Figure 5.5, which will be the basis for further detailing of the method in the future. It presents a new process for SoC that aligns with the identified requirements (Table 5.3) and several of the suggested resources (Table 5.4). Requirements R1 to R18 are represented in the framework, while requirements R19 to R22 could be addressed in further detailed development of the method. Similarly, several suggestions in Table 5.4 are presented in the framework to illustrate when in the process they could be implemented and which requirements they could address.

The framework outlines the process for dealing with SoC in products, aligned with the double diamond diagram (Design Council, n.d.), integrating it into the overall design process while reflecting an iterative approach. The design process itself takes place within a context. The context for dealing with SoC in products is influenced by relevant stakeholders and considers the factors mentioned by participants (Section 5.4.3). The framework depicted in Figure 5.5 considers all elements of Method Content Theory as follows:

Method goal: The main goal of the DSSS Method (R6) is to achieve a product without SoC or a product containing SoC with minimized risks. The intermediate goals (R7, marked in yellow after each step in Figure 5.5) are intended to help the designer track their progress and describe what should be achieved after each step. For example, after analysing risks throughout the product's lifecycle, the designer should be able to determine which scenarios or lifecycle stages should be prioritised to minimise risk.

Method rationale: Designers need comprehensive guidance when dealing with SoC in products, which integrates seamlessly into their existing design process and incorporates a lifecycle perspective. The DSSS Method provides a systematic approach to deal with SoC in products in a variety of design assignments (e.g., design, redesign), adapting to contextual conditions. Furthermore, to measure progress towards the method goal, we have outlined assessment and validation steps to evaluate the performance of new concepts regarding substance safety and potential trade-offs. We have also defined an iterative approach for designers to assess concepts and address identified trade-offs.

Method procedure: The framework outlines the prescribed steps, their order, and several entry points based on the type of task the designer is undertaking. The workflow of Unknown SoC (in orange) is meant for redesign assignments in which

the identity of the SoC first needs to be established. If a task centres on dealing with a specific (known) SoC in a product, the Known SoC redesign workflow (in blue) will be appropriate. The shortcut (in a green dashed line) eliminates the need to assess the risks posed by the SoC throughout the product's lifecycle if a safe alternative can be identified or the SoC can be avoided entirely. Finally, in the case of a design task (not redesign), the designer might only need to become aware of potential SoC during the ideation phase, for which the Design workflow (in red) is appropriate.

Method mindset: When using the DSSS Method, designers must adopt a lifecycle approach. Designers will require a collaborative approach to involve stakeholders, to obtain data, and receive their input when formulating the problem and developing alternatives. Designers should also be resilient and comfortable with iterative approaches and with dealing with uncertainty, as there is a learning curve to SoC. Finally, designers should be open to considering potential solutions at different levels, e.g., product, component, material, chemical, and system.

Method framing:

- **Context:** The method is aimed specifically at product designers or developers. It is intended for the development of safe(r) products or to reduce risks posed by SoC throughout the lifecycle of products. It can be adapted to any product category and used for design and redesign assignments. Furthermore, the method supports the integration of relevant stakeholders throughout the process of dealing with SoC.
- **Pre-requisites:** The necessary resources and guidance have been listed to enable designers to complete each step, according to the requirements and suggestions (Tables 5.3 and 5.4). These resources have been mapped to their corresponding step in the framework. Those resources listed in blue could be implemented in the short term or were already implemented in the first version of the method, while those listed in green require further research and development. In addition to resources, the list of requirements includes functions the DSSS Method is expected to provide, such as continuous documentation and updating of collected information, which should be considered in the detailed development of the method.
- **Positioning in the design process:** The framework depicts the integration of the method into the design process (represented by the Double Diamond diagram) (Figure 5.5). Each step corresponds to the convergent and divergent stages of a design process.
- **Task:** While using the DSSS Method, designers are tasked with completing a variety of tasks. These include qualitative and semi-quantitative analyses of risks and assessments of concepts in terms of their performance in reducing risks and their potential trade-offs. Designers will also perform several forms of research, including consulting databases and collaborating with relevant

stakeholders. Designers are also required to develop concepts based on the insights from their research and the provided strategies (Avoid, Reduce, and Control).

5.4.3. Factors influencing the successful use of the method

The development of the new version of the method should also consider additional insights that we extracted from the analysis of the sessions (Table 5.5). These insights include factors that can positively or negatively affect the successful application of the method. For example, the barriers, challenges, and opportunities participants shared during the sessions. Table 5.5 depicts each of the factors linked to the corresponding codes from which they were derived.

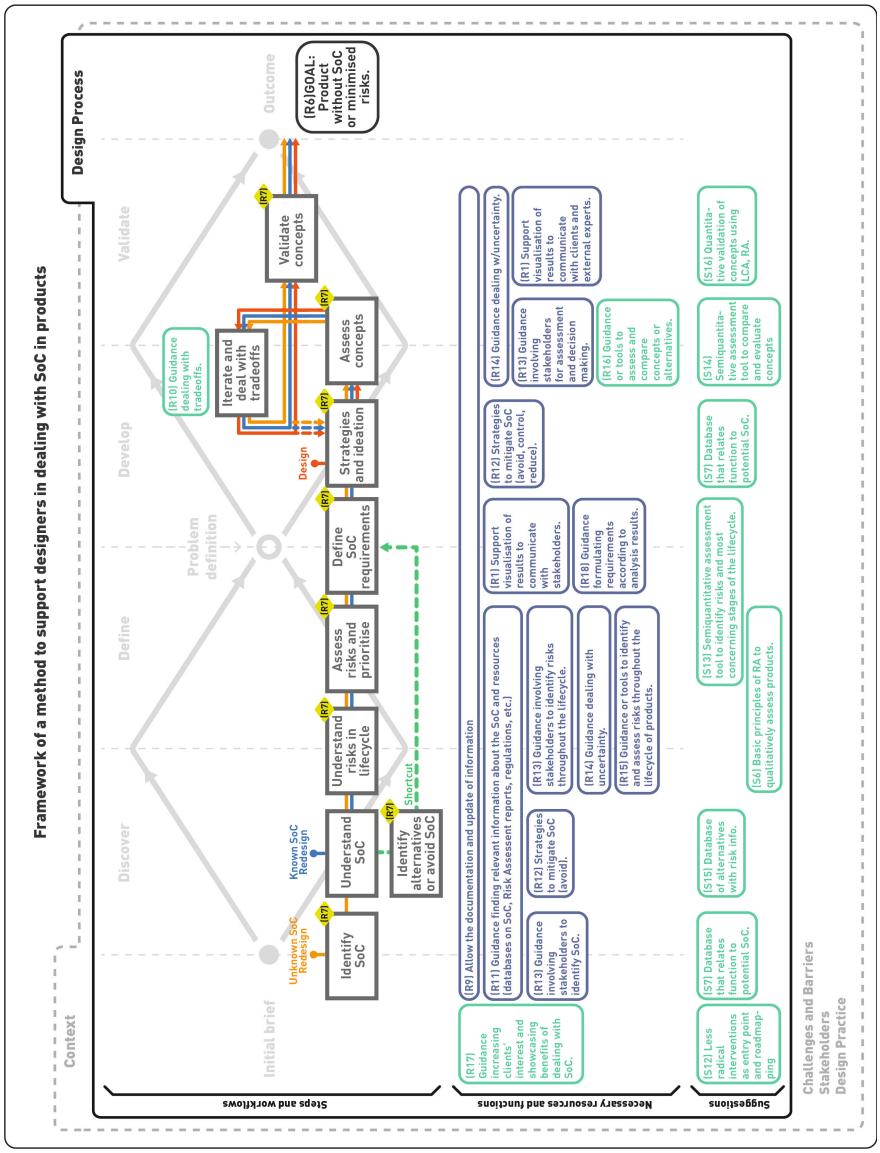


Figure 5.5. Co-created version of the DSSS Method, a framework for designers to deal with SoC in products.

Table 5.5. Factors influencing the successful use of the method.

	Identified Factors	Description	Corresponding codes
Factors with a potential negative influence	Information limitations and lack of data	- Reliable, quantifiable information on SoC or potential alternatives may not be available or accessible to designers. The lack of data hinders assessment results and argumentation. - Suppliers may not be willing or able to provide information. Additionally, accessing the "right person" to talk to in other organizations is a challenge for designers. - Access to resources (experts) and information on product and material composition is subject to the level of involvement in a project and/or organization.	C2
	Trade-offs	- Trade-offs such as new forms of risk, new forms of environmental impact, increased costs, or loss of performance may overrule the mitigation of SoC in a product.	C1, C2
	Dealing with SoC is not prioritized	- Limited budget and time allocation, and lack of interest from clients. - Clients may be unaware that designers can be involved in the mitigation of SoC in a product, they are expected to contact material suppliers directly instead.	C2
	Lack of influence in material decision making	- Concern for a lack of influence in material selection. Suppliers or internal development teams may overrule proposed material selections.	C2
	Lack of alternatives	- Designers report a concern for a lack of safe(r) alternatives that provide similar performance or are ready for implementation in large scale production.	C2
	Lack of knowledge or expertise	- Designers express doubt in their knowledge and expertise to deal with SoC, specifically chemicals.	C2
	Complexity	- Products with many components and variety in materials are expected to be more challenging when identifying/ dealing with SoC.	C2

Table 5.5. *(Continued)*

	Identified Factors	Description	Corresponding codes
Factors with a potential positive influence	Raising awareness and involving clients	- Designers believe they can raise awareness of SoC in their clients and motivate them to consider this aspect as part of assignments/briefs. - Designers expect clients to be motivated to deal with SoC, from a regulatory, and marketing advantage point of view. The topic of SoC could be easier to add to sustainability-oriented assignments.	C1, C2, C6, C11
	Solutions at other levels other than substitution	- Designers naturally ideate potential solutions at a product, component, and system level, and not exclusively at a material/substance level. Avoid strategies are naturally prioritized (alternative ways of delivering the same function).	C11, C1
	Addressing SoC as early as possible	- Addressing SoC in early stages of the development process makes strategies more likely to be implemented since changes are easier to make/implement. Prototyping was repeatedly mentioned as a strategy to obtain information for the assessment of a concept while remaining at a stage where changes are easier to implement.	C3, C8, C11
	Incremental vs radical interventions	- Designers mention the importance of prioritizing strategies that require the least modifications to the product as possible. Radical interventions can be harder to implement, due to time restrictions and lack of interest from the client.	C4, C11
	Dealing with uncertainty at different stages of the development process	- Designers appear to be familiar with the concept of uncertainty. Designers report using tools/methods more vaguely at initial stages and in more detail in later stages of the development process when more information is available. Prototyping was proposed as a strategy to reduce uncertainty, through testing. Examples of the implementation of strategies or alternatives in equivalent products or by competitors, were mentioned as useful to reduce uncertainty.	C2, C3, C11

These factors were extensively discussed during the workshops. Many emerged from conversations in which designers repeatedly expressed concerns about the client's willingness or ability to prioritize SoC in a given design project. In some cases, SoC may not be prioritized, and the complexity and potential trade-offs associated with addressing SoC can present significant obstacles. However, designers shared ideas on how they could raise client awareness about SoC and acknowledged their role in influencing clients' decisions to incorporate it into design assignments. Another key point of discussion was the prevalent lack of data surrounding SoC. Designers had differing views on this issue. Some were concerned about data availability, the difficulty of navigating existing data, and the challenges of dealing with uncertainty:

Quote 1: Having the information on the chemical and its risks is very important and super difficult, but then we can tell a story and make good arguments. And that is what we need to convince our clients.

Quote 2: I think another problem would be if we suggest alternative materials, do we have the data to know that this is actually a better solution?

Quote 3: One of the main barriers is that we don't know. If you ask suppliers specific questions about materials or recycling, they just don't know the answers.

In contrast, other designers suggested that working with approximate data, leveraging expert discussions, and iterative processes could help address the lack of precise data and still support decision-making:

Quote 4: Well, you want to be sure to have reliable information, right? But when doing these cases, I don't need the decimals; even if we are working with assumptions, that's still going to be the key hotspot. You could also do a rough estimation.

Quote 5: I think sometimes you have a few options, and you just discuss them with the clients and go through the pros and cons. And of course, they have an expertise as well. And sometimes we don't know everything yet, for example, about production, so we also need to sometimes have a chat with the injection moulding to know more.

Overall, the mood during the sessions was positive. Despite recognizing the limitations and barriers, many designers were quick to suggest potential solutions. Moreover, when applying the first version of the method to a case, designers were able to identify risks across the product lifecycle, generate ideas to address SoC at various levels (material, product, system, etc.), and evaluate proposed alternatives. They used basic information on the chemical, which we provided during the session, along with estimates based on their expertise and group discussions.

5.5. Discussion

In this section, we first compare the initial version of the DSSS Method to the revised framework. We subsequently discuss co-creation and Method Content Theory to support method development, while providing recommendations for future development and research. We then discuss some of the identified factors that influence the successful use of the DSSS Method. Finally, we present the limitations of this study and establish the following steps for the detailed development of the revised version of the DSSS Method.

5.5.1. Evolution of the DSSS Method

We can distinguish several characteristics that demonstrate the evolution of the first version of the method developed based on theoretical insights. The revised version introduces specific steps, replacing the initial version's general three-step approach. These steps are now explicitly aligned with the design process, as represented by the Double Diamond diagram, providing a clear and structured framework. Shortcuts and flexible entry points have been incorporated to accommodate different types of assignments (e.g., design, redesign) and scenarios (e.g., known or unknown SoC). This flexibility, combined with clear guidance on applying the method across various contexts, addresses a requirement repeatedly highlighted by participants.

The revised steps correspond to the divergent and convergent stages of the design process. For example, steps involving SoC analysis are mapped to a divergent stage, while steps focused on prioritizing identified risks and defining requirements are mapped to a convergent stage. This, we expect, will provide designers with the means to integrate SoC into the larger, more complex design process. Additionally, the updated method specifies the necessary resources and functions for each step. These include existing resources and resources that should be further developed and studied. The framework offers a variety of approaches for completing a step (e.g., rules of thumb, databases, semi-quantitative assessment methods), allowing the designer to select tools based on the product's level of development and available data. This reinforces the framework's iterative characteristics and enables its use across different contexts. Finally, in this new version of the method, designers can track their progress throughout the process, guided by a main goal and intermediate goals. We expect this to enhance communication with stakeholders, such as clients, by facilitating progress updates, comparing results, and setting goals.

The new DSSS Method meets several needs identified in design for sustainability (DfS) research. As sustainability challenges grow more complex, Ceschin & Gaziulusoy (2016) argue that designers require methods that are adaptable, lifecycle-oriented, and supportive of systemic change, as well as frameworks that bridge

theory and practice. The updated DSSS Method addresses these requirements while integrating a relevant topic that designers are typically not involved in into the DfS spectrum. It guides designers toward a holistic, lifecycle approach to SoC that accounts for potential trade-offs and a diversity of stakeholders and supply chain structures.

5.5.2. Influence of Method Content Theory and Co-creation

For the development of the revised version of the DSSS Method, we have used co-creation to involve professional designers and to gather their input, informed by Method Content Theory as a guiding framework. This combination has yielded insights to adapt the method to professional practice while ensuring its completeness. First, the new version of the DSSS Method clearly establishes a specific method goal and considers all the elements established by Method Content Theory. Meanwhile, co-creation has enabled us to understand designers' everyday workflows better and to create a flexible process. Both co-creation and Method Content Theory have also allowed us to identify the necessary resources of different natures for designers to address SoC. Furthermore, we have been able to allocate which steps of the process each of these resources is necessary for. Co-creation has also been useful for obtaining suggestions from designers to address certain requirements, providing insights into how to operationalize the required resources according to the method user needs.

Utilizing the Method Content Theory as a guiding framework has facilitated a more comprehensive approach to developing the DSSS Method. Specifically, it has enabled us to address aspects previously overlooked, including integrating the method into the broader design process and clarifying the method goal. Furthermore, Method Content Theory provided a useful framework for developing the co-creation sessions and analysing the results. While Method Content Theory has enabled us to define the elements and structure of the DSSS Method and establish a framework, it is worth noting the difficulty of interpreting some of its elements. The definition of the method rationale proved challenging and was subject to interpretation among our research team. For this study, we considered Method Rationale to be the justification for the method and a means to measure progress. While the method provides several checkpoints to measure progress toward its goal, the co-creation sessions revealed additional ways to assess progress. Participants highlighted the importance of visualizing results, as this helps engage clients and other stakeholders. Clear communication of results supports the evaluation of success and further definition of strategies to reach the goal, whether through radical or incremental interventions.

Directly applying the elements of Method Content Theory to develop the new DSSS Method through co-creation was not feasible. Many of the discussion topics for the

sessions addressed multiple elements of the theory simultaneously, resulting in a complex coding scheme. However, the coding scheme we developed enabled us to translate session observations into relevant insights for each theoretical element. Method Content Theory served as both a checklist and a framework, guiding the development of co-creation sessions and activities, informing the evaluation of the initial method, and facilitating discussions on the design process in relation to SoC.

Co-creation provided specific insights and feedback for refining the method, including its tools and mechanisms. While feedback sessions on the method's first version helped identify its limitations, the most valuable insights into desired functions and procedural requirements emerged when participants independently developed hypothetical processes to address SoC. In-depth discussions about contextual factors and limitations also highlighted functional features that could help address challenges, such as result visualization, stakeholder involvement throughout the process, and an iterative approach—all of which should be incorporated in future development stages.

5.5.3. Factors that influence the use of the method and recommendations for future research

The most significant challenge identified by the participants was the limited availability of data on SoC and potential alternatives. In particular, access to detailed material compositions is limited, even though this information is essential for identifying potential SoC in materials. Additional gaps include data on chemical safety, including alternatives, and on chemical properties such as volatility and solubility. Such data may either be non-existent or inaccessible to designers. In the absence of quantitative information—such as comprehensive chemical databases and transparent material composition data—accurate assessment methods, including Risk Assessment (RA) and Life Cycle Assessment (LCA), cannot be effectively conducted. Consequently, qualitative guidance for risk identification and alternative comparison becomes essential, alongside strategies that support designers in managing uncertainty. Further study is needed to incorporate fundamental principles of risk assessment and to increase designers' awareness of SoC and the potential trade-offs associated with alternative solutions. Other techniques for obtaining data to support prospective LCA and evaluate potential environmental trade-offs should be further explored for integration with the method. For instance, designers could use patents to extract information on future impacts, as suggested by Spreafico et al. (2025), since these resources are often accessible and can provide reasonable approximations for decision-making during the design phase.

The advancement and increased accessibility of quantitative resources and information regarding product and material composition are essential for supporting designers in dealing with SoC. Digital Product Passports (European Commission,

2009, 2022) are an example of such developments. In addition to such resources, designers frequently mentioned various stakeholders who could potentially serve as sources of relevant information. Future research should focus on mapping these stakeholders and determining the types of information they can provide.

Designers emphasized that semi-quantitative assessment methods, such as simplified versions (scoring systems) of Risk Assessment (RA) and Life Cycle Assessment (LCA), could accelerate and simplify specific processes within the method while still providing adequate data for argumentation and validation. Nonetheless, it is necessary to further evaluate the trade-offs between speed and thoroughness, as well as the advantages and limitations of each approach. The future research agenda should also address issues related to managing uncertainty and dealing with trade-offs and ethical dilemmas.

The co-creation sessions allowed us to observe designers' familiarity with uncertainty. They tend to use methods in an imprecise manner in initial phases, refining their approach as they gather more information throughout the process. This is especially positive in a field with significant data limitations. However, designers continue to require support with decision-making, especially when data limitations are present. Techniques such as prototyping and iterative approaches were highlighted as effective for gathering information, while examining competitors' solutions or analogous products was noted as a valuable strategy for reducing uncertainty. This aligns with previous research identifying the strategies designers use to address different types of uncertainty (Lasso et al., 2020). These insights should be further developed in the context of SoC, specifically by enabling designers to systematically document and update information and results throughout the design process, and encouraging prototyping and testing. Additional techniques for managing uncertainty in the context of SoC, such as the precautionary principle, rules of thumb, and other preventive rather than reactive approaches at the product level, should be further explored to develop guidelines relevant to design. Furthermore, methods such as Bayesian networks, which aim to manage uncertainty in multi-variable problems by assigning probabilities based on expert opinion, could be further explored in the context of SoC, involving stakeholders to estimate risk and assess alternatives in their trade-offs (Puga et al., 2015).

Participants raised concerns that trade-offs may overshadow efforts to mitigate Substances of Concern (SoC) in products. Although regulation should play a role in prioritizing safety, participants identified other strategies to address these concerns. Addressing SoC as early as possible in the design process, when changes are still relatively easy to implement, was proposed as a solution to this issue and has been incorporated into the revised method. Future guidance should further explore strategies for managing trade-offs by combining interventions at various

levels, including material, product, and component levels. Furthermore, navigating trade-offs and ethical dilemmas remains a complex issue that requires further research to develop comprehensive guidance that quantifies and balances the competing demands of safety, sustainability, performance, and circularity.

Finally, participants were concerned that clients may not prioritize mitigating Substances of Concern (SoC) in products, resulting in insufficient time and budget for addressing this issue in project assignments. This challenge is not unique to SoC; previous research has highlighted that the incorporation of sustainable aspects into design projects is often hampered by factors such as insufficient demand for improved environmental performance, internal organizational processes within companies, lack of stakeholder cooperation, and misalignment with business interests (Baldassarre et al., 2020; Boks, 2006; Luttropp & Lagerstedt, 2006). Similar to the trade-offs issue, regulations that prioritize safety may be the main driver of resource allocation to address SoC in products. However, to further address client reluctance, guidance could focus on developing roadmaps that advocate an incremental approach to integrating SoC considerations into products, gradually leading to more radical interventions. Additionally, participants noted that clients are expected to address SoC issues directly with material suppliers, rather than involving design agencies. Raising awareness of the designers' role in mitigating risks from SoC in products is then necessary. Tools that effectively illustrate potential benefits and regulatory and market advantages could prove valuable. Moreover, it is necessary to guide designers on incorporating SoC considerations early in the design process, particularly when project scope and specific requirements are being defined in collaboration with clients.

The next step in developing the method is to refine it in detail based on the established requirements, the revised framework structure, and the recommendations established above. Several requirements, such as integrating the steps into the design process and affording different entry points, have already been incorporated into the framework. However, others should be addressed during the detailing phase. Finally, the revised method should be tested in real-life cases, preferably with design professionals, focusing on its usability and effectiveness in mitigating SoC-related risks in product development, following, for example, Cash et al. (2023).

5.5.4. Limitations of the study

While this study has provided valuable material for further development and research, several limitations that may have affected the collected data must be acknowledged. Participants had limited time during the co-creation sessions to complete all of the defined activities. This may have limited their input when asked to develop their own process to deal with SoC. It may also have affected the provision of feedback on the method's initial version. Additionally, the workshop set-

ting did not reflect a typical real-life design process. In a more ideal scenario, the participants could have been asked to use the initial version of the method in a longer-term, realistic assignment.

Furthermore, the number of participants was limited. The size of the groups in the sessions, however, was challenging enough to interpret and generate transcripts of the recorded conversations. Ideally, more groups would have been part of the study to increase the pool and diversity of participants. In addition, the study was done exclusively with design agencies. By excluding other product development settings, such as research and development departments within manufacturers, we miss insights into their approach to SoC. These include specific challenges or benefits to the process of dealing with SoC as internal teams, with perhaps better access to information.

5.6. Conclusion

This study co-created a revised version of the Design for Substance Safety and Sustainability (DSSS) Method with design professionals to address the urgent need for tools to help designers manage Substances of Concern (SoC). Guided by Method Content Theory and insights from co-creation workshops conducted in design agencies, we transformed the method, originally theoretical, into a practical framework tailored for professional use. Co-creation workshops conducted in design agencies yielded valuable insights for further developing the method, resulting in a revised framework, a set of procedural and functional requirements, and both qualitative and quantitative resources to help designers address Substances of Concern (SoC) in products.

The DSSS Method is designed to address SoC in products comprehensively, through a holistic approach that considers the entire product lifecycle. The revised DSSS Method integrates into iterative design processes, as represented by the Double Diamond diagram. Its primary aim is to eliminate SoC from products or, when unavoidable, mitigate associated risks. The framework depicts a systematic step-by-step approach, flexible entry points to suit various assignments, and relevant resources for each stage of the process. In developing the DSSS Method, we also identified factors that may influence its successful application, either positively or negatively.

This work represents a significant advancement in the field of design, where methods to address SoC remain scarce despite their critical role in promoting sustainability and circularity. Participants' enthusiasm to engage with this topic and their interest in addressing SoC highlight the pressing need for such a resource. While further testing in real-world contexts is necessary, this study has already made

substantial progress by integrating the perspectives of professional designers and applying Method Content Theory to ensure the method aligns with the principles of "good" design methods. This work also sets a future research agenda, focusing on the advancement of qualitative and quantitative resources to support designers, such as simplified forms of RA and LCA to estimate risks throughout the lifecycle of products and assess alternatives, guidance dealing with uncertainty throughout the design process, and guidance estimating and dealing with potential trade-offs. Ultimately, the DSSS Method equips designers with a powerful framework to mitigate the harmful impacts of SoC on human health and the environment, contributing to the creation of safer, more sustainable, and circular product designs.

5.7. Appendices

Supplementary Material 5A – This document presents the first version of the DSSS Method.

Supplementary Material 5B – This document provides a detailed description of the co-creation sessions and the protocol followed.

Supplementary Material 5C – This Excel document presents a complete set of the quotes obtained during the co-creation sessions organized according to the pre-defined codes/topics.

Supplementary Material 5D – This document contains the detailed analysis and translation of the obtained quotes into requirements for the method development.

Supplementary Material 5E – This document includes images of the processes to deal with SoC proposed by the participants during the sessions.

These appendices are available in: https://data.4tu.nl/datasets/f8ee9ffd-c7cb-4287-8693-399ff93c802c

The dataset containing the full transcript of the co-creation sessions is openly available through the 4TU.Research Data repository and has the following DOI: https://data.4tu.nl/datasets/3a718f3f-0830-41f5-bb8d-4f808597ac3a

5.8. References

Alaranta, J., & Turunen, T. (2021). How to Reach a Safe Circular Economy?—Perspectives on Reconciling the Waste, Product and Chemicals Regulation. Journal of Environmental Law, 33(1), 113–136. https://doi.org/10.1093/JEL/EQAA016

Apel, C., Kümmerer, K., Sudheshwar, A., Nowack, B., Som, C., Colin, C., Walter, L., Breukelaar, J., Meeus, M., Ildefonso, B., Petrovykh, D., Elyahmadi, C., Huttunen-Saarivirta, E., Dierckx, A., Devic, A. C., Valsami-Jones, E., Brennan, M., Rocca, C., Scheper, J., … Soeteman-Hernández, L. G. (2024). Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives. In Current Opinion in Green and Sustainable Chemistry (Vol. 45). Elsevier B.V. https://doi.org/10.1016/j.cogsc.2023.100876

Bakker, C. A., Wever, R., Teoh, C., & de Clercq, S. (2010). Designing cradle-to-cradle products: A reality check. International Journal of Sustainable Engineering, 3(1), 2–8. https://doi.org/10.1080/19397030903395166

Baldassarre, B., Keskin, D., Diehl, J. C., Bocken, N., & Calabretta, G. (2020). Implementing sustainable design theory in business practice: A call to action. Journal of Cleaner Production, 273, 123113. https://doi.org/10.1016/J.JCLEPRO.2020.123113

Barouta, D., Alassali, A., Picuno, C., Bruno, M., Syranidou, E., Fiore, S., & Kuchta, K. (2022). E-plastics in a circular economy: A comprehensive regulatory review. Journal of Cleaner Production, 355, 131711. https://doi.org/10.1016/J.JCLEPRO.2022.131711

Beekman, M., Bakker, J. B. C., van Leeuwen, L., Waaijers-van der Loop, S., Zijp, M., & Verhoeven, J. (2020). Coping with Substances of Concern in a Circular Economy.

Bluesign. (n.d.). Solutions and services for a sustainable textile industry. Retrieved August 23, 2024, from https://www.bluesign.com/en/

Bodar, C., Spijker, J., Lijzen, J., Waaijers-van der Loop, S., Luit, R., Heugens, E., Janssen, M., Wassenaar, P., & Traas, T. (2018). Risk management of hazardous substances in a circular economy. Journal of Environmental Management, 212, 108–114. https://doi.org/10.1016/J.JENVMAN.2018.02.014

Boks, C. (2006). The soft side of ecodesign. Journal of Cleaner Production, 14(15–16), 1346–1356. https://doi.org/10.1016/J.JCLEPRO.2005.11.015

Bolaños Arriola, J. (2025). Transcripts of co-creation sessions with design agencies. Underlying data for the article: Safe and sustainable by design: co-creating a design method for dealing with harmful substances in product design (dataset). https://doi.org/https://data.4tu.nl/datasets/3a718f3f-0830-41f5-bb8d-4f808597ac3a

Bolaños Arriola, J., Aghaeian, S., Bakker, C., & Balkenende, R. (2024). Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases. Circular Economy and Sustainability, 1–20. https://doi.org/10.1007/S43615-024-00449-4/FIGURES/1

Brandsma, S. H., Leonards, P. E. G., Koekkoek, J. C., Samsonek, J., & Puype, F. (2022). Migration of hazardous contaminants from WEEE contaminated polymeric toy material by mouthing. Chemosphere, 294, 133774. https://doi.org/10.1016/J.CHEMOSPHERE.2022.133774

Brezet, H., & van Hemel, C. (1997). Ecodesign : a promising approach to sustainable production and consumption. United Nations Environment Programme, Industry and Environment, Cleaner Production.

Cash, P., Daalhuizen, J., & Hekkert, P. (2023). Evaluating the efficacy and effectiveness of design methods: A systematic review and assessment framework. Design Studies, 88, 101204. https://doi.org/10.1016/j.destud.2023.101204

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. Design Studies, 47, 118–163. https://doi.org/10.1016/J.DESTUD.2016.09.002

Chemsec. (n.d.). SIN List. Retrieved August 23, 2024, from https://sinlist.chemsec.org/

Cradle to Cradle Products Innovation Institute. (n.d.). Cradle to Cradle- The standard. Retrieved August 23, 2024, from https://c2ccertified.org/the-standard

Daalhuizen, J., & Cash, P. (2021). Method content theory: Towards a new understanding of methods in design. Design Studies, 75, 101018. https://doi.org/10.1016/J.DESTUD.2021.101018

de Koning, J. (2023). Exploring co-creation with agri-food smallholders in Vietnam. International Journal of Food Design. https://doi.org/https://doi.org/10.1386/ijfd_00056_1

de Koning, J. (Jotte I. J. C., Crul, M., & Wever, R. (2016). Models of co-creation. Proceedings of the ServDes.2016 Conference. https://www.researchgate.net/publication/303541138

Delft University of Technology. (2024). Idemat. https://www.ecocostsvalue.com/ecocosts/

Design Council. (n.d.). Framework for Innovation. Retrieved August 28, 2024, from https://www.designcouncil.org.uk/our-resources/framework-for-innovation/

ECHA. (n.d.). Information on chemicals. Retrieved August 23, 2024, from https://echa.europa.eu/information-on-chemicals

Ecoinvent. (n.d.). Ecoinvent 3,1. Retrieved August 23, 2024, from https://ecoinvent.org/

Ellen Macarthur Foundation. (2016). Safe and Circular Material Choices. https://www.ellenmacarthurfoundation.org/circular-design-guide/methods

European Commission. (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex-%3A32009L0125

European Commission. (2018). Regulation (EC) No 1907/2006 Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). 219–219. https://doi.org/10.4324/9781315270326-156

European Commission. (2020). Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN

European Commission. (2022). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT On making sustainable products the norm. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0140&qid=1649112555090

European Commission. (2024). Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401781

Faludi, J., Hoang, T., Gorman, P., & Mulvihill, M. (2016). Aiding alternatives assessment with an uncertainty-tolerant hazard scoring method. Journal of Environmental Management, 182, 111–125. https://doi.org/10.1016/J.JENVMAN.2016.07.028

Hahladakis, J. N., Iacovidou, E., & Gerassimidou, S. (2023). An overview of the occurrence, fate, and human risks of the bisphenol-A present in plastic materials, components, and products. Integrated Environmental Assessment and Management, 19(1), 45–62. https://doi.org/10.1002/IEAM.4611

Hill, P. J., Taylor, M., Goswami, P., & Blackburn, R. S. (2017). Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance. Chemosphere, 181, 500–507. https://doi.org/10.1016/J.CHEMOSPHERE.2017.04.122

Hosea, L., & Salvidge, R. (2024a). 'Forever chemicals' found in drinking water sources across England. The Guardian . https://www.theguardian.com/environment/2023/nov/28/forever-chemicals-found-in-drinking-water-sources-across-england

Hosea, L., & Salvidge, R. (2024b). Landfills across England could be leaking harmful toxic ooze, warn experts. The Guardian. https://www.theguardian.com/environment/article/2024/jun/28/landfill-sites-across-england-could-be-leaking-harmful-toxic-ooze-warn-experts-forever-chemicals-pfas

Lasso, S., Kreye, M., Daalhuizen, J., & Cash, P. (2020). Exploring the link between uncertainty and project activities in new product development. Journal of Engineering Design, 31(11–12), 531–551. https://doi.org/10.1080/09544828.2020.1839743; WGROUP:STRING:PUBLICATION

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., de Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy — weeding out the toxics first. Environment International, 94, 230–234. https://doi.org/10.1016/J.ENVINT.2016.05.012

Luttropp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. Journal of Cleaner Production, 14(15–16), 1396–1408. https://doi.org/10.1016/J.JCLEPRO.2005.11.022

Main, D. (2024). Microplastics are infiltrating brain tissue, studies show: 'There's nowhere left untouched.' The Guardian . https://www.theguardian.com/environment/article/2024/aug/21/microplastics-brain-pollution-health

Mattelmäki, T., & Sleeswijk Visser, F. (2011). LOST IN CO-X INTERPRETATIONS OF CO-DESIGN AND CO-CREATION.

NRDC. (2021). A review of PFAS as a chemical class in the textile sector.

Perkins, T. (2024). It's 'almost impossible' to eliminate toxic PFAS from your diet. Here's what you can do. The Guardian . https://www.theguardian.com/us-news/article/2024/jul/22/pfas-forever-chemicals-diet

Puga, J. L., Krzywinski, M., & Altman, N. (2015). Points of Significance: Bayesian networks. Nature Methods, 12(9), 799–800. https://doi.org/10.1038/NMETH.3550

Sanders, E., & Stappers, P. (2012). Gathering data in the field . In Convivial Toolbox -Generative Research for the Front End of Design (pp. 147–197). BIS Publishers.

Sleeswijk Visser, F., Jan Stappers, P., van der Lugt, R., B-N Sanders, E., Van Der Lugt, R., & B-n Sanders, E. (2005). Contextmapping: experiences from practice. CoDesign, 1(2), 119–149. https://doi.org/10.1080/15710880500135987

Spreafico, C., Thonemann, N., Pizzol, M., Arvidsson, R., Steubing, B., Cucurachi, S., Cardellini, G., & Spreafico, M. (2025). Using patents to support prospective life cycle assessment: opportunities and limitations. International Journal of Life Cycle Assessment, 30(2), 201–220. https://doi.org/10.1007/S11367-024-02404-9/TABLES/8

Straková, J., Grechko, V., Sara, B., Karlsson, T., & Vito, B. (2022). PFAS in Clothing,: Study in Indonesia, China, and Russia Shows Barriers for Non-toxic Circular Economy. (Issue February).

TÜVRheinland. (2024). Whitepaper – Restricted Substances List (RSL). www.tuv.com

United Nations. (2011). Globally harmonized system of classification and labelling of chemicals (GHS). United Nations.

United Nations Environment Programme. (2009). Design for Sustainability: A Step-by-Step Approach. United Nations Environment Programme (UNEP). https://wedocs.unep.org/xmlui/handle/20.500.11822/8742

Usman, A., & Ahmad, M. (2016). From BPA to its analogues: Is it a safe journey? Chemosphere, 158, 131–142. https://doi.org/10.1016/J.CHEMOSPHERE.2016.05.070

van Dam, S., Sleeswijk Visser, F., & Bakker, C. (2021). The Impact of Co-Creation on the Design of Circular Product-Service Systems: Learnings from a Case Study with Washing Machines. The Design Journal, 24(1), 25–45. https://doi.org/10.1080/14606925.2020.1851427



Chapter 6

Mapping uncertain risks and impacts of substances of concern in product life cycles, an SSbD tool for product developers

This chapter was submitted as:

Bolaños Arriola, J., Weber, M., van Dulmen, N., Guinée, J., Vijver, M.G., & Balkenende, R. Mapping uncertain risks and impacts of substances of concern in product life cycles - an SSbD tool for product developers. Circular Economy and Sustainability.

Abstract

Current tools in Safe and Sustainable by Design (SSbD) frameworks, such as those proposed by the Joint Research Centre, support the development of safer, more sustainable substances, materials, and manufacturing processes. However, these tools were not designed for product developers or designers and therefore do not align with the iterative and creative nature of product development, nor with its specific needs and constraints. Broad adoption of SSbD requires tiered, resource-efficient assessments tailored to the specific needs of different professionals. The product developer's perspective is essential for creating safer, more sustainable products, enabling context-specific evaluation of chemical applications, substances of concern (SoC), and product life cycles. In a circular economy, where products, parts, and materials circulate, holistic views become critical, as emissions and exposures may increase and accumulate. Therefore, we developed the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) tool, which integrates principles of Life Cycle Assessment (LCA) and Risk Assessment (RA) into a product development context. Through iterative development based on real-life cases of products containing SoC, we combined essential elements of RA and LCA into a product development workflow. Expert input on environmental assessment and ecotoxicology informed each iteration of the process. MAPSSS supports product developers in identifying and assessing SoC risks, trade-offs, uncertainty levels, and environmental impacts across the product life cycle. It enables the identification of risk hotspots in reference products, supporting mitigation strategies and comparison with new solutions. This represents an initial step toward a product-specific SSbD assessment tool for early design stages.

6.1. Introduction

Safe and Sustainable by Design (SSbD) aims to be a transformative concept in which chemical safety and sustainability are integral values throughout the innovation process. SSbD is approached from a strong chemicals and materials development perspective, focusing on delivering functionality while avoiding harmful impacts on human health and the environment (Apel et al., 2024; Caldeira et al., 2022). However, these approaches do not necessarily incorporate a product design perspective. Ideally, the processes involved in implementing the SSbD concept are carried out by interdisciplinary teams. In practice, however, products are often developed outside such environments. Decision-making often falls in the hands of product developers, who may lack the resources and knowledge to conduct intensive sustainability assessments, limiting their ability to make informed choices that effectively prevent risk.

Products, which we define as physical artifacts designed to fulfil a function or user need directly, are made from materials, and those materials are made of chemical substances. The chemistry hidden inside everyday products can be hazardous. Many products contain and release Substances of Concern (SoC) throughout their life cycle, generating potential risks to human and environmental health. For illustration, over 60% of the 285 tons of chemical substances produced in Europe in 2022 were classified as hazardous to the environment or human health (Eurostat, 2022). A 2025 study assessing 16,325 chemicals used in plastics found that 10,726 (65.7%) lacked sufficient data to determine their safety, while 4,219 (25.9%) were identified as SoC (Monclús et al., 2025). Meaning we can conclude only 1,380 chemicals (8.4%) could be characterized as safe. In fact, only a small proportion of the chemicals in use have been rigorously assessed for hazards, and even fewer are regulated to limit their use in specific applications (European Environment Agency, 2019).

Health and environmental hazards of SoC include mutagenicity, reprotoxicity, and carcinogenicity, among others (UNECE, 2023). In addition, chemicals that are persistent, bioaccumulative, and/or toxic (PBT), and/or mobile (PMT) are also classified as SoC (UNECE, 2023). Once in the environment, they can have large-scale impacts that threaten the integrity of Earth system processes (Persson et al., 2022). The transition to a circular economy could further aggravate the risks of SoC, as these substances are emitted and accumulated in the environment not only throughout their initial life cycle, but also during subsequent life cycles of products, components, and materials (e.g., through reuse, recycling) (Bodar et al., 2018). Regulatory involvement and public awareness towards SoC in products and the CE are increasing, as evident from, for example, the European Chemicals Strategy for Sustainability (European Commission, 2020) and the Ecodesign for Sustainable

Products Regulation (European Commission, 2024), which establishes ecodesign requirements in products, including the phasing out of substances that hinder circularity.

Current SSbD strategies addressing SoC predominantly focus on the development of inherently safer chemicals and processes (see e.g., van Dijk et al. (2022, 2025)). However, implementing such approaches is not always feasible (Soeteman-Hernández et al., 2023). In many cases, the available data remains insufficient to substantiate claims that proposed alternatives offer reduced impacts on human health and the environment (Beekman et al., 2020). This data insufficiency is particularly pronounced during early stages of substance and product development, where solution spaces are still broad and characterized by high uncertainty (Collingridge, 1980). Consequently, these complexities and data demands may constrain widespread adoption or lead to paralysis by analysis (van Dijk et al., 2025).

To operationalize SSbD, available SSbD frameworks integrate life cycle assessment (LCA) and chemical risk assessment (RA) (See e.g., the Joint Research Centre (JRC) SSbD framework, European Environment Agency (EEA), CEFIC, and TNO (Braakhuis & Fransman, 2024; Caldeira et al., 2022; CEFIC, 2024; European Environment Agency, 2021)). In the context of SSbD, LCA is used to determine the total potential impacts on human and environmental health of a product over its entire life cycle, enabling comparisons between product alternatives. The assessment is holistic and cannot assess actual environmental concentrations and effects, because it lacks the necessary temporal and spatial information (Guinée et al., 2017). RA, on the other hand, quantifies risk characterizations of chemicals by specifying emissions at particular points in a product's life cycle, site, and time. The results of LCA and RA, therefore, serve as complementary tools in an SSbD assessment (see Guinée et al. (2017)).

With around 80% of a product's environmental impact determined during the design phase (European Commission, 2018), the product developer's perspective plays a crucial role in creating safer, more sustainable products. A product perspective allows for context-sensitive considerations related to the specific application of a SoC and the life cycle of the product containing it. For instance, the question of whether certain SoC, such as Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS), are essential may be more appropriately evaluated from a product perspective, which can reveal that specific substances are not always required for particular applications (Cousins et al., 2019; Schellenberger et al., 2019). Furthermore, trade-offs associated with chemical substitution are often only evident when assessed at the product level, preferably considering the full life cycle of the product. For instance, PFAS in synthetic textiles can be replaced with non-fluorinated water-repellent treatments or weaving techniques that achieve waterproofing without additives. However, these alternatives may lead to lower performance, material integrity

issues, or functional trade-offs, such as stiffer fabrics unsuitable for specific applications (Hill et al., 2017; Holmquist et al., 2016).

Since a complete characterization of a SoC is not always feasible, product design can offer a systems-thinking lens to anticipate product-specific conditions and potential behaviours of SoC. Such an approach also opens possibilities for interventions at multiple levels: material, component, product, system, and process (Bolaños Arriola et al., 2024). Despite this potential, the role of product developers in addressing SoC remains limited and is rarely discussed in the scientific literature. The involvement of product developers, such as industrial designers, requires novel approaches and/or tools specific to their expertise, which are currently not available. Alongside the general limitations of SSbD discussed earlier, current frameworks, such as the JRC's, do not adequately serve product developers. Several reasons explain this mismatch: The frameworks are linear as per the stage-gate model and focus on assessment over ideation. In other words, existing frameworks do not leverage the iterative, learning-by-doing nature of product development, nor its strengths in stakeholder management and research in the face of inherent uncertainty (Cross, 2001). Furthermore, the necessary material and process safety data are rarely accessible to product developers, such as design engineers in design agencies, due to confidentiality issues along the value chain (Olisah et al., 2025), and are often difficult for non-experts to interpret and manage.

To address this gap, assuming the product developer must tackle all the aforementioned challenges without support from other experts, we aim to develop a pragmatic tool that operationalizes the principles of LCA and RA in a manner directly applicable to real-world design practice and the product development process. By combining relevant principles from these methods, we aim to build on the increasingly adopted JRC SSbD framework from a product design perspective. Previous research on designing for substance safety, which has identified criteria for developing design tools and methods to address SoC (Bolaños Arriola et al., 2023, 2024, 2025), served as a starting point.

This paper presents a first version of the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) tool for product developers. The tool supports the assessment of SoC risks throughout the life cycle of products and their alternatives. The identification of potential hazardous substances in the product and the provision of strategies to deal with the identified SoC risks or trade-offs fall outside the scope of the assessment tool. We envision the further development of this tool as an iterative process, in which subsequent research refines the initial version and incorporates new aspects in the future. After outlining its development process, we present the tool, describing its workflow and components, and illustrate its use with a case study. The paper focuses on the description of the

assessment tool and does not focus on providing recommendations for potential design solutions to SoC risks.

6.2. Method – Tool development process

To develop the MAPSSS tool, we integrated key elements of Risk Assessment (RA) and Life Cycle Assessment (LCA) into a product development workflow. The current version was created by adapting LCA and RA principles, drawing on theoretical foundations, expert collaboration, and repeated testing on two case studies that informed the design and refinement of its components. The tool has been developed through a learning-based approach, and we envision its continued evolution as an iterative and incremental process, in which ongoing research will further refine this initial version and incorporate new functionalities over time. In this section, we present: 1) tool development criteria, 2) case selection and iterative development process of the tool, 3) adaptation of extracted LCA elements for the tool, 4) adaptation of extracted RA elements for the tool, and 5) tool integration into the product development process.

6.2.1. Criteria for the development of the tool

We built on previous research that explored approaches and strategies for product developers to address the risks of SoC in products. Bolaños Arriola et al. (2025) established requirements for the development of tools and methods that support product developers in mitigating SoC risks and minimizing the overall footprint of chemical, material, and product life cycles. Based on this research, we defined the following criteria for the development of the tool:

C1. Support the identification and assessment of SoC risks throughout the product life cycle by a product developer.
C2. Support the identification of knowledge gaps and uncertainty by a product developer.
C3. Support decision-making under uncertainty by a product developer.
C4. Support the comparison of product design alternatives, regarding SoC risks and potential environmental trade-offs over the life cycle.
C5. Integrate into the product development process, considering an iterative approach and a life cycle perspective.
C6. Consider potential data limitations and the disciplinary boundaries of product development expertise while leveraging the strengths of design practice, such as problem framing, systems thinking, and stakeholder involvement.

The remainder of the method section describes the approach for fulfilling these criteria.

6.2.2. Selection and iterative analysis of cases for tool development

To develop the tool, we analysed and repeatedly applied versions of the MAPSSS tool to two different cases of products containing SoC for which alternative options exist. For each case, we considered a non-exhaustive list of previously implemented risk mitigation strategies (hereafter referred to as alternatives) (Table 6.1). The analysis involved adapting elements of RA and LCA to create life cycle maps for both the reference products and their respective alternatives. This analysis focused on identifying and prioritizing SoC risk hotspots throughout the product life cycle, as well as evaluating potential trade-offs. The iterative process of mapping the cases helped refine the adapted RA and LCA elements, define the tool steps, and improve visualization features. The two different cases allowed us to develop a versatile tool applicable to a wide range of product types, containing several SoC that behave differently, resulting in various possible risk characterization scenarios.

The two cases are representative of:

- Different SoC types with different emission mechanisms and hazard profiles, as defined in the introduction.
- Differences in exposed populations and use patterns result in a variety of risk hotspots.
- Different risk mitigation strategies. To describe the strategies applied in the alternatives, we used the framework by Bolaños Arriola et al. (2024) which defines three categories of design strategies to address SoC in products: Avoid (any intervention that prevents the use of the SoC), Reduce (any intervention that lowers the content of a SoC in a product), and Control (any intervention that prevents emissions of, or exposure to a SoC throughout a product's lifecycle).

Table 6.1. The selected cases and their alternatives for the analysis and iterative development of the MAPSSS tool per risk mitigation strategy (Bolaños Arriola et al., 2024)

Selected product and SoC (reference product)	Risk mitigation strategy	Selected alternatives
Polyurethane foam mattresses containing hazardous flame retardant, Tris(chloropropyl) phosphate (TCPP).	Avoid: Alternative function	Polyester 3D structure that is inherently flame-retardant replaces the foam.
	Reduce: Reduce SoC content Avoid: Substitution	Denser foam with improved fire retardancy replaces the low-density foam; the flame-retardant content is reduced and replaced by melamine.
	Control: Controlled recovery	Closed-loop recycled foam.
Agricultural mulch film generating microplastics. Polyethylene (PE) film (non-biodegradable), no recovery.	Avoid: Substitution	Polybutylene adipate terephthalate (PBAT) film (biodegradable) onsite degradation.
	Control: Controlled recovery	PE film (non-biodegradable) with recovery.

Both cases were analysed using the following protocol:

1. A life cycle map indicating exposure scenarios and risk hotspots was made for the reference product.
2. A life cycle map indicating exposure scenarios and risk hotspots was made for each of the selected alternatives.
3. The maps of the reference products were compared to those of their corresponding alternatives to identify potential risks and environmental trade-offs.

Data on the cases was collected through desk research as well as personal correspondence with manufacturers and other stakeholders throughout the value chain. The mapping process was conducted independently by three researchers, following the protocol. The results were reviewed collaboratively to refine the tool elements and ensure alignment with the previously established criteria. Additionally, RA and LCA experts were consulted to revise the resulting maps and assess the tool's alignment with the established criteria. All of the resulting maps can be found in Supplementary Material 6A. The mattress containing flame retardants is used as a case study in section 6.3.2 to illustrate the tool and its components.

6.2.3. Adaptation of LCA elements for product developers

We extracted elements of life cycle assessment (LCA) and adapted them to meet the criteria introduced in section 6.2.1. We did this based on existing LCA guides that apply the method in accordance with ISO standards, such as the Handbook of

LCA (Guinée et al., 2002). Three LCA elements were extracted and adapted to fulfil the criteria presented in section 6.2.1 (specifically C2, C4, and C5):

1. Visual elements of lifecycle mapping or system mapping to represent the life cycle of the product, including unit processes, inflows and outflows, and a system boundary.
2. The definition of a functional unit and reference flows to enable the comparison of the reference product to its alternatives.
3. A set of rules to support the identification of environmental impacts that may emerge when mitigating chemical risks through redesign, across a product's life cycle. We developed a list of what we defined as trade-off rules by characterizing typical trade-offs associated with design interventions at the chemical, material, component, product, and system levels. For this, we incorporated the same risk mitigation strategies introduced in section 6.2.2 (Avoid, Reduce, Control) (Bolaños Arriola et al., 2024). We organized the resulting rules by the life cycle stage they address, resulting in an initial list.

Since this is a high-level approach to estimating potential environmental trade-offs, the trade-off rules currently only consider climate change and resource use as environmental impact categories. The adaptation of these LCA elements was refined through the iterative process presented in section 6.2.2 and by incorporating expert feedback.

6.2.4. Adaptation of RA elements for product developers

We extracted elements of chemical risk assessment (RA) and adapted them to meet the established criteria. Our adaptation aligns with established RA frameworks (Boersema & Reijnders, 2009; Guinée et al., 2017; Van Leeuwen & Vermeire, 2007). We adapted these frameworks to facilitate a combined qualitative and semi-quantitative identification and prioritization of SoC risks to human and ecosystem health throughout the life cycle of products or their alternatives. Previous research has identified the possibility and highlighted the value of conducting preliminary safety evaluations in the early stages of development, despite data limitations (Subramanian et al., 2023). Similarly, in view of the data availability limitations in the early stages of development, the JRC also recommends a tiered approach for the assessment (Abbate et al., 2024). Chemical risk assessment is inherently adaptable and can be tailored to fit an intended purpose, considering the nature and availability of data, as well as practical constraints. To this end, we followed the recommendations of the Swedish Chemical Agency (2020) on how to assess risk scenarios qualitatively in case of uncertainty or data scarcity. Therefore, we developed a framework that follows a similar structure to the original, but we excluded RA elements for which data may not be available to product developers, or are outside their expertise, such as hazard identification and deriving predicted no-effect concentrations.

We identified and reformulated the necessary variables for product developers to describe and assess risk scenarios based on the effects, characteristics, usage patterns, and behaviour of a substance throughout the product's life cycle. Throughout the iterative process of mapping the cases, we developed visualization elements for product developers to describe exposure scenarios relevant to human and ecosystem health using the reformulated variables. These include, but are not limited to:

- Hazard category of the substance
- Volume of the emitted substance
- Use pattern and exposed population
- Use conditions and contextual factors
- Risk mitigation measures

We also formulated a scoring system with those variables as input for product developers to assign a value to the identified risk scenarios and use the obtained results to identify potential risk hotspots and facilitate comparison. This scoring system calculates what we refer to as the concern score. We defined options from which product developers can choose to describe and assess each of the defined variables. Each option was assigned a value to express its contribution to risk, translating the qualitative assessment into quantitative indicators. These values were assigned based on existing RA theory, available information on SoC, and input from RA experts. The adaptation of these RA elements was refined through the iterative process presented in section 2.2 and by incorporating expert feedback.

In addition to the concern score calculator, we also developed an uncertainty calculator, which allows product developers to indicate the level of uncertainty (low, medium, or high) for each of the concern score variables. This addition meets criteria points C2 and C6 by facilitating estimations when data is limited, while providing an indication of the reliability of the assessment, and highlighting data gaps. Finally, to meet criteria C3 and C4, we developed a set of interpretation guidelines for product developers to a) identify risk hotspots, b) gain awareness of uncertainty, and c) compare alternatives to the reference product, using the resulting maps.

6.2.5. Integration with product development workflow

Finally, to establish the necessary steps of the MAPSSS tool in accordance with product development practices, we defined a workflow by integrating the tool's intended use into the double diamond design process model (UK Design Council, 2005). This model was selected over, for example, the stage-gate model, as it represents the exploratory and converging nature of the product development process, implying the type of iterative process that we want to support. The model outlines the four main phases of the product development process: discover, define, develop, and deliver.

We defined the tool's workflow by establishing tool stages containing steps that correspond to each phase of the product development process: for the Discover phase, steps are set to explore the current problems in the reference product, for the Define phase, steps are set to identify and define risk hotspots in the reference product, for the Develop and Deliver phases, steps are set to explore alternatives, while identifying their effects on SoC risks, potential trade-offs, and to compare results to inform decision making for further development.

6.3. Results – the Mapping Assessment for Product Substance Safety and Sustainability Tool

This section presents the tool, starting with a detailed description of all its components (Section 6.3.1): mapping elements, concern and uncertainty score calculators, interpretation and comparison guidelines, and trade-off rules to identify potential trade-offs. We then illustrate the use of these elements with an example case: hospital mattresses containing toxic flame retardants (FR), which we will refer to as the reference product (Section 6.3.2). We emphasize that the use of this case is for illustrative purposes only. The complete set of resulting maps of the mattress case and the mulch film case is available as Supplementary Material 6A. Finally, we present the proposed set of steps for applying the tool and integrating its elements into the design process (Section 6.3.3).

6.3.1. Tool components

Below, we explain the adapted RA and LCA elements that constitute the tool. A protocol document guiding product developers in applying the components is available in Supplementary Material 6D.

Mapping elements

The tool provides a set of mapping elements for the product developer to describe the product system, the presence of the SoC throughout the product's lifecycle, and all identified exposure scenarios. These elements are used both to map the reference product and its potential design alternatives. These resources support users with limited LCA and RA experience, promoting the standardization of maps and enabling comparison across cases. The mapping elements are built upon ISO standards for LCA, as elaborated by Guinée et al. (2002), and existing RA guidelines (Swedish Chemical Agency, 2020; Van Leeuwen & Vermeire, 2007).

First, the tool provides a lifecycle template (Figure 6.1) that serves as a basis for all other visual elements (Figures 6.2 and 6.3). The template requires product developers to define a functional unit for comparing different product alternatives and to indicate the reference flow for assessing a specific alternative (Figure 6.1). The template predefines five life cycle stages:

- Chemical production: all processes required to produce the analysed substance and other relevant substances in materials.
- Product manufacturing: material production, processing, and assembly.
- Retail: processes required to deliver the product to its use.
- Use: activities related to product operation and maintenance, including potential misuse.
- End-of-life (EoL): processes to destroy, repurpose, or reprocess the used product.

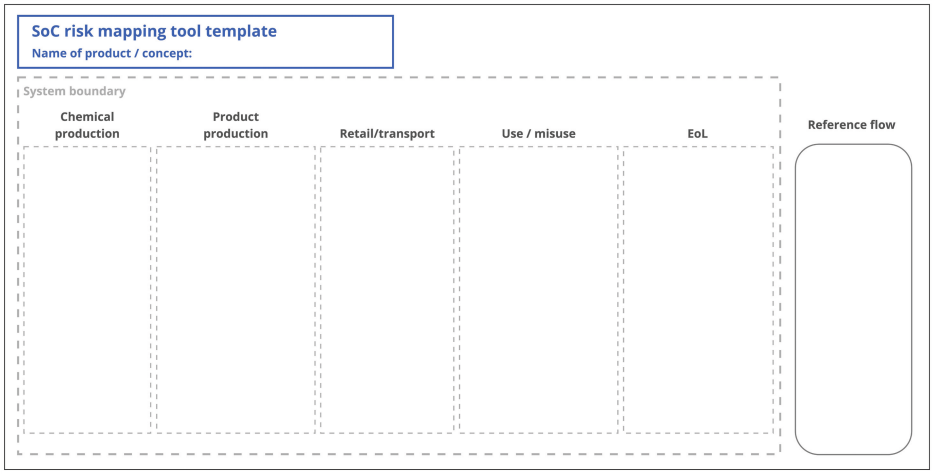


Figure 6.1. The life cycle template has five predefined lifecycle stages. The template serves as a basis for system and exposure scenario mapping and presents the reference flow of the analysed product or alternative.

The elements provided in Figure 6.2 can be used to map relevant unit processes, along with their inputs and outputs, considering the system boundary (e.g., waste generated during production can be indicated as an output that leaves the system boundary). Processes should be described in as much detail as possible, considering contextual conditions (e.g., location), to enhance the accuracy of the analysis. Initial assessments based on approximations are possible, since the level of detail can be increased as more data becomes available during product development (e.g., bill of materials), through stakeholder collaboration, consultation of LCI databases, or expert consultation. The visualization of circular scenarios is supported whenever applicable.

The tool also supports mapping the presence of SoC across the product life cycle. This is done by placing rhomboid markers (Figure 6.2) on the inputs and outputs where the SoC is expected to be present. This indicates the behaviour of the SoC and identifies “contaminated” inputs and outputs. In products where circular economy strategies are implemented, potentially contaminated outputs can flow back

into the system (in the case of closed-loop circularity) or out of the system (in the case of open-loop circularity). The pink (filled) marker identifies substances that are known as SoC. Conversely, the blue (outline) marker highlights substances with unknown or inconclusive safety profiles. This helps product developers determine which processes may be of concern and which are already addressed by mitigation strategies. In addition, these indicators flag potential risks from outputs crossing the system boundary, as their fate is unknown and their impacts can therefore not be assessed. Figure 6.4 illustrates an example of the proposed convention for utilizing the described mapping elements (Figures 6.2 and 6.3).

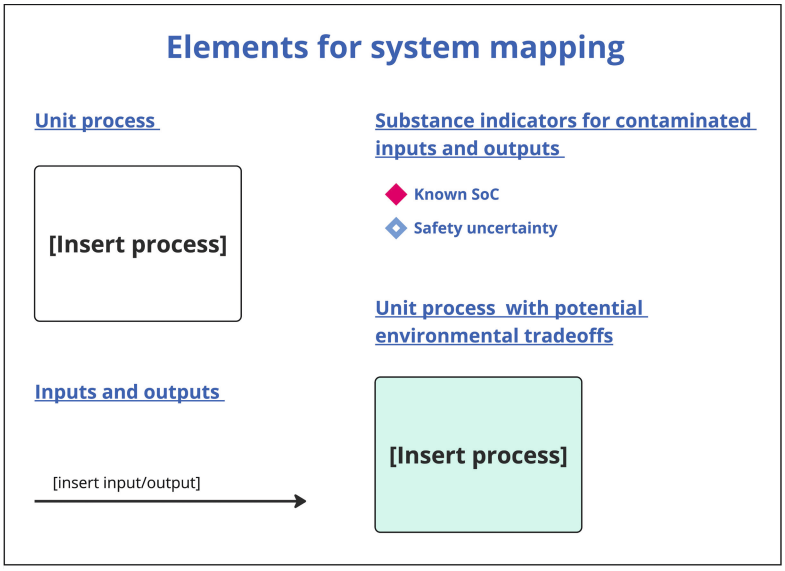


Figure 6.2. Visual elements for system mapping, indicators for "contaminated" inputs and outputs, and indicators for potential environmental trade-offs.

The tool provides a system for identifying and describing exposure scenarios throughout the product's life cycle (Figure 6.3). Exposure scenarios are defined by three variables: whether humans and/or ecosystems are impacted, the points at which exposure can occur (e.g., soil, water), and the exposed population (e.g., occupational, bystanders, vulnerable ecosystems) (Figure 6.3).

Product developers can define multiple exposure scenarios per unit process as indicated in the example in Figure 6.4. For human health, a scenario is created for each exposed group of people; for ecosystem health, one scenario is considered per unit process. The example in Figure 6.4 illustrates three scenarios: two for human health (both via air, affecting two distinct groups: bystanders and workers) and one for ecosystem health (via water and soil). An additional specification (pink asterisk) can be added if aggravating conditions are suspected, e.g., temperature or

humidity variation, wear and tear from behaviour or machinery, or interaction with other substances during maintenance. Product developers should assess whether design-specific conditions (e.g., use at high temperatures, shredding at end of life) combined with intrinsic substance characteristics (e.g., solubility, volatility, adsorption) may aggravate emissions. With these elements, the tool leverages the ability of product developers to consider a variety of product-specific scenarios, including relevant stakeholders, and other aspects such as contextual factors and behaviour.

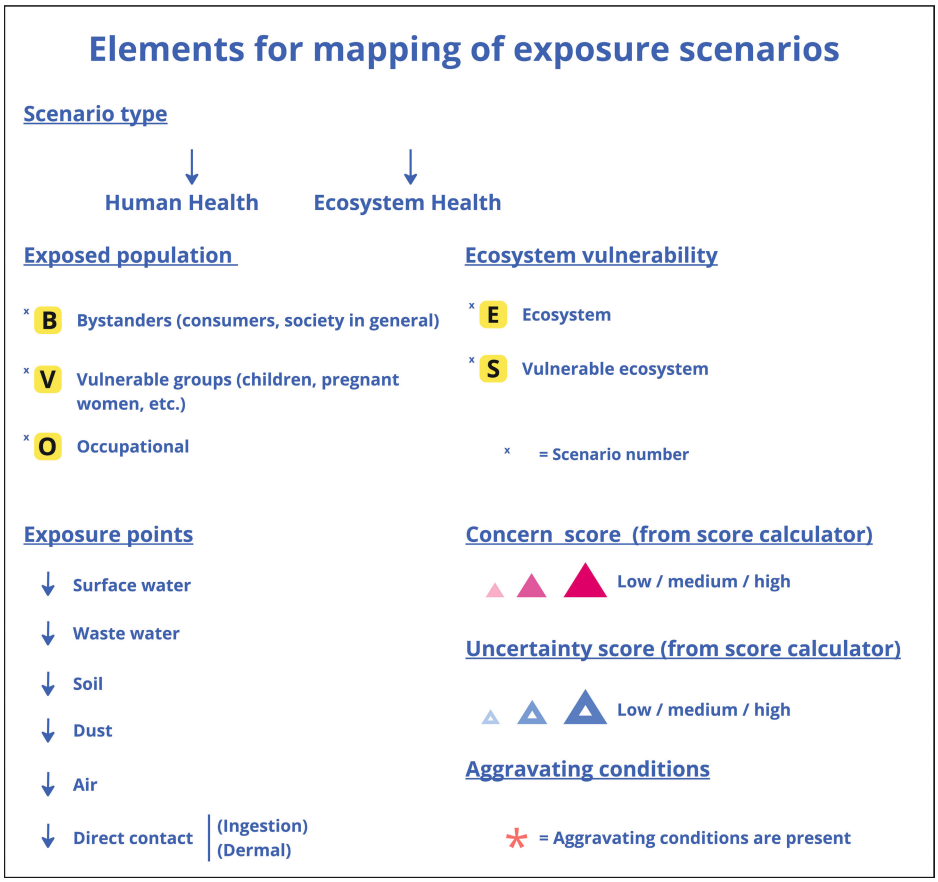


Figure 6.3. Visual elements to map and describe exposure scenarios, indicating whether human health or environmental health is affected (scenario type), the exposed groups (exposed population or ecosystem vulnerability), exposure points, potential presence of aggravating conditions (e.g., heat, misuse, etc.), and resulting concern and uncertainty scores.

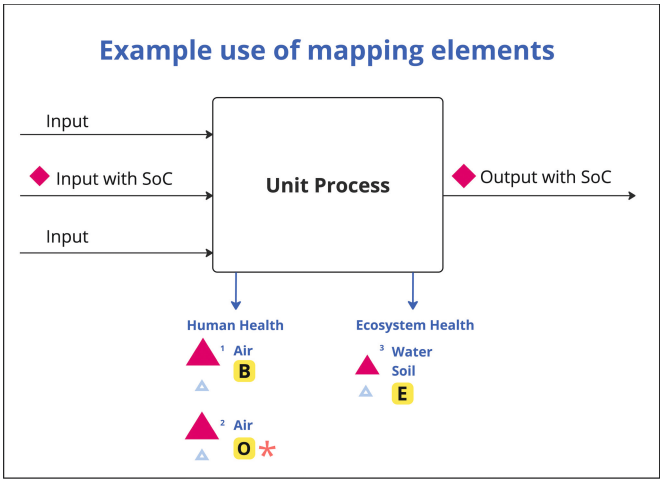


Figure 6.4. Proposed convention to apply the tool's mapping elements. The example depicts a unit process with a contaminated input and output, and describes three exposure scenarios, two for human health via air to bystanders and occupational, and one for ecosystem health via water and soil. Aggravating conditions appear to be present for the occupational exposure scenario.

Concern and Uncertainty score calculator

The exposure scenarios defined on the map can be assessed and scored to identify hotspots within the product life cycle. To achieve this, the tool offers a concern score calculator, a methodological adaptation and simplification of the RA framework. Figure 6.5 illustrates how the RA framework was adapted for product developers, as well as the variables used to calculate the concern score.

The original RA framework was adapted according to the predefined criteria (Section 6.2.1) to meet the product developer's needs (Bolaños Arriola et al., 2025), considering their workflows, scope of their capabilities, and resources available to them when assessing chemical-related risks. The tool, therefore, excludes quantitative forms of assessment that rely on complex inputs or data obtained from lab and field tests. Through a semi-quantitative approach, product developers can translate qualitative information on the characteristics and behaviour of the substance throughout the product's life cycle into semi-quantitative scores. The scoring system is based on pre-defined variables that include options to describe and assess exposure scenarios through pre-assigned weights (Tables 6.2 and 6.3). Currently, the concern score calculator is made available to product developers as an Excel template (Supplementary material 6C), which incorporates all elements and calculations described below. In this section, we provide a detailed explanation of the working principles of the concern score calculator and its variables. A complete explanation of the adaptation of all RA elements is available as Supplementary Material 6B.

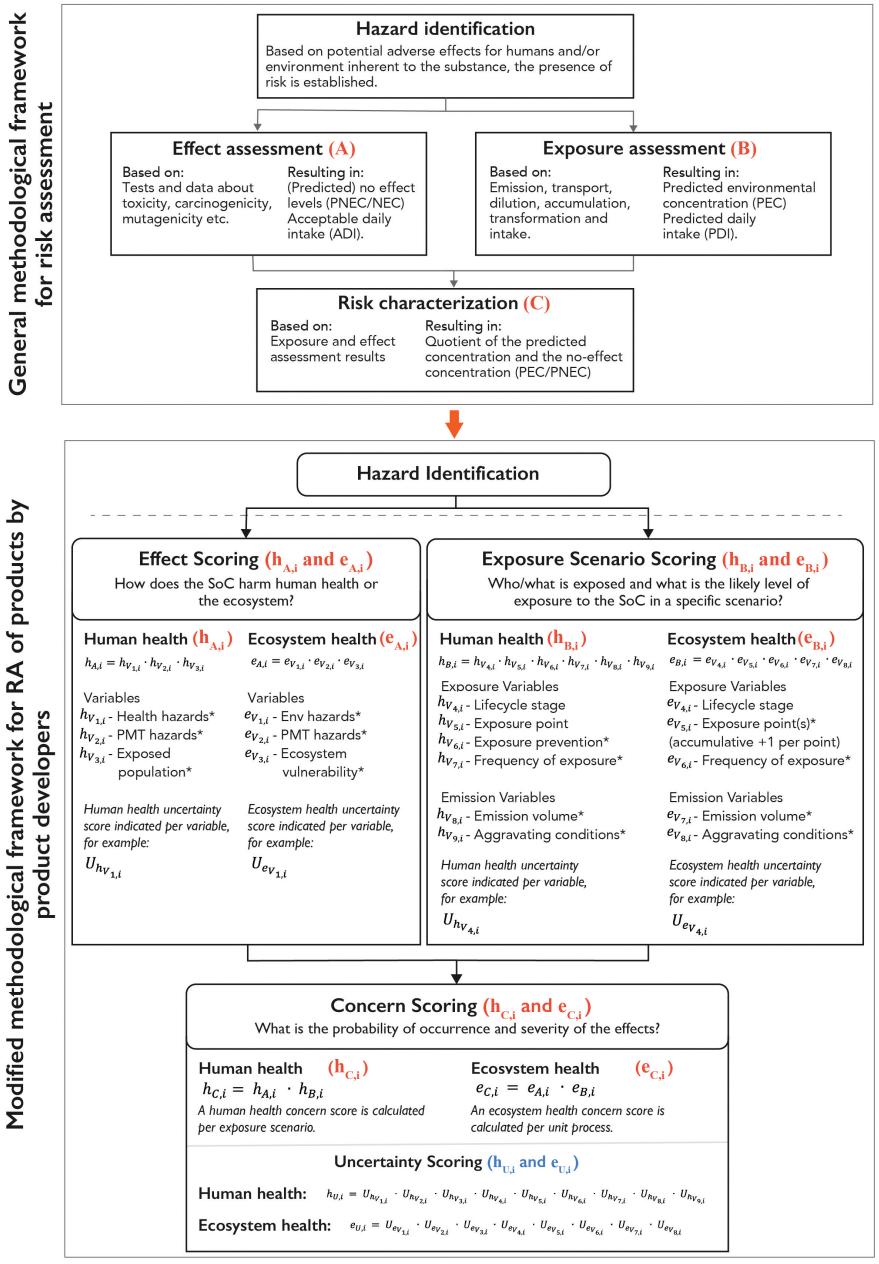


Figure 6.5. Overview of how the methodological RA framework (as described, for example, by Boersema & Reijnders, (2009)) was modified for product developer use. The top panel depicts the RA framework, and the bottom panel depicts the modified approach to calculate the concern score including all considered variables to assess human health and ecosystem health related risks. Variables marked with a star weight the concern score calculation, while those without it are only descriptive. The concern, effect, and exposure scenario scores are highlighted in red, while all uncertainty scores are highlighted in blue.

In traditional RA, chemical hazard identification aims to recognize and document all chemicals that could cause harm to people, property, or the environment. It is done based on chemical data, through analysis of lab and *in situ* data. For this tool, we assume that the SoC and its hazards have been previously identified through bill of materials (BOM) analysis, material safety data sheets, and available hazard data. This hazard identification element of risk assessment is thus not explicitly supported by the tool.

The concern score calculator follows two different pathways to support the assessment of scenarios that impact human health and scenarios that impact ecosystem health. In Figure 6.5, we observe that a human health concern score ($h_{C,i}$) or an ecosystem health concern score ($e_{C,i}$) corresponds to the risk characterization step in the RA framework. In this formula the *i* refers to a particular SoC. Concern scores should be calculated for each of the exposure scenarios previously defined by the product developer in the map. A concern score ($h_{C,i}$ and $e_{C,i}$) is obtained by multiplying the results from the Effect score ($h_{A,i}$ and $e_{A,i}$) by the results obtained from the Exposure score ($h_{B,i}$ and $e_{B,i}$):

$$h_{C,i} = h_{A,i} \cdot h_{B,i} \quad (1)$$

and

$$e_{C,i} = e_{A,i} \cdot e_{B,i} \quad (2)$$

The effect score ($h_{A,i}$ and $e_{A,i}$), which is equivalent to the effect assessment step in the RA framework, is calculated by multiplying three variables (Figure 6.5 and Table 6.2). In case of a human health scenario, the human health hazard category of the substance ($h_{V_{1,i}}$), its persistence/mobility/accumulation characteristics ($h_{V_{2,i}}$), and the exposed population ($h_{V_{3,i}}$) determine the effect score ($h_{A,i}$). If ecosystem health is affected, the ecosystem health hazard category of the substance ($e_{V_{1,i}}$), its persistence/mobility/accumulation characteristics ($e_{V_{2,i}}$), and the ecosystem vulnerability ($e_{V_{3,i}}$) determine the effect score ($e_{A,i}$).

The exposure score ($h_{B,i}$ and $e_{B,i}$), which is equivalent to the exposure assessment step in the RA framework, is calculated by multiplying several variables (Figure 6.5 and Table 6.3). In the case of a human health scenario, the exposure score ($h_{B,i}$) considers four variables describing exposure ($h_{V_{4,i}}$ to $h_{V_{7,i}}$) and two variables describing emissions ($h_{V_{8,i}}$ and $h_{V_{9,i}}$) (Table 6.3). In the case of an ecosystem health scenario, the exposure score ($e_{B,i}$) considers three variables describing exposure ($e_{V_{4,i}}$ to $e_{V_{6,i}}$), and two describing emissions ($e_{V_{7,i}}$ and $e_{V_{8,i}}$) (Table 6.3).

Product developers are provided with predefined options to describe and score each of the mentioned variables (Tables 6.2 and 6.3). Each of these options is assigned a weight that determines its contribution to the overall concern score ($h_{C,i}$ and $e_{C,i}$). The weighting of the variables and subsequent options is based on existing guidance and expert judgment. For example, following the ECHA Guidance (European Chemicals Agency, 2014) threshold values, a substance with the hazard category *Very persistent and very bioaccumulative (vPvB)* is assigned a higher weight than the category *Persistent and bioaccumulative.* All variables and their predefined options, along with their respective scores, are presented in Tables 6.2 and 6.3. The motivation for the selected variables and the weighing of their options is explained in full in Supplementary Material 6B.

The variables and the options to describe and score them were developed with the intention of supporting product developers in describing the specific situation that applies to the product they are analysing. The purpose is to draw attention to factors that contribute to the concern score and can be influenced through design.

Table 6.2. Variables to calculate the effect score ($h_{A,i}$ and $e_{A,i}$) as indicated in Figure 6.5. Each variable has predefined options that the product developer can select from to describe and assess them. Each option has an assigned weight (points). For example, if the variable $e_{V_{1,i}}$ Hazard category is marked as toxic to the aquatic environment, then $e_{V_{1,i}}$ = 4pts.

Human health Effect scoring ($h_{A,i}$), $h_{A,i} = h_{V_{1,i}} \cdot h_{V_{2,i}} \cdot h_{V_{3,i}}$			**Ecosystem health Effect scoring ($e_{A,i}$), $e_{A,i} = e_{V_{1,i}} \cdot e_{V_{2,i}} \cdot e_{V_{3,i}}$**		
Variable	**Options to describe variable**	***Weight (pts)***	**Variable**	**Options to describe variable**	**Weight (pts)**
($h_{V_{1,i}}$) Hazard category	A. Systemic health hazards: Carcinogenic, mutagenic or toxic to reproduction (CMR)	*4*	***($e_{V_{1,i}}$) Hazard category***	A. Toxic to aquatic environment	4
	B. Physical hazards (explosive, corrosive, flammable, gas under pressure, oxidizing)	2		B. Damage to the ozone layer	2
	C. Direct health hazards: acute toxicity, specific organ toxicity, skin corrosion, skin or respiratory sensitization, eye damage	2			
($h_{V_{2,i}}$) Persistence / mobility / bioacc.	A. Very persistent and very bioaccumulating or Very Persistent, very Mobile (vPvB or vPvM)	4	***($e_{V_{2,i}}$) Persistence / mobility / bioacc.***	A. Very persistent and very bioaccumulating or Very Persistent, very Mobile (vPvB or vPvM)	4
	B. Persistent, bioaccumulating or mobile, and toxic (PBT or PMT)	3		B. Persistent, bioaccumulating or mobile, and toxic (PBT or PMT)	3
	C. Not applicable	1		C. Not applicable	1
($h_{V_{3,i}}$) Exposed population	A. Vulnerable groups (children, pregnant, etc.)	*3*	***($e_{V_{3,i}}$) Ecosystem vulnerability***	A. Vulnerable ecosystem	3
	B. People (consumers, society)	1.5		B. Ecosystem	1.5
	C. Occupational	1.5			

Table 6.3. Variables to calculate the exposure scenario score ($h_{B,i}$ and $e_{B,i}$) as indicated in Figure 6.5. Each variable has predefined options that the product developer can select from to describe and assess them. Each option has an assigned weight (points). For example, if the variable $e_{V_{6,i}}$ Frequency of exposure is marked as chronic, then $e_{V_{6,i}}$ = 2.5 points. Variable $e_{V_{5,i}}$ gets an accumulative weight of +1 for each selected exposure point (e.g., Air + Wastewater = 2). Variables marked as descriptive have no assigned weight as they characterize the scenario but have no influence on the resulting concern score ($h_{C,i}$ and $e_{C,i}$). The variable Exposure prevention is, in this case, not applicable to ecosystem health.

	Human health exposure scoring ($h_{B,i}$), $h_{B,i} = h_{V_{4,i}} \cdot h_{V_{5,i}} \cdot h_{V_{6,i}} \cdot h_{V_{7,i}} \cdot h_{V_{8,i}} \cdot h_{V_{9,i}}$			**Ecosystem health exposure scoring ($e_{B,i}$),** $e_{B,i} = e_{V_{4,i}} \cdot e_{V_{5,i}} \cdot e_{V_{6,i}} \cdot e_{V_{7,i}} \cdot e_{V_{8,i}}$		
	Variable	**Options to describe variable**	**Weight (pts)**	**Variable**	**Options to describe variable**	**Weight (pts)**
Exposure description variables	**($h_{V_{4,i}}$) Life cycle stage (descriptive)**	Life cycle stage and unit process in which the scenario occurs		**($e_{V_{4,i}}$) Life cycle stage (descriptive)**	Life cycle stage and unit process in which the scenario occurs	
	($h_{V_{5,i}}$) Exposure point (descriptive)	Point in which a population comes in contact with the substance. Air, wastewater, surface water, soil, dust, direct contact, (ingestion or dermal)		**($e_{V_{5,i}}$) Exposure point. Several can be selected. The weight increases according to the number of selected points (accumulative)**	A. Air	+1
					B. Wastewater	+1
					C. Surface water	+1
					D. Soil	+1
					E. Dust	+1
	($h_{V_{6,i}}$) Exposure prevention	A. Not in place	1			
		B. In place and exposure is reduced	0.5			
		C. In place and exposure is eliminated	0			
	($h_{V_{7,i}}$) Frequency of exposure	A. Chronic	2.5	**($e_{V_{6,i}}$) Frequency of exposure**	A. Chronic	2.5
		B. Repeated	2		B. Repeated	2
		C. Single	1.5		C. Single	1.5

Table 6.3. *(Continued)*

	Human health exposure scoring ($h_{B,i}$), $h_{B,i} = h_{V_{4,i}} \cdot h_{V_{5,i}} \cdot h_{V_{6,i}} \cdot h_{V_{7,i}} \cdot h_{V_{8,i}} \cdot h_{V_{9,i}}$			**Ecosystem health exposure scoring ($e_{B,i}$), $e_{B,i} = e_{V_{4,i}} \cdot e_{V_{5,i}} \cdot e_{V_{6,i}} \cdot e_{V_{7,i}} \cdot e_{V_{8,i}}$**		
	Variable	**Options to describe variable**	**Weight (pts)**	**Variable**	**Options to describe variable**	**Weight (pts)**
Emission description variables	**($h_{V_{8,i}}$) Emission volume (According to risk management measures that reduce emissions)**	A. No control mechanism in place - emissions occur	1	**($e_{V_{7,i}}$) Emission volume (According to risk management measures that reduce emissions)**	A. No control mechanism in place - emissions occur	1
		B. Control mechanism in place – reduced emissions	0.5		B. Control mechanism in place – reduced emissions	0.5
		C. Control mechanism in place – no emissions occur	0		C. Control mechanism in place – no emissions occur	0
		D. Known concentrations and/or emissions remain below threshold values	0		D. Known concentrations and/or emissions remain below threshold values	0
	($h_{V_{9,i}}$) Aggravating conditions	A. No aggravating conditions	1	**($e_{V_{8,i}}$) Aggravating conditions**	A. No aggravating conditions	1
		B. Aggravating conditions that have a small effect on emissions	1.5		B. Aggravating conditions that have a small effect on emissions	1.5
		C. Aggravating conditions that have a large effect on emissions	2		C. Aggravating conditions that have a large effect on emissions	2

As users apply the tool during the early stages of product development, a relatively high level of uncertainty is inherent. To address this, an Uncertainty Score ($h_{U,i}$ for human health scenarios or $e_{U,i}$ for ecosystem health scenarios) (highlighted in blue in Figure 6.5) is calculated for each exposure scenario, complementing its Concern Score ($h_{C,i}$ and $e_{C,i}$). This helps indicate data gaps while allowing flexibility when data is limited, inconclusive, or unavailable. When assessing each exposure scenario and selecting from the variable options (Tables 6.2 and 6.3), the product developer can also indicate the level of uncertainty of their answer for each variable. Each indication of uncertainty has a predefined weight (in points), as shown in Table 6.4 below. For example, if the variable $e_{V_{6,i}}$ *Frequency of exposure* is marked as chronic, but the product developer is not entirely sure the data point is correct, then its uncertainty weight can be marked as $U_{e_{V_{6,i}}}$ = 2 points (medium uncertainty).

Table 6.4. Weights assigned to indicate the level of uncertainty for each variable (e.g., $h_{V_{1,i'}}$ $e_{V_{1,i'}}$ etc.). These weights are used to calculate the overall uncertainty score for each exposure scenario.

Level of uncertainty	Description	Weight (pts)
No uncertainty	The data point is certain (within 10%)	1
Low uncertainty	The data point is a reasonable estimation based on other available data (10-50%)	1.5
Medium uncertainty	The data point is not a reliable estimation or comes from an unreliable source, and requires further research (50-200%)	2
High uncertainty	The data point is a guess to illustrate a scenario but requires further research (>200%)	3

To calculate the uncertainty scores ($h_{U,i}$ and $e_{U,i}$) for the analyzed exposure scenario, the tool multiplies the uncertainty levels (Table 6.4) indicated for each variable (Tables 6.2 and 6.3):

$$h_{U,i} = U_{hV_{1,i}} \cdot U_{hV_{2,i}} \cdot U_{hV_{3,i}} \cdot U_{hV_{4,i}} \cdot U_{hV_{5,i}} \cdot U_{hV_{6,i}} \cdot U_{hV_{7,i}} \cdot U_{hV_{8,i}} \cdot U_{hV_{9,i}} \quad (3)$$

And

$$e_{U,i} = U_{eV_{1,i}} \cdot U_{eV_{2,i}} \cdot U_{eV_{3,i}} \cdot U_{eV_{4,i}} \cdot U_{eV_{5,i}} \cdot U_{eV_{6,i}} \cdot U_{eV_{7,i}} \cdot U_{eV_{8,i}} \quad (4)$$

A higher uncertainty score indicates that the concern score is inconclusive and requires further research, either by gathering additional data for the specific scenario or by identifying potential hotspots to be addressed through preventive design strategies. Product developers receive an interpretation guide to support the si-

multaneous assessment of concern and uncertainty scores. This interpretation guide is included in the MAPSS *Tool protocol and steps*, available as Supplementary Material 6D.

Visualizing and interpreting concern and uncertainty scores

For each exposure scenario, a concern score ($h_{C,i}$ and $e_{C,i}$) and an uncertainty score ($h_{U,i}$ and $e_{U,i}$) are calculated, reflecting the potential risk level and the confidence in the underlying data. As numerous scenarios may be assessed and the individual scores are not intended for quantitative interpretation, the tool consolidates the results into a three-tier scale (low, medium, high), indicating the overall level of concern. This supports the identification of risk hotspots, data gaps, and comparisons between reference products, alternatives, or new designs. The results can be visualized alongside each exposure scenario, as shown in Figure 6.4. The concern scores are represented by small, medium, or large filled pink triangles, and uncertainty scores by open blue triangles of corresponding sizes (Figure 6.3)..

Product developers can use the following guidelines to interpret the maps and identify next steps:

- Prioritize high-scoring scenarios and assess their relevance to the product design; some may fall under the responsibility of other stakeholders, such as suppliers.
- Analyse score origins by reviewing the selected options to describe variables. If high scores result from aggravating conditions, preventing these may be a suitable strategy.
- Interpret combinations of concern and uncertainty scores:
    - Low concern – low uncertainty – The information is sufficient, and the scenario can be considered of low concern.
    - High concern – low uncertainty – The scenario represents a clear hotspot that requires mitigation through alternatives.
    - High concern – high uncertainty – Additional information is needed to confirm the concern; preventive measures should be considered.
    - Low concern – high uncertainty – The scenario demands caution. The low concern can be misleading and a result of a lack of data or an underestimation of risks. Therefore, additional information is likely necessary, and preventive measures should be considered.

Rules to identify trade-offs

The tool provides the means to perform a qualitative analysis to identify potential environmental trade-offs from design changes or mitigation strategies addressing the SoC. This allows product developers to reflect on the balance between safety and sustainability and to compare system maps of the reference product with those

of alternatives or new designs. The analysis is guided by a set of rules based on LCA theory and literature, considering climate change and resource use as impact categories. The product developer is provided with an initial list of trade-off rules (Table 6.5) to analyse and identify any potential trade-offs on the system maps of each alternative. The assessment can draw on sources such as bills of materials, basic (open source) LCI databases, analysis of user behaviour, or product performance tests. Trade-offs are indicated on the maps by highlighting the relevant unit processes in green (Figure 6.2).

Table 6.5. Initial list of rules to identify potential environmental impact trade-offs that occur as a consequence of reducing risks related to SoC.

Production	Transport	Use	EoL
The extraction of the substitute material or additive is more impactful (Meng et al., 2024) (e.g., stainless-steel container instead of plastic with additives that are SoC)	**Transportation impact is increased due to increase in mass, variety of materials, supplier location, etc.** (Bolaños Arriola et al., 2024; Kravchenko et al., 2020) (e.g., longer distances as a consequence of substitution, substitute for PVC cables is denser and requires a thicker layer)	**The durability is reduced necessitating earlier replacement** (Bolaños Arriola et al., 2024; Meng et al., 2024) (e.g. substituting plastics with materials like glass or metal resulted in higher overall environmental impacts, partly due to increased material fragility, substitute additives in PVC cables reduce durability)	**New processing steps or infrastructure are necessary** (Bolaños Arriola et al., 2024; Fenwick et al., 2023) (e.g. reducing SoC impacts by increasing useful life in electronics through applying composite materials can require additional steps like cleaning, sorting, and material separation during EoL processing)

Table 6.5. *(Continued)*

Production	Transport	Use	EoL
Processing is more complex or requires more steps and/or is energy intensive (Bolaños Arriola et al., 2024; Kravchenko et al., 2020) (e.g. Reduction of VOC content in chemicals complicates the processing of the chemical, higher production costs and changes in the production methods are a consequence of substitute blowing agents)		**The alternative requires maintenance or repairs** (Bolaños Arriola et al., 2024; Sandionigi, 2024) **(**e.g. material efficiency in electronics vs reliability and safety, increasing the useful life of products can require additional maintenance and repair)	**Processing waste/ resources is more energy intensive** (Meng et al., 2024) (e.g. recycling aluminum is more impactful than microplastic generating PET)
More material is necessary to meet a function, due to performance, or to prevent risk (Bolaños Arriola et al., 2024; Kravchenko et al., 2020) (e.g. small amounts of a toxic material vs larger amount of a less toxic material, additional components to prevent risk)		**The alternative has higher energy consumption / reduced efficiency / more waste generated** (Bolaños Arriola et al., 2024; Byggeth & Hochschorner, 2006; Luttropp & Lagerstedt, 2006) (e.g**.** substitute refrigerant gases can have consequences on the appliance performance and energy consumption)	**Processing techniques are not available (close by)** (Beames et al., 2021) (e.g. disassembly of mattresses needs large ovens to melt adhesive which are only available in specific areas, additional logistical challenges)

Table 6.5. *(Continued)*

Production	Transport	Use	EoL
'Known' less sustainable material vs 'unknown' potentially more sustainable material (Bolaños Arriola et al., 2024; Kravchenko et al., 2020) (e.g., Substitution of PFAS with non-fluorinated substances, often with an unknown safety profile)			**The new material/ product/chemical hinders circularity** (Bolaños Arriola et al., 2024; Thompson et al., 2020) (e.g. Containment of components for safety inhibits disassembly, material is not recyclable)
New impacts when transitioning to a service/digital product (Bolaños Arriola et al., 2024; Chen & Huang, 2019) (e.g., additional infrastructure is necessary to meet the function)			

Guidelines for comparing resulting maps

Comparison of maps can be performed once the reference product and one or more alternatives or new designs have been mapped. The simultaneous analysis focuses on three aspects: 1) SoC safety, 2) risk trade-offs (considering uncertainty), and 3) potential environmental trade-offs, as defined by the tool development criteria in section 6.2.1. Product developers can follow these guidelines for analysis:

- Observe if any changes to "contaminated" inputs and outputs are present. Especial attention should be given to inputs and outputs marked with blue (outline) rhomboids, indicating substances with unknown or inconclusive safety profiles. Marked outputs that exit the system boundary or generate circular scenarios should be treated with caution.
- Compare all resulting concern and uncertainty scores. Numerical results from the concern score calculator should not be used quantitatively, as this is a semi-quantitative assessment. The focus should be on reducing or eliminating

risk hotspots while preventing uncertainty hotspots. The creation of new risk scenarios should also be evaluated.

- Analyse the presence of potential environmental trade-offs. This streamlined form of LCA provides indicators to obtain further information and help prevent unforeseen impacts.

6.3.2. Use of the tool in an example case – Hospital mattress containing flame retardants

In this section, we present the application of the tool elements described above using a case example. While the case is used solely for illustrative purposes, the product and its alternatives represent real, commercially available examples. We present the resulting map of the reference product (Figure 6.6), a polyurethane foam hospital mattress containing TCPP, a hazardous flame retardant, and the maps of two possible alternatives: a denser foam mattress with reduced flame-retardant content that uses melamine as a substitute to TCPP (Figure 6.7), and a mattress with a polyester 3D structure that is inherently flame-retardant (Figure 6.8). The functional unit defined to analyse the mattress case is: Providing pressure-relieving support for hospital patients for 5 years, under typical clinical use conditions, 24-hour use, with an average of 1 patient/day and cleaning between patients, with a standard-size mattress that meets flammability norms. Each map indicates the reference flow for each product. The data used can be found in Supplementary Material 6A.

Figure 6.6 shows the processes, inputs, and outputs of the reference mattress system. In this specific case, TCPP contaminates several inputs and outputs, including some that extend beyond the system boundary, such as shredded foam from recycling and foam waste from cutting operations. Potential human health concerns arise, e.g., for vulnerable individuals in direct contact during use, for workers during curing and shredding, and for hospital staff during cleaning. Curing and cleaning could aggravate TCPP emissions, as heat can increase the substance's volatility. The presence of water problematizes its solubility and consequent emissions. Environmental health concerns are highest for foam cutting and EoL processes, where the SoC is released into the air and wastewater. High uncertainty exists during misuse (cover damage) and EoL scenarios due to limited data on emissions and exposure.

Comparing all three maps (the TCPP reference mattress and two alternatives) reveals several points. Substituting TCPP with melamine offers little to no improvement, as melamine is also a SoC, contaminating multiple inputs and outputs and generating similar concerning scenarios, particularly when contaminated outputs cross the system boundary (Figure 6.7). A slight improvement is observed during foam curing, as melamine is not as volatile. However, no improvements are seen

in concerning scenarios involving patients during the use phase. In contrast, the polyester labyrinth alternative shows no concern scenarios. However, its inputs and outputs are flagged as uncertain because the safety data for some substances (such as water-repellent treatments) is inconclusive. Figure 6.8 also indicates that while the polyester structure reduces SoC risks, potential environmental trade-offs must be considered due to the change in core material and the need for additional cleaning and maintenance processes. Furthermore, Figure 6.8 highlights a potential circular scenario where shredded foam re-enters the system, for which risks from recycled foam sources and other contaminants should be considered.

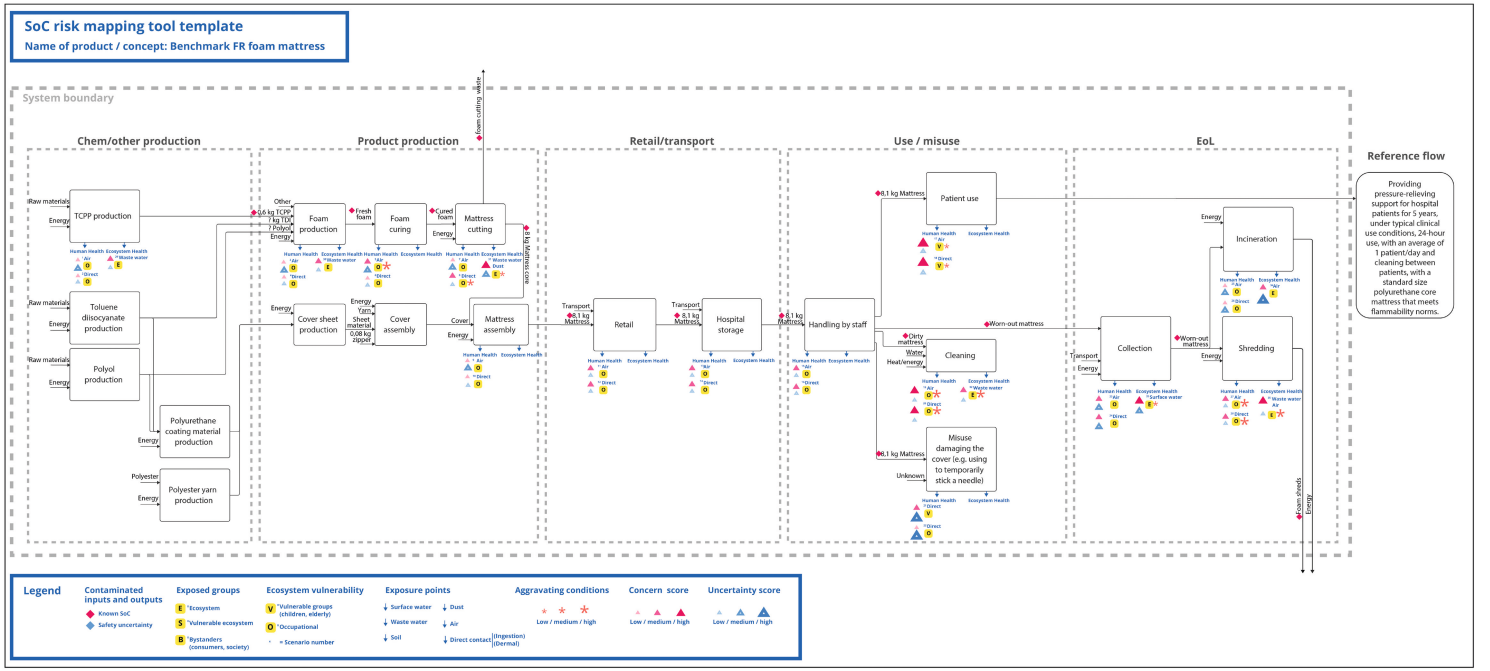


Figure 6.6. Resulting map of the reference hospital mattress containing TCPP as a flame retardant. The map illustrates the use of the tool elements, including system mapping of the product, indicators of contaminated inputs and outputs, exposure scenarios for human and environmental health, results for concern and uncertainty scores, and aggravating conditions.

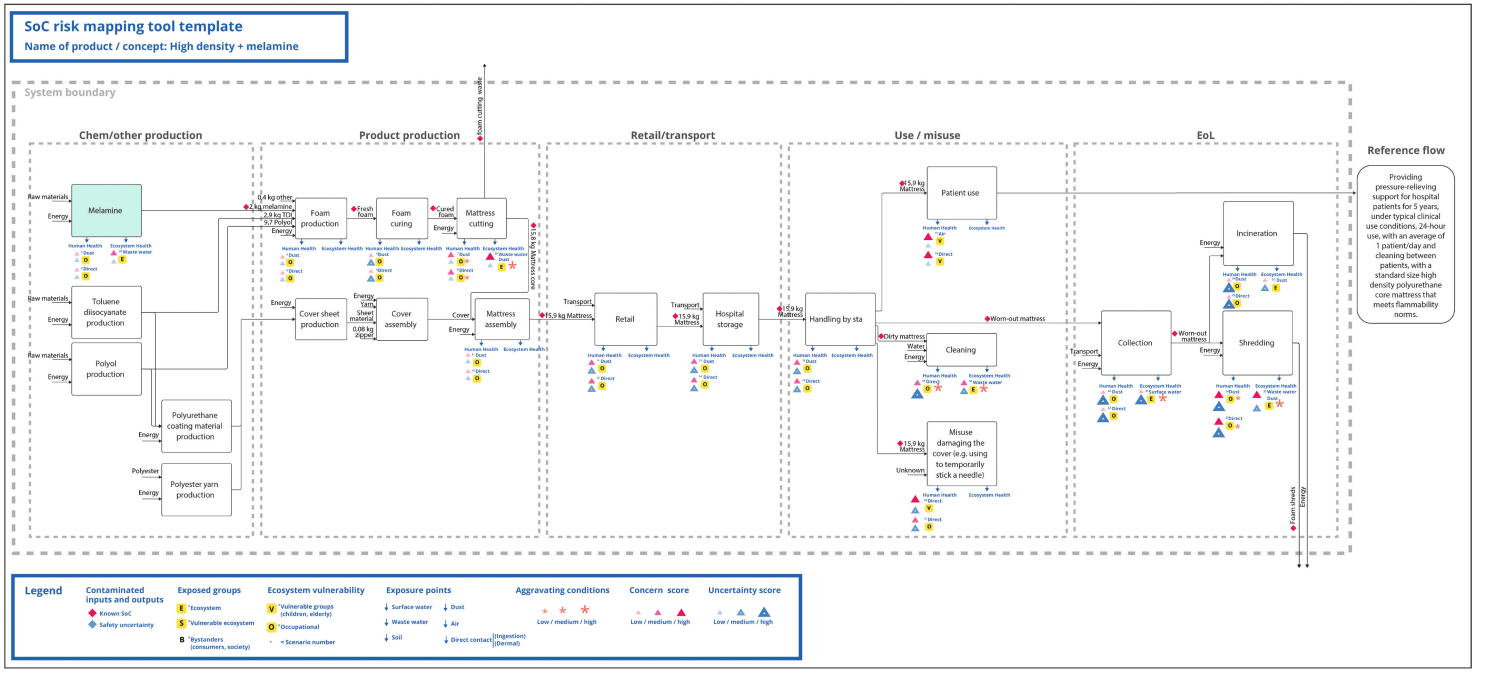


Figure 6.7. Resulting map of the alternative high-density foam hospital mattress containing melamine as a flame retardant. The map illustrates the use of the tool elements, including system mapping of the product, indicators of contaminated inputs and outputs, exposure scenarios for human and environmental health, results for concern and uncertainty scores, and aggravating conditions. Potential environmental trade-offs are indicated by unit processes highlighted in green.

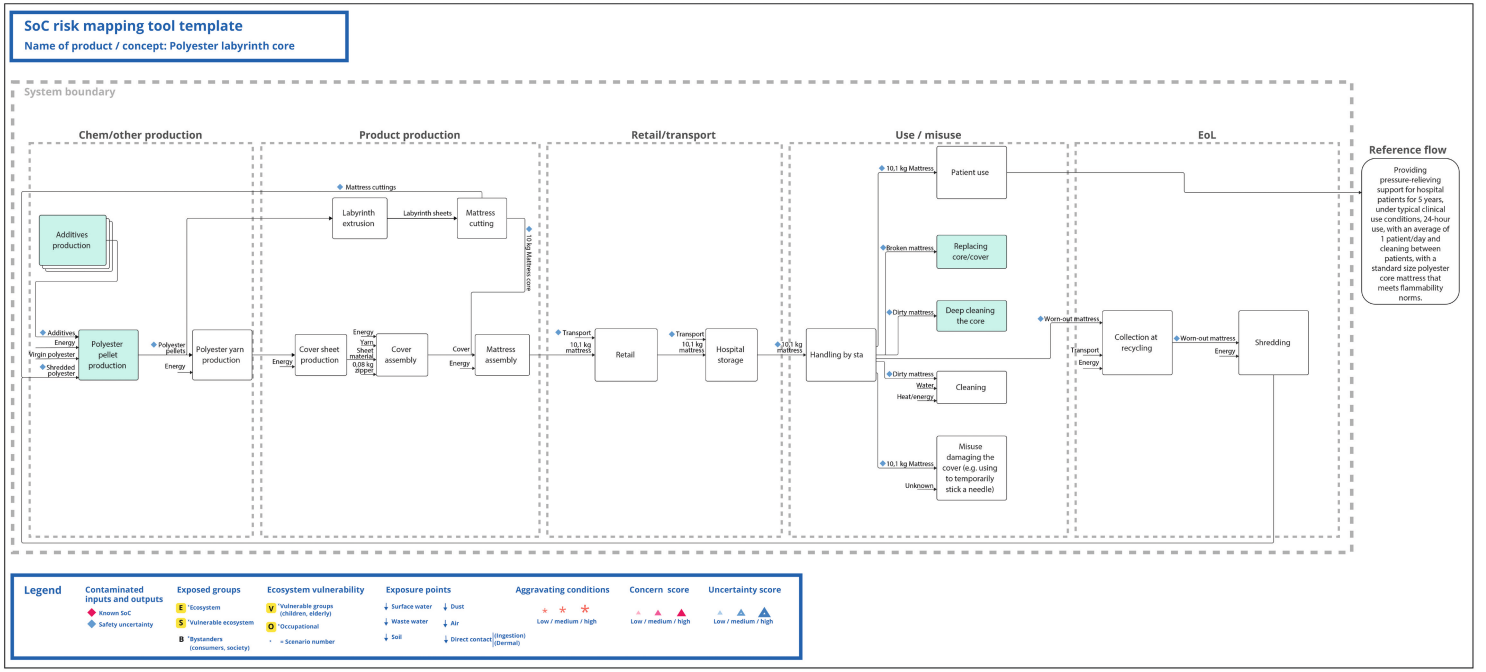


Figure 6.8. Resulting map of the alternative hospital mattress with a polyester labyrinth core. The map illustrates the use of the tool elements, including system mapping of the product, indicators of contaminated inputs and outputs, exposure scenarios for human and environmental health, results for concern and uncertainty scores, and aggravating conditions. Potential environmental trade-offs are indicated by unit processes highlighted in green.

6.3.3. Integration of the tool into the product development process

The MAPSSS tool is targeted at product developers to support them in dealing with the risks generated by SoC in products. It is an assessment tool that aims to provide indicators that highlight risk hotspots and support decision-making, especially in the early stages of the development process with high uncertainty. Based on this assessment, product developers can start to design based on the three strategies introduced earlier: avoid, reduce, and control (Bolaños Arriola et al., 2024). Figure 6.9 provides an overview of the three main stages proposed for product developers to integrate the tool elements into the design process. Each of the tool stages contains a set of steps that correspond to the main goal or activity of the design process phase to which it belongs. A protocol document was also developed to guide product developers through these steps, which is available in Supplementary material 6D.

Stage 1 - Mapping and Risk Assessment of the reference product

During this stage, product developers map and assess the SoC risks for the reference product or design, using the mapping elements, concern and uncertainty score calculators, and interpretation guidelines. This process occurs during the Discover and Define phases, necessitating several iterations to gather all the necessary information for the assessment and establish a problem definition. It is assumed that the product developer is aware of or suspects the presence of a SoC in the reference product before commencing Stage 1. Stage 1 concludes with the identification of substance risks and uncertainty hotspots in the reference product.

Stage 2 - Mapping and Risk Assessment of new design(s)

After developing concepts that address the risk hotspots identified during Stage 1, product developers can map and assess the substance risks associated with these new concepts or designs during Stage 2. An assessment must be performed for each concept, following the same set of steps used to assess the reference product. During this stage, product developers also conduct a qualitative analysis to identify potential environmental trade-offs resulting from the design changes, applying a list of trade-off rules. This supports early identification of unintended environmental impacts. Stage 2 takes place during the Development phase of the design process.

Stage 3 - Comparison of maps of existing product and new design(s)

After assessing the reference product and new concepts, product developers can proceed to compare the resulting maps. Stage 3 provides guidance for comparing risk mitigation, potential environmental trade-offs, and uncertainty. This stage occurs late in the Development phase of the design process and should provide product developers with information for comparing concepts and making informed

decisions. Stage 3 should also provide uncertainty indicators that should be addressed throughout the Deliver phase of the process.

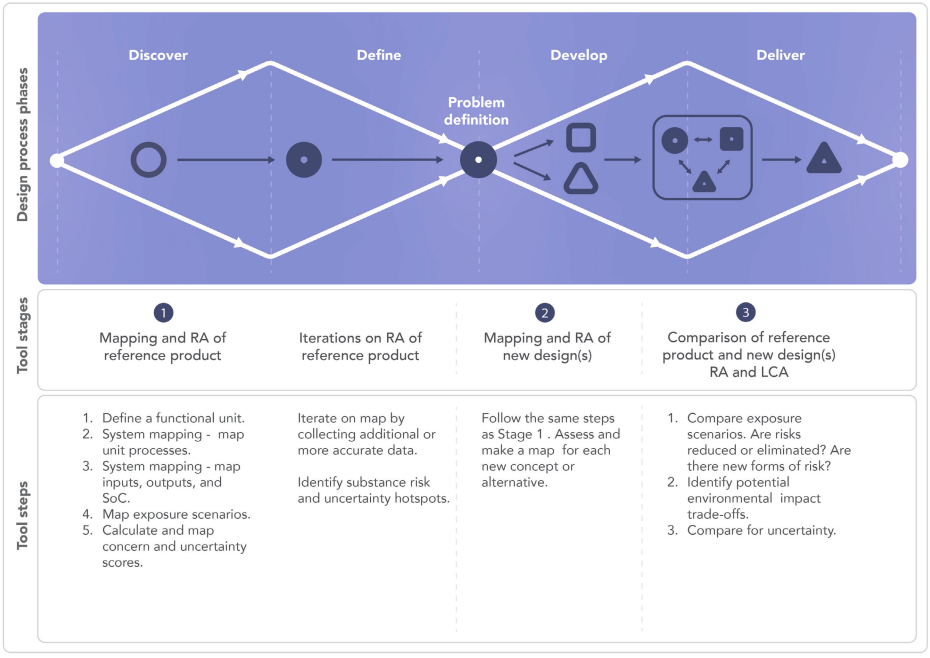


Figure 6.9. Stages, steps, and integration of the MAPSSS tool into the design process. The level of knowledge of the analysed product is represented by the circle filling in as the process progresses. The other geometrical figures represent new designs or alternatives.

6.4. Discussion

This study set out to develop a tool that integrates the principles of Life Cycle Assessment (LCA) and Risk Assessment (RA) within a product development context. The following discussion examines how the resulting tool meets the predefined criteria established to achieve this aim, its contribution to the realm of Safe and Sustainable by Design (SSbD), and the study's limitations and future research directions.

6.4.1. Criteria compliance

Here, we discuss how and to what extent the MAPSSS tool meets the criteria (C1-C6) established in section 6.2.1. The tool's elements enable product developers to identify and visualize the risks posed by hazardous chemicals and materials across the entire product life cycle, including circular scenarios. Through the concern score, product developers can prioritize and locate risk hotspots (C1). There are situations where prioritizing hotspots may still fail. For example, if the maps

cannot be refined—because data on the SoC is missing or the value chain lacks transparency—uncertainty remains high across all exposure scenarios, making it impossible to identify hotspots. The tool may also fail this criterion when all exposure scenarios receive a high concern score. In this case, no hotspots can be identified, and thus no targeted solutions can be designed. This result, however, could indicate that the SoC is unacceptable for use altogether, suggesting that it should be avoided in the product developer's or company's full portfolio and that internal restricted substances lists should be established.

The tool captures uncertainties, including assumptions about processes or data points that are unavailable. The uncertainty score estimates their magnitude, and the map highlights data gaps and areas where further research is needed (C2). Uncertainty is never considered negligible, especially since the tool itself is already a simplification of the much more detailed RA and LCA methods. Instead, the tool highlights high uncertainty as a risk. This aligns with other proposed approaches to uncertainty in SSbD, where uncertain scenarios are minimized as much as possible and highlighted as sensitive if uncertainty cannot be reduced (Blanco et al., 2025). The maps provide a visual overview of the entire life cycle(s) and the identified uncertainties attached to each exposure scenario, supporting both the analysis of the reference product and its potential alternatives (C3). Although the uncertainty is self-reported, which may potentially introduce under- or overestimation of the level of uncertainty, product developers are encouraged to assume the worst-case scenario. The uncertainty score can only decrease in an iteration of the map after new data is found. Making the uncertainty score an integral part of the tool aims to address some of the known challenges in uncertainty analysis and consequent poor application in LCA (Bisinella et al., 2021; Lo Piano & Benini, 2022).

Product developers can visually compare alternatives in terms of safety and potential environmental impact trade-offs using the lifecycle maps (C4). The tool thus enables transparency in the choices made by the product developer, supporting the assessment and comparison of interventions at different levels, such as alternative chemicals or materials, or alterations to the product design. The tool locates SoC and allows for prioritization, which, to date, remains underrepresented in product development compared with environmental impact assessments based on, for instance, existing fast-track LCA methods such as the Eco Audit Tools or Idemat (ANSYS, 2024; Vogtländer, 2010). This aligns with the SSbD approach in the JRC framework, which prioritizes substance safety across the life cycle before addressing other environmental, social, or economic aspects (Caldeira et al., 2022).

Guidance is provided for when and how to apply the tool throughout the development process, considering an iterative approach (C5). Specific tool steps support specific phases of the product development process. The map facilitates an incre-

mental, iterative approach to the assessment. Early analyses can be conducted even with limited data, drawing on assumptions, analogous cases, or qualitative observations. Naturally, this approach is not without risks. Product developers risk placing undue confidence in preliminary assessments and neglecting subsequent re-evaluations, having prematurely regarded product safety as resolved. Iteratively, these assessments need to be refined as more information becomes available. Oversimplification or the use of unrepresentative analogues are pitfalls, too. However, this is not unique to this tool; it is a known pitfall for lifecycle assessment in general (Beemsterboer et al., 2020). Guidance for using the tool will outline critical and iterative thinking.

Finally, the tool supports a simplified scenario-based risk screening assessment, encouraging product developers to consider different stakeholders and contextual dimensions in their evaluations (C6). It inspires problem framing through hotspot identification and, subsequently, creative ideation for intervention options.

6.4.2. Building on SSbD

This paper offers a product development perspective to complement existing approaches to SoC. The JRC SSbD framework takes safety and sustainability assessment as the starting point (Caldeira et al., 2022). The by-design element in this framework refers to the design of chemicals and materials. The product perspective is only assumed at specific levels of assessment, where it is a necessary evil rather than a perspective that is leveraged to enable safety and sustainability.

In contrast, our approach begins with a reference product containing a SoC and aims to improve from a product perspective. This shifts the focus to the actual context in which a substance is used and encourages product developers to identify risks directly relevant to their product system. By doing so, opportunities for mitigation can be identified at the product level, which reduces reliance on the availability of safer chemicals. By treating uncertainty as a potential risk in our tool, we encourage product developers to adopt a precautionary mindset and consider combinations of mitigation strategies.

It is essential to acknowledge the distinctions in scope and assessment between the SSbD concept and the MAPSSS Tool. The JRC SSbD framework provides a much more comprehensive environmental sustainability assessment than our tool. It covers a broad set of impact categories, whereas our current focus is high-level and limited to rules of thumb for climate change and resource use. This is due to our tool being developed to enable product developers to perform semi-quantitative assessment without expert involvement in early development. We realize that the simplification of RA and LCA in our tool may lead to biased designs in practice. The only way to avoid this is to work with interdisciplinary teams, including product

developers, RA and LCA experts, and other relevant experts, as needed. That, however, requires a fundamental shift in current business concepts. Such development processes require a variety of resources that are currently unavailable.

Finally, the JRC framework is aimed at research and innovation teams, but does not specify a clear target group or the expertise required. In practice, a relatively high level of RA and LCA expertise is often required, making it difficult for product developers to apply (Apel et al., 2024). Here, our tool provides an entry point. The MAPSSS tool supports early assessments that can be further developed with the involvement of RA and LCA experts, provided resources are available. This aligns with the JRC framework's tiered approach. Our tool can be used for the simplified and/or intermediate assessment steps within its structure, depending on to-be-determined thresholds or criteria. For instance, in previously described situations of high uncertainty or high concern scores throughout the exposure scenarios, the product developer might escalate to the next assessment tier. In this way, the tool complements the existing framework.

6.4.3. Limitations and recommendations

The MAPSSS tool is currently based on theoretical cases, literature, and expert input on the application of the assessment elements from RA and LCA experts, which makes it entirely theoretical. Its further development requires application by product developers in real, "unsolved" cases. Such testing should focus on enhancing usability and integrating it into the product development process. At present, the tool is intended to be usable without prior expertise in chemicals, RA, or LCA. Further testing should explore how the tool can support the identification of SoC in products, since it currently operates under the limitations that the presence of a hazardous substance is known. Next-level verification involves comparative studies designed to assess the risks and environmental trade-offs of a product and its alternatives. At the same time, a full RA and LCA are conducted in parallel. Such comparisons could provide valuable insights into the tool's accuracy in identifying hotspots and trade-offs. Iterations of case studies will, in due time, allow for refinements, including, for example, the refinement of concern and uncertainty score methodologies and the weights assigned to variables in the calculations.

The current assessment of environmental trade-offs enabled by the tool is limited to climate change and resource use, relying on rules of thumb rather than comprehensive analysis. In addition to environmental trade-offs, we foresee that, in the coming decades, social and economic sustainability will gain greater interest and thus lead to greater data availability. This will be an opportunity for the current tool to include more diverse data and assessment methods.

6.5. Conclusion

Broad adoption of SSbD requires tiered, resource-efficient assessments, tailored to specific professionals' needs. Early analyses, which are based on limited data and can be refined as more information becomes available, are essential. Streamlining is therefore necessary to support product development teams that may not have the means to perform resource-intensive assessments. Our tool addresses this need through its accessible, user-friendly interface, specifically tailored for product developers. The MAPSSS tool supports product developers in addressing the presence of SoC in products, making use of LCA and RA principles. It is an assessment and visualization tool that enables the identification and evaluation of SoC risks, potential trade-offs, uncertainty levels, and environmental impacts throughout the product life cycle. Product developers are guided to identify risk hotspots in the reference product, supporting the development of mitigation strategies. They can later compare the reference product with new designs, modifications, or alternatives, in terms of safety and environmental trade-offs. The tool's visual and iterative nature aligns with product development practices.

This work brings a product development perspective to current Safe and Sustainable by Design approaches, which have primarily focused on the search for alternatives to safer chemicals and materials. With this tool, an initial step toward developing a product-specific assessment tool for early design stages is taken, providing a foundation for future work that can strengthen the role of product developers in SSbD.

6.6. Appendices

Supplementary Material 6A – This document contains the background data used for the analysis and mapping of the cases and their alternatives.

Supplementary Material 6B – This document presents the detailed process and reasoning behind the adaptation of the risk assessment framework for product developers.

Supplementary Material 6C – This Excel document presents the concern and uncertainty score calculator.

Supplementary Material 6D- This document contains the MAPSSS Tool protocol and the steps for product developers to follow.

These appendices are available in: https://data.4tu.nl/datasets/f8ee9ffd-c7cb-4287-8693-399ff93c802c



6.7. References

Abbate, E., Garmendia Aguirre, I., Bracalente, G., Mancini, L., Tosches, D., Rasmussen, K., Bennet, M., Rauscher, H., & Sala, S. (2024). Safe and Sustainable by Design chemicals and materials-Methodological Guidance. https://doi.org/10.2760/28450

ANSYS, Inc. (2024). Ansys GRANTA EduPack software. In http://www.ansys.com/materials.

Apel, C., Kümmerer, K., Sudheshwar, A., Nowack, B., Som, C., Colin, C., Walter, L., Breukelaar, J., Meeus, M., Ildefonso, B., Petrovykh, D., Elyahmadi, C., Huttunen-Saarivirta, E., Dierckx, A., Devic, A. C., Valsami-Jones, E., Brennan, M., Rocca, C., Scheper, J., ... Soeteman-Hernández, L. G. (2024). Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives. In Current Opinion in Green and Sustainable Chemistry (Vol. 45). Elsevier B.V. https://doi.org/10.1016/j.cogsc.2023.100876

Beames, A., Claassen, G. D. H., & Akkerman, R. (2021). Logistics in the Circular Economy: Challenges and Opportunities. In Greening of Industry Networks Studies (Vol. 8, pp. 1–14). Springer Nature. https://doi.org/10.1007/978-3-030-55385-2_1

Beekman, M., Bakker, J. C., Bodar, C. W. M., van Leeuwen, L. C., Waaijers-van der Loop, S. L., Zijp, M. C., & Verhoeven, J. K. (2020). Coping with Substances of Concern in a Circular Economy. https://doi.org/10.21945/RIVM-2020-0049

Beemsterboer, S., Baumann, H., & Wallbaum, H. (2020). Ways to get work done: a review and systematisation of simplification practices in the LCA literature. In International Journal of Life Cycle Assessment (Vol. 25, Number 11, pp. 2154–2168). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s11367-020-01821-w

Bisinella, V., Christensen, T. H., & Astrup, T. F. (2021). Future scenarios and life cycle assessment: systematic review and recommendations. In International Journal of Life Cycle Assessment (Vol. 26, Number 11, pp. 2143–2170). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s11367-021-01954-6

Blanco, C. F., Behrens, P., Vijver, M., Peijnenburg, W., Quik, J., & Cucurachi, S. (2025). A framework for guiding safe and sustainable-by-design innovation. Journal of Industrial Ecology, 29(1), 47–65. https://doi.org/10.1111/JIEC.13609

Bodar, C., Spijker, J., Lijzen, J., Waaijers-Van Der Loop, S., Luit, R., Heugens, E., Janssen, M., Wassenaar, P., & Traas, T. (2018). Risk management of hazardous substances in a circular economy. https://doi.org/10.1016/j.jenvman.2018.02.014

Boersema, J. J., & Reijnders, L. (2009). Principles of environmental sciences. In Principles of Environmental Sciences. Springer Netherlands. https://doi.org/10.1007/978-1-4020-9158-2/COVER

Bolaños Arriola, J., Aghaeian, S., Bakker, C., & Balkenende, R. (2024). Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-024-00449-4

Bolaños Arriola, J., Subramanian, V., Bakker, C., & Balkenende, R. (2023). Safe and Circular Design – A design method for dealing with substances of concern in products. In K. Niinimäki & K. Cura (Eds.), 5th PLATE Conference Proceedings 2023. https://kth.diva-portal.org/smash/get/diva2:1795825/FULLTEXT01.pdf

Bolaños Arriola, J., Weber, M., Aghaeian, S., Bakker, C., & Balkenende, R. (2025). Safe and sustainable by design: co-creating a design method for dealing with harmful substances in product design. [Manuscript submitted for publication]. .

Braakhuis, H., & Fransman, W. (2024). The future of chemicals is Safe and Sustainable by Design.

Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in Ecodesign tools for sustainable product development and procurement. Journal of Cleaner Production, 14(15–16), 1420–1430. https://doi.org/10.1016/j.jclepro.2005.03.024

Caldeira, C., Farcal, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials: framework for the definition of criteria and evaluation pro- cedure for chemicals and materials. https://doi.org/10.2760/404991

CEFIC. (2024). SAFE AND SUSTAINABLE-BY-DESIGN: A GUIDANCE TO UNLEASH THE TRANSFORMATIVE POWER OF INNOVATION. www.cefic.org

Chen, Z., & Huang, L. (2019). Application review of LCA (Life Cycle Assessment) in circular economy: From the perspective of PSS (Product Service System). Procedia CIRP, 83, 210–217. https://doi.org/10.1016/j.procir.2019.04.141

Collingridge, D. (1980). The Social Control of Technology. By David Collingridge. (Vol. 76). St. Martin's Press. https://doi.org/10.2307/1960465

Cousins, I. T., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C. A., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z., & Dewitt, J. C. (2019). The concept of essential use for determining when uses of PFASs can be phased out. In Environmental Science: Processes and Impacts (Vol. 21, Number 11, pp. 1803–1815). Royal Society of Chemistry. https://doi.org/10.1039/c9em00163h

Cross, N. (2001). Designerly Ways of Knowing: Design Discipline versus Design Science. Cross Source: Design Issues, 17(3), 49–55. https://doi.org/154.59.124.113

European Chemicals Agency. (2014). Guidance on information requirements and chemical safety assessment Chapter R11 : PBT/vPvB assessment (Number 2, pp. 1–119). http://echa.europa.eu/documents/10162/13559/mb_63_2013_consultation_procedure_for_gui

European Commission. (2018). Report on the implementation of the Ecodesign Directive (2009/125/EC) | A8-0165/2018 | European Parliament. https://www.europarl.europa.eu/doceo/document/A-8-2018-0165_EN.html

European Commission. (2020). Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN

European Commission. (2024). Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401781

European Environment Agency. (2019). The European environment – State and outlook 2020 – Knowledge for transition to a sustainable Europe. Publications Office. https://doi.org/doi/10.2800/96749

European Environment Agency. (2021). Designing safe and sustainable products requires a new approach for chemicals. Publications Office. https://doi.org/doi/10.2800/48128

Eurostat. (2022). Chemicals production and consumption statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Chemicals_production_and_consumption_statistics#Effective_changes_in_the_production_of_chemicals_hazardous_to_health

Fenwick, C., Mayers, K., Lee, J., & Murphy, R. (2023). Recycling plastics from e-waste: Implications for effective eco-design. Journal of Industrial Ecology, 27(5), 1370–1388. https://doi.org/10.1111/jiec.13409

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Helias A., U. de H., de Bruijn, H., van Duin, R., & Huijbregts, M. A. J. (2002). Handbook on life cycle assessment. Operational guide to the ISO standards. Kluwer Academic Publishers.

Guinée, J. B., Heijungs, R., Vijver, M. G., & Peijnenburg, W. J. G. M. (2017). Setting the stage for debating the roles of risk assessment and life-cycle assessment of engineered nanomaterials. Nature Nanotechnology, 12(8), 727–733. https://doi.org/10.1038/nnano.2017.135

Hill, P. J., Taylor, M., Goswami, P., & Blackburn, R. S. (2017). Substitution of PFAS chemistry in outdoor apparel and the impact on repellency performance. Chemosphere, 181, 500–507. https://doi.org/10.1016/J.CHEMOSPHERE.2017.04.122

Holmquist, H., Schellenberger, S., van der Veen, I., Peters, G. M., Leonards, P. E. G., & Cousins, I. T. (2016). Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing. Environment International, 91, 251–264. https://doi.org/10.1016/J.ENVINT.2016.02.035

Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2020). DEVELOPING A TOOL to SUPPORT DECISIONS in SUSTAINABILITY-RELATED TRADE-OFF SITUATIONS: UNDERSTANDING NEEDS and CRITERIA. Proceedings of the Design Society: DESIGN Conference, 1, 265–274. https://doi.org/10.1017/dsd.2020.137

Lo Piano, S., & Benini, L. (2022). A critical perspective on uncertainty appraisal and sensitivity analysis in life cycle assessment. Journal of Industrial Ecology, 26(3), 763–781. https://doi.org/10.1111/jiec.13237

Luttropp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. Journal of Cleaner Production, 14(15–16), 1396–1408. https://doi.org/10.1016/J.JCLEPRO.2005.11.022

Meng, F., Brandão, M., & Cullen, J. M. (2024). Replacing Plastics with Alternatives Is Worse for Greenhouse Gas Emissions in Most Cases. Environmental Science and Technology, 58(6), 2716–2727. https://doi.org/10.1021/acs.est.3c05191

Monclús, L., Arp, H. P. H., Groh, K. J., Faltynkova, A., Løseth, M. E., Muncke, J., Wang, Z., Wolf, R., Zimmermann, L., & Wagner, M. (2025). Mapping the chemical complexity of plastics. Nature, 643(8071), 349–355. https://doi.org/10.1038/s41586-025-09184-8

Olisah, C., Melymuk, L., Vestergren, R., Rumar, K., Wickman, T., Melander, N., Talasniemi, P., Brandsma, S., Boije af Gennäs, U., & Scheringer, M. (2025). Toward Product Safety and Circularity: Understanding the Information Structure of Global Databases on Chemicals in Products and Articles. Environmental Science and Technology. https://doi.org/10.1021/acs.est.4c07992

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environmental Science and Technology, 56(3), 1510–1521. https://doi.org/10.1021/ACS.EST.1C04158/ASSET/IMAGES/LARGE/ES1C04158_0002.JPEG

Sandionigi, C. (2024). Eco-reliability: A new metric for the eco-design of electronic systems.

Schellenberger, S., Hill, P. J., Levenstam, O., Gillgard, P., Cousins, I. T., Taylor, M., & Blackburn, R. S. (2019). Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. Journal of Cleaner Production, 217, 134–143. https://doi.org/10.1016/J.JCLEPRO.2019.01.160

Soeteman-Hernández, L. G., Blanco, C. F., Koese, M., Sips, A. J. A. M., Noorlander, C. W., & Peijnenburg, W. J. G. M. (2023). iScience Life cycle thinking and safe-and-sustainable-by-design approaches for the battery innovation landscape. https://doi.org/10.1016/j.isci

Subramanian, V., Peijnenburg, W. J. G. M., Vijver, M. G., Blanco, C. F., Cucurachi, S., & Guinée, J. B. (2023). Approaches to implement safe by design in early product design through combining risk assessment and Life Cycle Assessment. Chemosphere, 311, 137080. https://doi.org/10.1016/J.CHEMOSPHERE.2022.137080

The Swedish Chemicals Agency. (2020). Hazard and risk assessment of chemicals-an introduction. www.kemi.se/en/guidance-on-national-chemicals-control

Thompson, D. L., Hartley, J. M., Lambert, S. M., Shiref, M., Harper, G. D. J., Kendrick, E., Anderson, P., Ryder, K. S., Gaines, L., & Abbott, A. P. (2020). The importance of design in lithium ion battery recycling-a critical review. In Green Chemistry (Vol. 22, Number 22, pp. 7585–7603). Royal Society of Chemistry. https://doi.org/10.1039/d0gc02745f

UK Design Council. (2005). The Double Diamond. https://www.designcouncil.org.uk/our-resources/the-double-diamond/

UNECE. (2023). Globally Harmonized System of Classification and Labelling of Chemicals. https://unece.org/transport/dangerous-goods/ghs-rev10-2023

van Dijk, J., Flerlage, H., Beijer, S., Slootweg, J. C., & van Wezel, A. P. (2022). Safe and sustainable by design: A computer-based approach to redesign chemicals for reduced environmental hazards. Chemosphere, 296. https://doi.org/10.1016/j.chemosphere.2022.134050

van Dijk, J., Sharma, A., Nowack, B., Wang, Z., & Scheringer, M. (2025). From Ambition to Action: Navigating Obstacles and Opportunities of "Safe and Sustainable by Design." Environmental Science & Technology, 59(29), 14832–14841. https://doi.org/10.1021/ACS.EST.4C09863

Van Leeuwen, C. J., & Vermeire, T. G. (2007). Risk Assessment of Chemicals: An Introduction. In C. J. van Leeuwen & T. G. Vermeire (Eds.), American Journal of Therapeutics (Number 3). Springer Netherlands. https://doi.org/10.1007/978-1-4020-6102-8

Vogtländer, J. G. (2010). A practical guide for students, designers and business managers A "Fast Track" guide to LCA. www.ecocostsvalue.com



Chapter 7

Discussion

Throughout this research, we explored safety aspects in the circular economy from a product design perspective. We looked at this from two angles: first, how product design can influence risks associated with product lifetime extension; and second, how it can influence lifecycle risks arising from the materials in the product. We approached this by examining two topics: designing for safe non-professional repairs and mitigating the risks posed by Substances of Concern (SoC) throughout product lifecycles. We researched design for safe non-professional repairs, since safety is presented as the justification for preventing this group from performing them, thereby limiting the potential positive effects of this circular strategy (Svensson-Hoglund et al., 2021). We researched SoC risks across product lifecycles, as SoC can harm human health and the environment (UNECE, 2023), material recirculation can reintroduce contaminants or amplify existing risks (Beekman et al., 2020; Bodar et al., 2018; Wassenaar et al., 2017), or resources may not be recirculated if they are contaminated (Briassoulis et al., 2013; Miliute-Plepiene et al., 2021).

As a starting point, we identified a lack of methods that help designers address safety in circular product design. For SoC risks, existing assessment methods and risk mitigation strategies cater to other expertise areas, with a strong chemical focus, and do not explicitly address risks at the product level. In the case of repair safety, design for repair theory and available methods do not explicitly address safety. Therefore, our main research objective was: To develop methods that support designers in developing products that can safely cycle in a circular economy.

To achieve our aim, we conducted five studies. Chapter 2 is dedicated to designing for safe repairs, focusing on the role of design in reducing repair risks for non-professional repairers and on developing a method for designers to address repair safety. Chapters 3 to 6 are dedicated to exploring the role of design in mitigating SoC risks across product lifecycles and to developing a design method for identifying, assessing, and mitigating substance-related risks. Table 7.1 summarises the five studies and their main outcomes.

Table 7.1. Summary of studies and main outcomes.

	Chapter	Chapter aim	Main Outcomes
Safe Repairs	2	To develop a method for identifying, assessing, and mitigating repair safety risks from a product design perspective, to ensure safe repairs by non-professional repairers.	- Product design plays a critical role in reducing repair risks, making repairs accessible to non-professionals. - Relatively small design interventions can reduce risks both during and post repair. - List of repair risks in washing machines and their related design features and product architecture. - Method to identify and visualize risks in product architecture. - Design guidelines to mitigate repair risks.
Risks of SoC in products	3	To identify the contribution designers can offer in dealing with SoC in products and derive requirements for the future development of design methods and guidelines.	- The risks posed by SoC in products may not only be addressed at a chemical or material level, but also at a component, product, and system level. - Potential benefits and drawbacks of risk mitigation strategies. - Broader classification of SoC relevant to circular product design. - Design strategies to mitigate the risks of SoC identified from the analysis of five cases: Avoid, Control, and Reduce. - Recommendations for the development of design methods and guidelines.
	4	To develop a method for designers to deal with SoC in products to mitigate or manage health and environmental risks and make them fit the CE.	- First version of the Design for Substance Safety and Sustainability (DSSS) Method, based on desk research and insights obtained during the investigation of the five cases in Chapter 3. - Process to address SoC risks through a holistic, product lifecycle approach, considering trade-offs and unintended consequences. - Qualitative approach to risk assessment.

Table 7.1. *(Continued)*

Chapter	Chapter aim	Main Outcomes
5	To co-create a Design for Substance Safety and Sustainability (DSSS) method with and for design professionals.	- Derived requirements for a method to address SoC in products, including necessary resources, method functions, and procedures. - Revised version of the DSSS Method, co-created with design professionals. Practical framework for professional use. - Combination of Method Content Theory and co-creation for design method development. - List of factors with a positive or negative influence on the successful use of the method.
6	To develop a tool that applies the principles of LCA and RA in a way that caters to a product development context.	- Development of the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) Tool. - Assessment and visualization tool that allows the identification and assessment of SoC risks, whilst accounting for uncertainty. - Adaptation of RA and LCA principles into a semiquantitative assessment tool for use by designers and product developers.

7.1. Design for safe repairs – discussion of main findings

To address the main research aim from the repair perspective, we built on previous research (Bolaños Arriola et al., 2019; De Fazio et al., 2021; Ingemarsdotter et al., 2021) and conducted a study to analyse repair risks in washing machines and their relation to design features and product architecture (Chapter 2). Our findings led to the development of a method for designers to identify, assess, and visualize repair safety risks, as well as a set of preliminary guidelines for design for safe repair. This study provided insight into the scope of safety in circular product design from a product lifetime extension perspective, in which the product is the unit of analysis to ensure its continued safe use and performance.

Our analysis of the washing machines revealed a number of repair-related risks and their links to design features and product architecture. Yet, many of these risks can be addressed through relatively small design interventions. Examples include using reusable connectors, providing visual guidance, and improving visibility and accessibility. We also observed that some of these features are already present in certain components of the washing machine, confirming their feasibility. This suggests that the current restrictive approach to safety in repair can be reconsidered, and that designers can help expand repair practices to include non-professional repairers, supporting more widespread repair activities.

The distinction between safety for professional and non-professional repairers lies in the level of knowledge, experience, and available equipment, among other factors. However, both groups are exposed to the same risks during repair. Our study indicates that repair safety is dependent on deliberate design decisions. Products can therefore be smartly designed to eliminate risks, regardless of the level of expertise of the group performing the repair. When products are made non-repairable or repairable only by specific groups, such decisions should be justified by limitations or concerns that cannot be resolved through product design, for instance, extreme hazards, such as radiation. However, trade-offs that outweigh the benefits, such as increased environmental impact, may justify restricting repair. For example, if an excessive increase in material use is necessary to prevent risk, or design alterations to prevent risk lead to a loss of product durability.

Expanding repair to non-professionals, however, will require more than products that are designed to be safe to repair. Other aspects should be considered to guarantee safe non-professional repairs, such as repair information availability and accessibility (Bolaños Arriola et al., 2019; Sandez et al., 2023), spare part availability (Dangal et al., 2021), and a design that supports fault diagnosis (Pozo Arcos et al., 2021), among others.

The method we developed provides a practical approach for estimating the objective dangers of repair, enabling designers to identify and mitigate risks intentionally. By mapping risks onto the product architecture, designers can gain valuable insights into both the risks and their underlying causes. The proposed design guidelines, based on the analysis of the washing machines, may be generalized to products with similar electromechanical, water, and heating systems. However, not all guidelines can be universally applied. Strategies for mitigating risks during repair often depend on the specific systems present in the product and its overall architecture, which may require adaptation across different product groups. In contrast, several guidelines that target post repair risks, such as visual guidance for disassembly and reassembly, and the use of reusable connectors, may be broadly applicable.

Our findings also indicate that addressing repair risks closely aligns with existing design-for-repair principles (Dangal et al., 2022). If design for repair aims to expand the reach and impact of repair activities, then design for safe repair can be understood as an extension, or even a prerequisite, of design for repair.

7.2. Mitigating the risks of SoC in product lifecycles through design – discussion of main findings

To address the aim from the SoC perspective, we conducted four studies. Through the analysis of five cases of products containing SoC in Chapter 3, we identified the role of design in mitigating SoC risks, defined 3 main design strategies: Avoid, Reduce, and Control, and defined a broader classification of SoC relevant to circular product design. The remaining studies constitute the several stages we went through to develop a method for designers to identify, assess, and mitigate risks arising from SoC throughout the lifecycle of products. Chapter 4 resulted in a first version of the Design for Substance Safety and Sustainability (DSSS) method to address SoC risks in products. This version was developed based on the findings of the analysis of the five cases and the strategies obtained in Chapter 3. In Chapter 5, we further developed the DSSS method to address SoC risks in products, co-created with and for design professionals, while identifying challenges and barriers. Chapter 6 presents the development of the Mapping Assessment for Product Substance Safety and Sustainability (MAPSSS) tool. A design-specific method for assessing and mapping SoC risks, adapting risk assessment (RA) and life cycle assessment (LCA). This method specifically addresses one of the key issues for designers when addressing SoC in products: the lack of design-specific assessment tools that support decision-making and ideation despite uncertainty. The MAPSSS tool, therefore, builds on the findings from Chapter 5 regarding designers' potential limitations and capabilities in implementing the DSSS method. Through these studies, we explored safety in circular product design from a lifecycle perspective, examining

the materials contained in a product. The methods and tools developed support designers in ensuring that materials circulate safely throughout product lifecycles.

The process followed to develop design-specific resources to deal with SoC in products was iterative and incremental. The resulting MAPSSS tool and the identified design strategies (Avoid, Reduce, Control) can be positioned within the broader scope of the DSSS Method framework (Figure 7.1). MAPSSS helps identify and assess SoC risks throughout the product lifecycle and define points of concern relevant to designers. The design strategies address these points of concern from a product design perspective. MAPSSS also supports the comparison of design alternatives. While both resources support many of the required processes and steps defined in the DSSS Method, several aspects remain open for further development. For instance, guidance on involving relevant stakeholders throughout the product development process to better understand exposure scenarios and SoC risks; guidance and resources for identifying SoC in products; and guidance on trade-offs.

SoC identification and the identification of safe chemical alternatives remain significant challenges, as information on chemical and material compositions is limited, complex (European Environment Agency, 2020; Monclús et al., 2025), and often inaccessible to designers. This calls for the development of alternative resources and approaches for SoC identification that are specifically suited to product designers, such as chemical and life-cycle inventory (LCI) databases (Rajagopal et al., 2025). SoC identification should also consider the proposed broader classification of SoC proposed in Chapter 3, as current classifications are limited to evidence on hazards. The broader classification based on novel entities (Rockström et al., 2009; Steffen et al., 2015) requires designers to reflect and consider hazardous substances or pollutants used and generated throughout a product's lifecycle, and not just those that are part of its composition. It also allows consideration of other pollutants, such as microplastics.

Guidance on trade-offs also requires further attention, as the methods proposed here consider only safety and environmental trade-offs, with the latter limited to two impact indicators. While product designers might be equipped to address trade-offs in cost, performance, and processing through design, further guidance is needed to consider additional sustainability and socioeconomic trade-offs that may raise ethical dilemmas. For instance, aspects of social life cycle assessment (S-LCA) could be integrated and adapted to assess socioeconomic trade-offs of risk mitigation strategies and alternatives (Abbate et al., 2024).

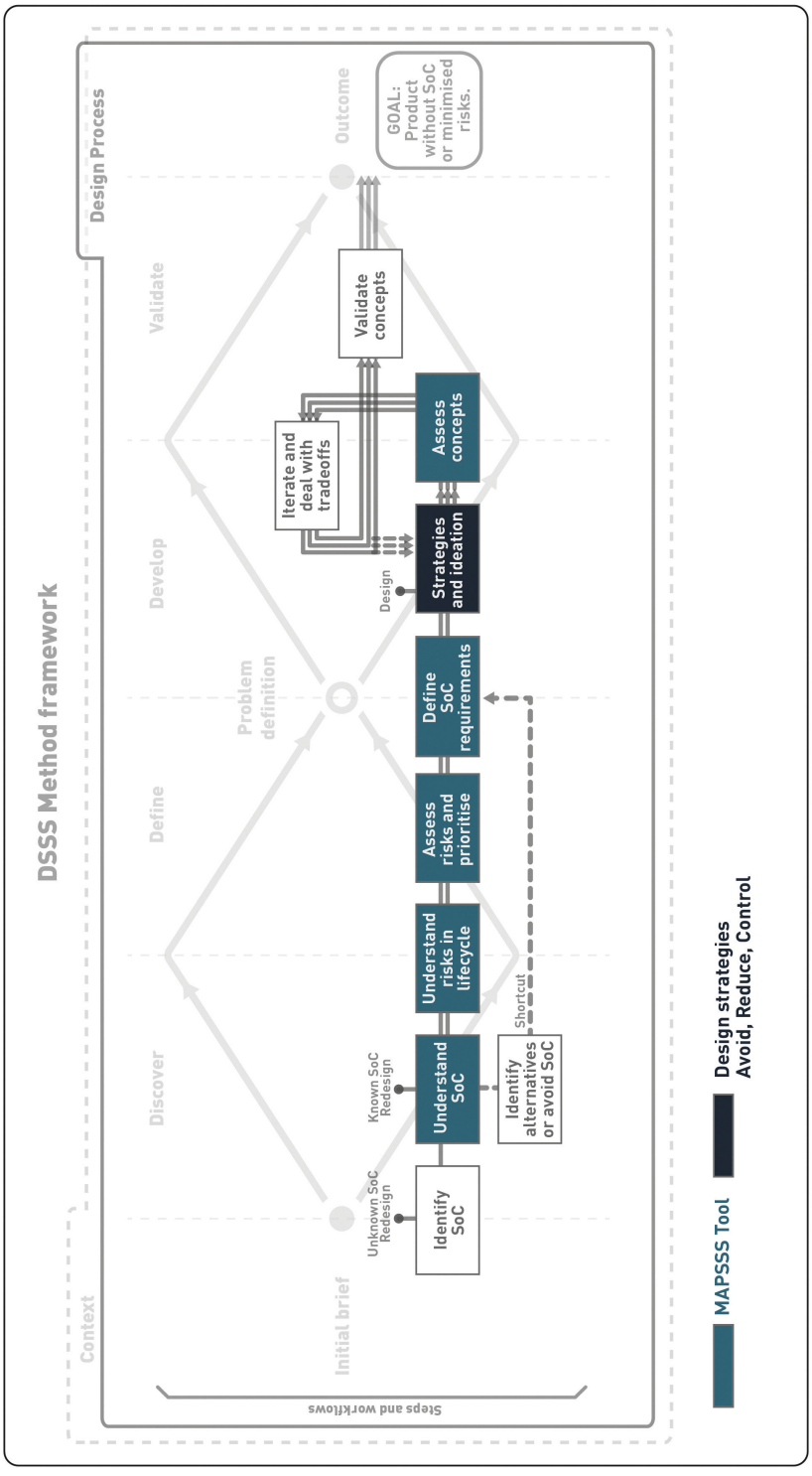


Figure 7.1. Integration of the MAPSS Tool and the design strategies into the DSSS Method framework (Adapted from figure 5.5, Chapter 5).

The methods developed use a semi-quantitative and qualitative approach to assessment, supporting design decision-making despite uncertainty. While quantitative resources such as LCA and RA provide thorough evaluations for SoC risks and environmental impacts, they remain inaccessible to designers. They are resource and data-intensive, which does not fit the initial stages of product development, or support the creative, iterative, and fast-paced nature of professional product design practice. The semi-quantitative and qualitative approaches proposed draw on design method theory and the inherent flexibility of design methods (Daalhuizen & Cash, 2021; Daalhuizen, 2014; Schønheyder & Nordby, 2018). The proposed methods require designers to reflect on a specific problem using the information available to them. Through this, we shift the focus from, for example, chemical-specific or exclusively quantitative information to contextual observable factors particular to the product designers are analysing. The methods provide a structure for managing and incrementally building information for decision-making, aligning with the design process. Qualitative and semi-quantitative approaches support early development stages, and quantitative approaches can be adopted later as data and collaboration with other experts become available.

The proposed strategies broaden the SoC approach beyond its current chemical and material focus. For instance, the Joint Research Commission's SSbD framework (Caldeira et al., 2022) aims to provide an approach that considers safety in the early stages of the development of chemicals, materials, and products. However, the product perspective remains almost entirely overlooked, with a focus on developing safe chemicals and materials. Our strategies provide designers with an array of options that are not dependent on the availability of safe alternatives or on the certainty of their safety. Risk mitigation and preventive measures can then also occur in the product design, with the focus shifting towards the safe use of substances in products. We also propose that this larger array of available strategies to mitigate SoC risks can also support designers in dealing with trade-offs. For instance, while substituting a hazardous chemical or material may address safety issues and prevent further environmental burden, it may also result in reduced performance, higher cost, or higher impact. However, by combining the substitution strategy with modifications or risk-mitigation strategies at the component or product level, the designer could target the trade-off. For instance, in Chapter 3, the PVC cable sleeve contaminated with a hazardous plasticizer could be substituted with an inherently flexible material. However, these could reduce durability, which could be further improved by adjusting the cable sleeve thickness and design.

7.3. Safety in circular product design – connections between the two approaches

Throughout this work, we addressed safety issues across product lifecycles from two angles. The topic of design for safe repair examined how design can influence the risks associated with product lifetime extension. The topic of SoC risks in product lifecycles explored how design can influence risks arising from the materials contained in the product. Both take the product as the unit of analysis, but the SoC topic also applies a broader lifecycle perspective. Together, they provide complementary perspectives on safety in circular product design. Two aspects common to both approaches will be discussed in more detail here: trade-offs and uncertainty.

Our studies indicate that trade-offs are common when addressing safety risks. Efforts to improve safety may lead to reduced performance, such as increased weight or slower operation. They may also result in higher costs, new or aggravated environmental impacts, or new and uncertain sources of risk. While it may not be possible to predict all trade-offs precisely, designers need tools to assess and navigate such tensions to anticipate and mitigate the unintended consequences of design interventions aimed at reducing risk. The visual aspect of methods such as the MAPSSS tool and repair safety mapping strengthens decision-making by making trade-offs more tangible and comparable. Visualization in design supports the structuring of complex information for analysis and communication (Daalhuizen, 2014). These methods then help design teams address complexity and understand the implications of their choices by comparing original products with redesigns or alternative concepts. Comparable visualization-based approaches are well established in design for sustainability (Faludi, 2015; Vezzoli et al., 2017), aiming to enable and enhance the integration of sustainability into design practices.

We have observed that adopting a holistic, lifecycle perspective, one that situates product lifecycles within their temporal, physical, and socio-economic contexts, can support designers in addressing safety considerations in circular product design while remaining aware of and balancing trade-offs, including those related to sustainability and performance.

Whilst considering trade-offs is important, it is equally crucial to reflect on their significance to prioritize them. Concepts such as essentiality (Cousins et al., 2019; Garnett & Van Calster, 2021), which question the necessity of certain chemicals in specific applications, and the criticality of performance requirements, can guide prioritization when making design decisions that affect both safety and sustainability.

Multiple layers of uncertainty characterize safe circular product design. As seen, for example, in Chapters 2, 5, and 6, designers must work with incomplete knowledge

of future impacts, uncertain trade-offs, and data gaps related to probabilities, severity, chemical properties, and exposure scenarios. These uncertainties highlight the need to anticipate emerging risks rather than react solely to those that have already been measured. This calls for design methods that help designers navigate uncertainty by fostering scenario, anticipatory, and reflective thinking, along with systemic perspectives, enabling informed decisions despite incomplete knowledge (Cucuzzella, 2016).

A lack of complete evidence should not justify inaction. When designers must act despite uncertainty, the Precautionary Principle, often applied in environmental policy, could guide them to act proactively. It is a concept and policy guideline that encourages precautionary measures to protect human health and the environment in the face of uncertain risks posed by an activity (Raffensperger & Tickner, 1999; Read & O'Riordan, 2017). In the context of circular product design, some aspects of this principle could help address both unknown trade-offs and data gaps, for instance, in substance safety.

The Precautionary Principle has been criticized for being paralyzing and threatening innovation (Aven, 2023; Read & O'Riordan, 2017). It is interpreted as overly restrictive and confused with, for example, the avoidance of certain substances. However, our work offers an alternative perspective or interpretation of this principle for its application in the context of circular product development. For instance, we found that Avoid strategies are not always feasible, or the safety of alternatives is not clearly defined. Still, Control strategies can be used as precautionary measures to allow the safe use of substances despite their potential hazardous properties. This shifts the approach to risks from strict avoidance to a careful, planned use of substances.

Hansson (2020) proposes that the Precautionary Principle should not be interpreted as absolute or as a demand for zero risk, but rather as a guide for decision-making in the face of uncertainty. This introduces a principle of proportionality, under which not all uncertain risks should trigger extreme precaution. For instance, potentially severe or more likely risks may justify stronger protective actions, while less likely or less severe risks call for more moderate measures. However, such an approach in the context of product design would require transparency and estimates that provide insights into the severity and probability of risks, to avoid overlooking or underestimating them.

7.4. Contributions to scientific knowledge

This dissertation contributes to the field of safety from a circular product design perspective, a topic that has received limited attention to date. It offers an initial

exploration of safety issues that arise across the product lifecycle, including those related to the materials in products and those arising from product lifetime extension strategies. By extension, this research contributes to the fields of Circular Product Design and Design for Sustainability.

The research introduces novel practical approaches to help designers integrate safety into the development of circular products. These methods draw on design method development theory, adapt existing risk assessment methodologies, and involve collaborative approaches with professional designers and experts. The dissertation contributes to design method development and demonstrates how interdisciplinary methodologies can be adapted for design practice. For instance, quantitative risk assessment approaches were translated into semi-quantitative and qualitative formats suited to design processes.

The findings also advance the field of design for repair by extending existing principles to include safety and by offering insights into how design influences repair risks. This dissertation also clarifies the role and influence of design in relation to SoC risks and expands the research domain of Safe and Sustainable by Design by moving beyond its current chemical and material focus to incorporate a product design perspective. Finally, we propose a broader classification of SoC from a circular product design perspective inspired by (Rockström et al., 2009; Steffen et al., 2015). Our classification considers a broader array of compounds of human origin (e.g., plastics), accounting for substances present in the product, those used during production, and those generated during other lifecycle stages (Chapter 4).

7.5. Societal relevance

Implications for design practice

This dissertation addresses a critical gap by providing practical approaches and guidance to address safety considerations in the design process of circular products. Designers can have a strong influence on the risks associated with SoC in products and those that arise during product repair. The developed resources include:

- A method that enables designers to evaluate repair risks and identify their origin in relation to the product design and architecture.
- A preliminary set of design guidelines for safe repair that provides insights to help designers mitigate repair-related risks.
- A set of design strategies to mitigate SoC risks in product lifecycles: Avoid, Control, Reduce. The strategies expand the current material and chemical focus, providing additional options for designers to address risk at the product level.

- A DSSS Method framework that defines the process and resources necessary for designers to address SoC risks throughout product lifecycles.
- A MAPSSS Tool for SoC risk identification and assessment that integrates and adapts LCA and RA for product designers. The tool provides qualitative and semi-quantitative approaches that address data gaps and information accessibility issues, while leveraging designers' expertise.

Implications for policy

Our research indicates that limited data availability significantly hinders progress in addressing risks related to SoC, and this challenge extends beyond the field of product design. To support safer design and more informed decision-making, policies could further promote transparency and improve the availability and accessibility of data on chemicals and material compositions throughout the supply chain.

Given our findings, we also suggest shifting from a reactive to a preventive approach to regulating SoC. Current regulations often require substantial evidence before substances can be classified as hazardous, which can delay timely action. Furthermore, while the development of safer chemicals and materials is essential, these alternatives often fail to meet performance requirements or lack sufficient data to be deemed safe. As a result, many SoC continue to be used due to their economic and functional advantages. Our expanded classification of SoC, along with the implications of their use across multiple lifecycles, suggests that addressing these substances will become increasingly complex. Product design plays a central role in mitigating SoC risks throughout product lifecycles. Policies could therefore promote broader strategies for the safe use of substances, moving beyond a solely chemical-focused perspective to also consider the product, its application, and lifecycle(s). Finally, substances with a high degree of uncertainty over their safety could be further regulated, setting limitations on their use and emissions.

European policy is increasingly addressing the repairability of products. While consulting these policies, we observed that some terminology would benefit from further clarification to support consistent interpretation. For instance, the Directive on common rules promoting the repair of goods, the Directive establishing ecodesign requirements for sustainable products, and the General Product Safety Regulation do not clearly define "professional repairer", nor do they offer guidance on what constitutes an "easy" and "safe" repair.

Moreover, as debates continue about which groups should be enabled to perform repair, our research highlights that deliberate design decisions strongly influence repair safety. These decisions ultimately shape who is enabled to carry out repairs. We also found that several repair-related risks can be mitigated through relatively simple design modifications. This suggests that limiting repair to professionals

cannot continue to be justified on safety grounds without evidence of impending risks or severe trade-offs, for example, in costs.

Our insights suggest that policy could encourage product designs that support safe non-professional repairs, thereby expanding repair opportunities and contributing to circularity targets. Product repairability requirements and metrics established in current directives could be modified and expanded to require manufacturers to enable non-professional repair by guaranteeing the availability of spare parts and repair information suitable for non-professionals, and addressing repair safety risks at the product level. As a starting point, Chapter 2 provides preliminary design guidelines for safe repair that align with known repairability guidelines, including the use of reusable connectors and improved visibility, which could be further encouraged.

7.6. Recommendations for future research

Since this dissertation presents an initial exploration of safety aspects in the circular economy from a product design perspective, it opens up several opportunities for future research:

1) **Further development and implementation of the proposed methods.** The studies presented here resulted in several design methods. Their continued development, however, requires testing and collaboration with practitioners to enable their incorporation in design practice. Future work could assess how these methods and guidelines influence decision-making and their impact on risk reduction, sustainability, and circularity. This applies to both SoC risks and repair risks.
2) **Expansion of the safe repair design guidelines to cover a broader range of product categories.** The study in Chapter 2 produced preliminary guidelines based on washing machines and (implicitly) on the products investigated in previous research (Ingemarsdotter et al., 2021). While many may be generalizable, further research could examine additional product categories to address chemical risks and other risk types not yet considered.
3) **Development of methods to estimate the severity and occurrence of repair safety risks.** Our approach to repair risks was entirely qualitative. Although useful for understanding risk-inducing features and product architecture, quantitative estimations could strengthen prioritization and decision-making.
4) **Development of chemical databases suited for designers.** Information on chemicals and material compositions remains limited and often inaccessible to designers due to complexity and prior-knowledge requirements. Databases designed for design practice could support SoC identification and risk assessment by including common applications, associated hazards, vulnerable groups,

and substance characteristics that, in combination with external factors, may increase emissions. Such resources may also present opportunities for artificial intelligence approaches.

5) **Development of guidance to support the identification of SoC in existing products.** Identifying SoC in products remains a significant challenge for designers and was not further explored in this dissertation. Initiatives such as digital product passports could address this issue by including additional information on chemical and material compositions. Alternatively, throughout Chapter 5, design professionals suggested developing resources based on heuristics that link material properties to potential substance risks.

7.7. References

Abbate, E., Garmendia Aguirre, I., Bracalente, G., Mancini, L., Tosches, D., Rasmussen, K., Bennet, M., Rauscher, H., & Sala, S. (2024). Safe and Sustainable by Design chemicals and materials-Methodological Guidance. https://doi.org/10.2760/28450

Aven, T. (2023). A risk and safety science perspective on the precautionary principle. Safety Science, 165, 106211. https://doi.org/10.1016/J.SSCI.2023.106211

Bolaños Arriola, J., de Fazio, F., Balkenende, R., Bakker, C., & Flipsen, B. (2019). Safe by Design - Safe self-repairs (Vol. 2019, Issue december). https://minienw.sitearchief.nl/?subsite=safebydesign#archive

Briassoulis, D., Babou, E., Hiskakis, M., Scarascia, G., Picuno, P., Guarde, D., & Dejean, C. (2013). Review, mapping and analysis of the agricultural plastic waste generation and consolidation in Europe. Waste Management & Research, 31(12), 1262–1278. https://doi.org/10.1177/0734242X13507968

Caldeira, C., Farcal, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials: framework for the definition of criteria and evaluation pro- cedure for chemicals and materials. https://doi.org/10.2760/404991

Cousins, I. T., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C. A., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z., & Dewitt, J. C. (2019). The concept of essential use for determining when uses of PFASs can be phased out. Environmental Science: Processes & Impacts, 21(11), 1803–1815. https://doi.org/10.1039/C9EM00163H

Cucuzzella, C. (2016). Creativity, sustainable design and risk management. Journal of Cleaner Production, 135, 1548–1558. https://doi.org/10.1016/J.JCLEPRO.2015.12.076

Daalhuizen, J., & Cash, P. (2021). Method content theory: Towards a new understanding of methods in design. Design Studies, 75, 101018. https://doi.org/10.1016/J.DESTUD.2021.101018

Daalhuizen, J. (2014). Method Usage in Design (Doctoral dissertation). Delft University of Technology. https://doi.org/10.4233/UUID:4AC01165-C6B5-4057-A2FE-3418907F251E

Dangal, S., Balkenende, R., Faludi, J., Den Berge, V., & Arcos, P. (2021). Perceived Capabilities and Barriers for Do-It-Yourself Repair. Product Lifetimes and the Environment (PLATE). https://www.researchgate.net/publication/361074098

Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. Sustainability (Switzerland), 14(14). https://doi.org/10.3390/su14148634

De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. Journal of Cleaner Production, 320, 128552. https://doi.org/10.1016/J.JCLEPRO.2021.128552

European Environment Agency. (2020). The European environment-state and outlook 2020. https://doi.org/10.2800/96749

Faludi, J. (2015). A sustainable design method acting as an innovation tool. Smart Innovation, Systems and Technologies, 35, 201–212. https://doi.org/10.1007/978-81-322-2229-3_18/FIGURES/5

Garnett, K., & Van Calster, G. (2021). The Concept of Essential Use: A Novel Approach to Regulating Chemicals in the European Union. Transnational Environmental Law, 10(1), 159–187. https://doi.org/10.1017/S2047102521000042

Hansson, S. O. (2020). How Extreme Is the Precautionary Principle? NanoEthics, 14(3), 245–257. https://doi.org/10.1007/S11569-020-00373-5/FIGURES/2

Ingemarsdotter, E., Stolk, M., & Balkenende, R. (2021). Design for Safe Repair in a Circular Economy. https://minienw.sitearchief.nl/?subsite=safebydesign#archive

Miliute-Plepiene, J., Fråne, A., & Almasi, A. M. (2021). Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries. In Cleaner Engineering and Technology (Vol. 4, p. 100246). Elsevier. https://doi.org/10.1016/j.clet.2021.100246

Monclús, L., Arp, H. P. H., Groh, K. J., Faltynkova, A., Løseth, M. E., Muncke, J., Wang, Z., Wolf, R., Zimmermann, L., & Wagner, M. (2025). Mapping the chemical complexity of plastics. Nature, 643(8071), 349–355. https://doi.org/10.1038/s41586-025-09184-8

Pozo Arcos, B., Dangal, S., Bakker, C., Faludi, J., & Balkenende, R. (2021). Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. Journal of Cleaner Production, 319, 128741. https://doi.org/10.1016/J.JCLEPRO.2021.128741

Raffensperger, C., & Tickner, J. (1999). Protecting public health & the environment : implementing the precautionary principle. Island Press. https://islandpress.org/books/protecting-public-health-and-environment

Rajagopal, R., Bohnes, F., Kukic, P., Rigarlsford, G., Vandenbossche-Goddard, E., Campos, B., Davies, C., Malcomber, I., Maxwell, G., & Sim, S. (2025). Optimizing the implementation of safe and sustainable by design to better enable sustainable innovation. IScience, 28(8), 113116. https://doi.org/10.1016/J.ISCI.2025.113116

Read, R., & O'Riordan, T. (2017). The precautionary principle under fire. Environment, 59(5), 4–15. https://doi.org/10.1080/00139157.2017.1350005;SUBPAGE:STRING:FULL

Rockström, J., Steffen, W. L., Noone, K., Persson, Å., Stuart, F., Iii, C., Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C. A., Hughes, T., … Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Planetary Boundaries: Exploring the Safe Operating Space for Humanity Space for Humanity Citation Details Citation Details.

Sandez, S., Pérez-Belis, V., Juan, P., & Bovea, M. D. (2023). Do users have the ability to self-repair non-complex electrical appliances? Design and development of a self-guided workshop with repair documentation in different formats. Sustainable Production and Consumption, 39, 244–256. https://doi.org/10.1016/J.SPC.2023.05.007

Schønheyder, J. F., & Nordby, K. (2018). The use and evolution of design methods in professional design practice. Design Studies, 58, 36–62. https://doi.org/10.1016/J.DESTUD.2018.04.001

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223). https://doi.org/10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. Journal of Cleaner Production, 288, 125488. https://doi.org/10.1016/J.JCLEPRO.2020.125488

UNECE. (2023). Globally Harmonized System of Classification and Labelling of Chemicals. https://unece.org/transport/dangerous-goods/ghs-rev10-2023

Vezzoli, C., Kohtala, C., Srinivasan, A., Diehl, J., Fusakul, S. M., Xin, L., & Sateesh, D. (2017). Methods and tools for system design for sustainability. Product-Service System Design for Sustainability, 87–195. https://doi.org/10.4324/9781351278003-5

8. List of Publications

Publications and conferences included in this dissertation

Journal Article

Bolaños Arriola, J., Aghaeian, S., Bakker, C., & Balkenende, R. (2024). Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases. Circular Economy and Sustainability, 1–20. https://doi.org/10.1007/S43615-024-00449-4/FIGURES/1

Conference proceedings

Bolaños Arriola, J., Subramanian, V., Bakker, C., & Balkenende, R. (2023). Safe and Circular Design – A design method for dealing with substances of concern in products. In K. Niinimäki & K. Cura (Eds.), 5th PLATE Conference Proceedings 2023. https://kth.divaportal.org/smash/get/diva2:1795825/FULLTEXT01.pdf

Conference presentation

Weber, M., Bolaños Arriola, J., & Balkenende, R. Mapping the uncertain risks and impacts of substances of concern in product lifecycles – a circular design tool for product developers. International Conference on Life Cycle Management (LCM) Proceedings 2025.

Journal article (submitted)

Bolaños Arriola, J., Ingemarsdotter, E., Bakker, C., Balkenende, R., Designing for safe repairs - Identifying and mitigating repair safety risks in washing machines. Sustainable Production and Consumption.

Journal article (submitted)

Bolaños Arriola, J., Weber, M., Aghaeian, S., Bakker, C., & Balkenende, R. Safe and sustainable by design: co-creating a design method for dealing with harmful substances in product design. Circular Economy and Sustainability.

Journal article (submitted)

Bolaños Arriola, J., Weber, M., van Dulmen, N., Guinée, J., Vijver, M.G., & Balkenende, R. Mapping uncertain risks and impacts of substances of concern in product life cycles - an SSbD tool for product developers. Circular Economy and Sustainability.

Publications and conferences outside this dissertation

Journal Article

Dangal, S., Sandez, S., Bolaños Arriola, J., Faludi, J., & Balkenende, R. (2025). Empirical evaluation of reparability scoring systems for validity and reliability. Resources,

Conservation and Recycling, 218, Article 108211. https://doi.org/10.1016/j.resconrec.2025.108211

Journal Article

van Oudheusden, A. A., Bolaños Arriola, J., Faludi, J., Flipsen, B., & Balkenende, A. R. (2023). 3D Printing for Repair: An Approach for Enhancing Repair. Sustainability, 15(6), Article 5168. https://doi.org/10.3390/su15065168

Book

Bolanos Arriola, J., van Oudheusden, A. A., Flipsen, B., & Faludi, J. (2022). 3D Printing for Repair Guide. TU Delft OPEN Publishing. https://doi.org/10.5074/t.2022.003

Conference proceedings

Samenjo, K., van Oudheusden, A., Bolaños Arriola, J., Flipsen, B., & Faludi, J. (2022). Opportunities For 3D-printable Spare Parts: Estimations From Historical Data. In C. Fitzpatrick (Ed.), 4th PLATE Virtual Conference 2021 https://doi.org/10.31880/10344/10236

Conference proceedings

De Fazio, F., Bolaños Arriola, J., Dangal, S., Flipsen, B., & Balkenende, R. (2020). Further development of the Disassembly Map, a method to guide product design for disassembly. In M. Schneider-Ramelow (Ed.), Electronics Goes Green 2020+ (EGG)

9. Acknowledgements

It is hard to write this section without ending up thanking everyone in your life for everything they have ever done for you. So, I will try to focus on the people who helped me make it to the end of this PhD (although, as I am writing this, I realize I have not actually defended yet). That said, I do want to use a few sentences to thank the people who give me their love, friendship, and support every day and make my life full and fun (in Mexico, the Netherlands, and other places of the world). Without that foundation, there is no me. The possibility of doing and (hopefully) concluding this PhD is the result of a lifetime of your support and love. Thank you, I love you all.

Ruud and Conny, thank you for all the opportunities to work and learn with you over the years. I feel lucky to have met you. Thank you for sharing your knowledge and experience, for the discussions, for always standing up for me, for allowing humour in our meetings, and most of all, for trusting and believing in me. With everything you have given me, I hope to keep doing research and contribute, in whatever scale I can, to better our world.

To the committee members, thank you for your interest in my work and for preparing questions that allow me to discuss and defend my dissertation and propositions.

Maaike, I cannot stress enough how happy your arrival at SDE made me. Thank you for making work and everyday life more fun, motivating, and interesting. Thank you for your friendship, for collaborating with me, and for the constant humour. Puck, thank you for being there for me. Your support and friendship, much like Maaike's, have made rough days easier and good days even better. Israel and Ayşegül, thank you for your friendship and for understanding me.

To my PhD and DfS colleagues and friends, past and present, across all floors and departments of IDE, you make work more fun and much easier every day. I appreciate each of you. Thank you for sharing both happy and not so happy moments, for your support, and for all the coffee dates and lunches. I feel grateful to have been part of these communities.

Soroush, thank you for your support and guidance during what I consider the hardest year of my PhD. Jeroen and Martina, thank you for guiding me through LCA and RA. Your enthusiasm has been incredibly motivating. Bas, thank you for all our repair collaborations. Martin, thank you for your support and for welcoming me into the Applied Labs. Martha, thank you for your support both inside and outside the PhD council. To everyone at the secretariaat, past and present, thank you for your help over the years. To the Board of the Justus en Louise van Effen Foundation,

thank you for giving me the opportunity to attend TU Delft all those years ago, I cannot thank you enough.

Finally, thank you to a few essential parts that kept me going through this PhD journey. Ma, pa, fue estresante, pero ya casi acabamos. Gracias por su amor, por enseñarme a trabajar duro, y por siempre estar ahí para mí. Los amo. Martijn, thank you for your immense patience and for an endless list of loving and supportive things you do every single day, I love you. The PhD is almost done. On to the next adventure. To all my favourite musicians out there, thank you for the music that filled my PhD years with energy and joy.



10. About the author

Julieta Bolaños Arriola was born on April 15, 1991, in Mexico City, Mexico. She completed her secondary education at Escuela Nacional Preparatoria No. 6 Antonio Caso. She then obtained a bachelor's degree in Industrial Design from Universidad Nacional Autónoma de México in Mexico City. During her studies, she completed an exchange year at NTNU in Trondheim, Norway. After graduating, Julieta worked as an Industrial Designer at the design firm TUUX in Mexico City. She later moved to the Netherlands to pursue a master's degree in Integrated Product Design at Delft University of Technology. During her master's, she focused on sustainability and obtained the annotation Technology in Sustainable Development. For her graduation project, she developed a washing machine suitable for service-based business models, in collaboration with Bundles and Miele.

Following her graduation, Julieta worked as a Sustainability Designer at the children's car seat brand BeSafe in Utrecht. There, she analysed the product portfolio to identify opportunities for circular design strategies. Driven by her interest in sustainable and circular product design, she returned to Delft University of Technology as a researcher in the Design for Sustainability group at the Faculty of Industrial Design Engineering. She first contributed to the Safe by Design project, which examined strategies to improve the safety of repairs carried out by non-professionals. She then worked on the Sharepair project, which aimed to support consumer product repair through digital tools and explored the use of additive manufacturing for spare parts. During this project, she developed a guide on 3D printing for repair and created a video series to support the design and production of spare parts.

Julieta then began her PhD within the same research group at Delft University of Technology. In her doctoral research, she studied how product design decisions influence safety across product lifecycles. She developed practical methods and guidelines to help designers ensure that products circulate safely within a circular economy. During her PhD, she enjoyed coaching courses on circular product design and design for repairability, wrote several academic publications, participated in conferences and workshops abroad, organized and facilitated workshops with other professionals, and spent many enjoyable hours in the lab disassembling and analysing products. In addition to her work, Julieta has spent the last twelve years climbing rocks outdoors and training indoors in climbing gyms with questionable air quality. She now aspires to start a business based on her research and doctoral work and to continue training so she can climb more rocks.



| Julieta Bolaños Arriola

Delft University of Technology |