Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases

Arriola, Julieta Bolaños; Aghaeian, Soroush; Bakker, Conny; Balkenende, Ruud

DOI
10.1007/s43615-024-00449-4

Publication date
2024

Document Version
Final published version

Published in
Circular Economy and Sustainability

Citation (APA)
Arriola, J. B., 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

Circular Economy and Sustainability
https://doi.org/10.1007/s43615-024-00449-4

ORIGINAL PAPER

Strategies for Dealing with Substances of Concern in Product Design – a Review of Five Cases

Julieta Bolaños Arriola[1] · **Soroush Aghaeian**[1] · **Conny Bakker**[1] · **Ruud Balkenende**[1]

Received: 5 April 2024 / Accepted: 23 September 2024

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 analyzed 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.

Keywords Substances of concern · Product design · Design strategies · Hazardous substances · Circular economy

---

✉ Julieta Bolaños Arriola
J.bolanosarriola@tudelft.nl

[1] Faculty of Industrial Design Engineering, Department of Sustainable Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, the Netherlands

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 [1, 2].

Examples of SoC in products include additives, such as phthalate-based plasticizers used in flexible plastic products [3, 4], PFAS, used for their water and oil repellent properties in food packaging and textiles [5, 6], or lead, used in metal alloys and solder for electronics [7, 8]. 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 [9]. 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 [10]. Health hazards of SoC can include acute toxicity, carcinogenicity, mutagenicity, and reproductive toxicity, among others [11]. 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 [11]. Furthermore, Persson et al. [12] 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 [12].

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 [11]. 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. [13, 14]) "*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 [15–17], and their ability to damage aquatic and terrestrial wildlife and cause respiratory problems and cardiovascular diseases in humans [18].

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 tradeoffs 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 [19]. This indicates that to mitigate the risks of SoC in products while minimizing potential tradeoffs, 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 [20–23]. 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 [20, 24]. Examples of this include contaminants deriving from recycled paper introduced in food packaging [25, 26], and toys containing contaminated recycled plastics derived from waste electrical and electronic equipment (WEEE) [27]. 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 [28, 29]. In transitioning to a Circular Economy (CE), products must thus be designed either without substances of concern (SoCs) 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 SoCs in products is predominantly focused on the development of non-toxic chemicals and safe material alternatives [20, 30, 31]; from the chemical engineering, biotechnology, and nanomaterials perspective in particular, with approaches such as the Safe and Sustainable by Design framework [32–34]. 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 [1]. 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 [35, 36]. 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 [37, 38].

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 the supplementary information S1), and a table summarizing all identified mitigation interventions. Finally, we discuss our results and their implications in design practice and design for the circular economy.

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.

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 [39]. 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 1 presents the selected five cases with background information about their regulatory status and function of the SoC in the product.

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.

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 analyzed each intervention through the following steps:

Table 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, [40]. Directive 2008/68/EC, on the inland transport of dangerous goods, [41]. Regulation (EC) No 1272/2008, on classification, labelling and packaging of substances and mixtures [42].	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) [43].	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) [43].	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) [43]. Regulation (EU) 2019/ 1021 on persistent organic pollutants [44]. 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.

- 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.
- Analyze 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.

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 analyzed in the same way and are presented in the supplementary information (S1). The results of all cases are then summarized and clustered, resulting in three major groups of mitigation strategies that can be followed by designers.

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 [45] and the regulations concerning substances that deplete the ozone layer [46], 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) [47, 48]. 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) [47, 48]. Among HFCs, HFC 134a (also known as 1,1,1,2-tetrafluoroethane), stands as the most used type [47, 49]. When utilized within the cooling system, HFC 134a circulates through the components of the hermetically sealed refrigerating unit [48, 50]. 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 [48, 50].

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) [51, 52], its elevated GWP makes HFC 134a a significant contributor to radiative forcing and, consequently, climate change [49, 53]. For this reason, the identification, containment, use, transportation, recovery, and destruction of fluorinated gases are subject to regulation in Europe [40–42], as well as the waste management of cooling equipment [54]. 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 [48, 50, 55–57]. HFC 134a is primarily released into the atmosphere, where it remains with an atmospheric lifetime of about 12 years [58]. Emissions into wastewater and water bodies are expected to volatilize and accumulation in any form of organism or to be absorption in soil is not expected [52]. Exposure scenarios are normally of low or no concern [52]. In case of spillage, it is recommended to wear personal and respiratory protection [52]. Overexposure via inhalation can cause central nervous system depression and cardiac sensitization [51].

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 2). For conciseness, we focused on identifying mitigation interventions related to currently prevalent refrigerants like HFC 134a and their associated risks. Table 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.

Summary of Identified Interventions in the Five Cases

Table 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 4. These strategy groups are also used as ordering principle in Table 3.

Table 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

Table 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, [57], [59].	- Decreased global warming potential and lower atmospheric lifetimes, [57], [59].	- No substance fulfills all criteria: no Ozone Depleting Potential (ODP), low GWP, non-flammable, non-toxic, and highly energy-efficient, [49], [60]. - CO2's higher operating pressures make it unsuitable for household applications, [59]. - Some alternative refrigerants have a lower energy efficiency, potentially increasing indirect environmental impact, [49].	- 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, [57], [59].	- Decreased global warming potential and lower atmospheric lifetimes, [57], [59].	- Higher production costs and changes in the production methods, [57]. - Risk of explosion and high flammability for the use phase and recycling processes, [57]. - No substance fulfills all criteria: no Ozone Depleting Potential (ODP), low GWP, non-flammable, non-toxic, and highly energy-efficient, [49], [60].	- 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, [50].	- When functioning correctly, hermetic systems can entirely prevent refrigerant emissions from the cooling system, [50], [61].	- Leakage may result from faulty or loose components, such as joints, [50]. - Servicing the system, which may require puncturing for recharging or releasing refrigerant, can lead to leakage [50]. - Damage during use or transportation is a potential source of leakage, [50], [56].	- 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, [62].	- Prompt detection and warning can result in immediate response, [62].	- Not currently applied to household refrigerators, only applied in professional refrigerating equipment, [62].	- The design of the product needs to be adapted to allocate new components.
Controlled recovery, and collection of refrigerant gases, [54].	- Refrigerants are collected to be recycled or destroyed, avoiding emissions of improper disposal, [48], [54], [56].	- Emissions resulting from the extraction process, due to puncture, faulty components, or operations, [48], [50], [55]. - Emissions resulting from the cooling system breakage during transportation or handling, [56].	- The product needs redesign associated with the development of new recycling systems and transportation protocols.
Collection of blowing agents at end-of-life, [48], [56].	- Blowing agents are collected during the shredding process in a controlled environment to then be recycled or destroyed, avoiding emissions of improper disposal, [48], [54], [56].	- The process can only be performed by specialized treatment plants due to explosion risk, [48], [54], [56].	- The product needs redesign associated with the development of new recycling and recovery systems.
Addition of a valve for extraction and recharge of refrigerants, [48].	- The puncturing of the hermetic system is no longer necessary, avoiding leakage during servicing and recovery processes, [48].	- The cooling system is hermetic by regulation, [40]. - The valve could increase risks of leakage during the use phase if users misuse it, [48].	- 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, [48], [56].	- Prevention of leakage caused by breakage during transportation and handling, [48], [56].	*- 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, [48].	- Lower refrigerant emissions, [48], [50].	- Reduction is constrained since the refrigerant volume influences the energy efficiency of the appliance, [48]. - Reduced energy efficiency could lead to an increased indirect environmental impact, [49].	- The refrigerator and its cooling system need redesign to avoid loss of performance.

emissions in different stages of the lifecycle. Table 4 presents each of the identified strategy groups and describes its characteristics as observed from the cases.

Figure 1 presents the strategy groups in a hierarchy that prioritizes *Avoid* over Control and *Reduce*, and examples for each of the strategy types.

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

Table 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, [57], [59].	• Hermetic cooling units, [50].	• Reducing the volume of refrigerant gas in the cooling system, [48].
	• Substitution of HFC 134a as a blowing agent with HFOs, inert gases, and hydrocarbons, [57], [59].	• Leakage detection systems, [62].	
		• Addition of a valve for extraction and recharge of refrigerants, [48].	
		• Strengthening or protecting the components of the cooling system, [48], [56].	
		• Infrastructure for controlled recovery, and collection of refrigerant gases, [54].	
		• Infrastructure for the collection of blowing agents, [48], [56].	
2) Charging cables containing DEHP (Bis(2-ethylhexyl) phthalate)	• Substitution of DEHP by another phthalate-based plasticizer (e.g., DINP and DIDP), [63].	• Infrastructure for controlled recovery [54].	• Increasing the useful life of cables through repair and durable design, to reduce accumulation at EoL (European Commission, 2019).
	• Substitution of DEHP by a non- phthalate-based plasticizer (e.g., DEHT, Dioctyl Adipate, biobased alternatives), [63].		
	• Substitution of the cable material (e.g., PE, PP, PUR, PS, rubber), [65].		
3) PVC flooring containing DEHP (Bis(2-ethylhexyl) phthalate)	• Substitution of DEHP by another phthalate-based plasticizer (e.g., DINP and DIDP), [63].	• Preventing emissions with layered materials, [66], [67].	• 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, [68].
	• Substitution of DEHP by a non- phthalate-based plasticizer, (e.g., DINCH), [69], [70], [71].	• Infrastructure for controlled recovery for controlled landfill and incineration of flooring waste, [72].	• Inform the user to reduce emissions and exposure: Improving indoor air quality, [4], [67], [73]. E.g., avoiding high temperatures and humid environments near PVC flooring, and cleaning contaminated dust, [66], [67], [74].
	• Substitution of the material (e.g., PE, PP, PUR, PS, rubber), [65].	• Infrastructure for recovery and recycling, [68], [72].	• Increasing the useful life of flooring products through maintenance and repair, to reduce accumulation at EoL, [68].
4) Emission of microplastics from agricultural mulch films	• Substitution of LDPE films for photodegradable and biodegradable materials, [75], [76].	• Automated mulch recovery systems, [75], [77], [78].	• Reduce mechanical degradation through reduced use of machinery or increase of film thickness, [78].
	• Substitution of LDPE films for paper mulch, [75].	• Infrastructure for recovery and recycling of used agricultural mulch films, [79], [80].	
	• Substitution of material for biobased alternatives (e.g., straw, woodchips, living mulches), [81].		
5) Synthetic textiles, such as outdoor garments, containing PFAS	• Substitution of long carbon chain PFAS with those with shorter carbon chains, [82].	• *No control interventions for PFAS were found.*	• Increasing the useful life of textile products through repair, reuse, and recycling, to reduce accumulation at EoL, [83], [84], [85].
	• Substitution of PFAS with non-fluorinated substances or materials (e.g., polyurethanes, dendrimers, silicones, hydrocarbons, and paraffin), [86].		• Reduce PFAS emissions from washing by providing washing instructions to users, [82].
	• Delivering waterproof function with non-chemical techniques (e.g., weaving and fiber control), [82], [87].		
	• Phasing out PFAS by re-evaluating functional requirements, [88], [89], [90].		

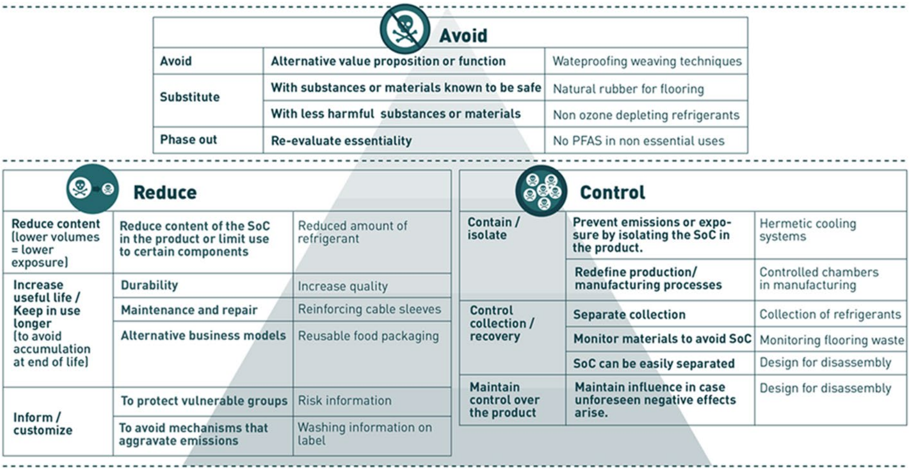
challenges of dealing with SoC and their potential relation to the field of design. Finally, we provide recommendations for future research, focusing on the development of methods to deal with SoC in products that are targeted at designers.

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.

Table 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.



Avoid

Avoid	Alternative value proposition or function	Wateproofing weaving techniques
Substitute	With substances or materials known to be safe	Natural rubber for flooring
	With less harmful substances or materials	Non ozone depleting refrigerants
Phase out	Re-evaluate essentiality	No PFAS in non essential uses

Reduce

Reduce content (lower volumes = lower exposure)	Reduce content of the SoC in the product or limit use to certain components	Reduced amount of refrigerant
Increase useful life / Keep in use longer (to avoid accumulation at end of life)	Durability	Increase quality
	Maintenance and repair	Reinforcing cable sleeves
	Alternative business models	Reusable food packaging
Inform / customize	To protect vulnerable groups	Risk information
	To avoid mechanisms that aggravate emissions	Washing information on label

Control

Contain / isolate	Prevent emissions or exposure by isolating the SoC in the product.	Hermetic cooling systems
	Redefine production/ manufacturing processes	Controlled chambers in manufacturing
Control collection / recovery	Separate collection	Collection of refrigerants
	Monitor materials to avoid SoC	Monitoring flooring waste
	SoC can be easily separated	Design for disassembly
Maintain control over the product	Maintain influence in case unforeseen negative effects arise.	Design for disassembly

Fig. 1 Hierarchy and examples of the identified strategy groups to deal with SoC in products (authors' interpretation)

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 SoCs. 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. 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 reducing 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.

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 [91] proposes a framework, the *Toxic-free hierarchy for chemicals management*, which prioritizes interventions that eliminate SoCs (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 [92], and the *Twelve principles of Green Chemistry and Green Engineering* [93, 94]. 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:

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.

Dealing with Tradeoffs

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 tradeoffs in performance, sustainability, and safety at a material, component, product, and system level.

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.

Impact on the Design Process and Need for Expertise

The implications for design of dealing with SoCs 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.

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.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-024-00449-4.

Acknowledgements We would like to thank Vrishali Subramanian and Jeroen Guinee, for their valuable insights and contributions to this study.

Author Contributions Julieta Bolaños Arriola: Conceptualization, Investigation, Writing – original draft.
Soroush Aghaeian: Writing – review & editing, Supervision.
Conny Bakker: Conceptualization, Writing – review & editing, Supervision.
Ruud Balkenende: Conceptualization, Writing – review & editing, Supervision.

Funding This work was funded by the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat). Project, Safe by Design– A design approach for dealing with hazardous substances in products, 2022.

Data Availability Data sharing not applicable – no new data generated.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Commission E (2020) A new circular economy action plan for a cleaner and more competitive Europe. Accessed: Nov. 21, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN
2. European Commission (2019) The European Green deal. https://doi.org/10.1017/CBO9781107415324.004
3. Luís C, Algarra M, Câmara JS, Perestrelo R (2021) Comprehensive insight from phthalates occurrence: from health outcomes to emerging analytical approaches. https://doi.org/10.3390/toxics9070157
4. Bialecka-Florjańczyk E, Florjańczyk Z (2007) Solubility of plasticizers, polymers and environmental pollution. Thermodyn Solubility Environ Issues 397–408. https://doi.org/10.1016/B978-044452707-3/50024-0
5. Schaider LA et al (2017) Fluorinated compounds in U.S. fast food packaging. Environ Sci Technol Lett. https://doi.org/10.1021/acs.estlett.6b00435
6. Holmquist H, Schellenberger S, van der Veen I, Peters GM, Leonards PEG, Cousins IT (May 2016) Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing. Environ Int 91:251–264. https://doi.org/10.1016/J.ENVINT.2016.02.035
7. Singh N, Duan H, Ogunseitan OA, Li J, Tang Y (Dec. 2019) Toxicity trends in E-Waste: a comparative analysis of metals in discarded mobile phones. J Hazard Mater 380:120898. https://doi.org/10.1016/J.JHAZMAT.2019.120898
8. Ogunseitan OA, Schoenung JM (2012) Human health and ecotoxicological considerations in materials selection for sustainable product development. MRS Bull 37(4):356–363. https://doi.org/10.1557/MRS.2012.8/TABLES/4
9. Eurostat (2023) Chemicals production and consumption statistics. Accessed: Jul. 10, [Online]. Available: 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
10. Agency EE (2020) The European environment-state and outlook 2020. https://doi.org/10.2800/96749

11. United, Nations (2011) Globally harmonized system of classification and labelling of chemicals (GHS). United Nations
12. Persson L et al (Feb. 2022) Outside the safe operating space of the planetary boundary for novel entities. Environ Sci Technol 56(3):1510–1521. https://doi.org/10.1021/ACS.EST.1C04158/ASSET/IMAGES/LARGE/ES1C04158_0002.JPEG
13. Rockström J et al (2009) Planetary boundaries: exploring the safe operating planetary boundaries: exploring the safe operating space for humanity space for humanity citation details citation details
14. Steffen W et al (2015) Planetary boundaries: Guiding human development on a changing planet. Science (1979) 347(no. 6223). https://doi.org/10.1126/SCIENCE.1259855/SUPPL_FILE/STEFFEN-SM.PDF
15. Muir D et al (2019) Levels and trends of poly- and perfluoroalkyl substances in the Arctic environment–an update. Emerg Contam 5:240–271. https://doi.org/10.1016/J.EMCON.2019.06.002
16. Bergmann M et al (2022) Plastic pollution in the Arctic. Nat Rev Earth Environ 3(no. 5):323–337. https://doi.org/10.1038/s43017-022-00279-8
17. Sharma S, Basu S, Shetti NP, Nadagouda MN, Aminabhavi TM (2021) Microplastics in the environment: occurrence, perils, and eradication. Chem Eng J 408:127317. https://doi.org/10.1016/J.CEJ.2020.127317
18. Karbalaei S, Hanachi P, Walker TR, Cole M (2018) Occurrence, sources, human health impacts and mitigation of microplastic pollution. Environ Sci Pollut Res 25(36):36046–36063. https://doi.org/10.1007/S11356-018-3508-7/FIGURES/2
19. 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. Elsevier, pp 87–118. doi: https://doi.org/10.1016/B978-0-444-53808-6.00003-2
20. Bodar C et al (2018) Risk management of hazardous substances in a circular economy. J Environ Manag 212:108–114. https://doi.org/10.1016/J.JENVMAN.2018.02.014
21. Alaranta J, Turunen T (2021) How to reach a safe circular economy?—Perspectives on reconciling the waste, product and chemicals regulation. J Environ Law 33(no. 1):113–136. https://doi.org/10.1093/JEL/EQAA016
22. Beekman M, Bakker JBC, van Leeuwen L, Waaijers-van der S, Loop M, Zijp, Verhoeven J (2020) Coping with substances of concern in a circular economy
23. Barouta D et al (2022) E-plastics in a circular economy: a comprehensive regulatory review. J Clean Prod 355:131711. https://doi.org/10.1016/J.JCLEPRO.2022.131711
24. Leslie HA, Leonards PEG, Brandsma SH, de Boer J, Jonkers N (Sep. 2016) Propelling plastics into the circular economy — weeding out the toxics first. Environ Int 94:230–234. https://doi.org/10.1016/J.ENVINT.2016.05.012
25. 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. J Food Nutr Res 55(4):361–373
26. Geueke B, Groh K, Muncke J (Aug. 2018) Food packaging in the circular economy: overview of chemical safety aspects for commonly used materials. J Clean Prod 193:491–505. https://doi.org/10.1016/J.JCLEPRO.2018.05.005
27. Brandsma SH, Leonards PEG, Koekkoek JC, Samsonek J, Puype F (May 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
28. Fenwick C, Mayers K, Lee J, Murphy R (2023) Recycling plastics from e-waste: implications for effective eco-design. J Ind Ecol 27(no. 5):1370–1388. https://doi.org/10.1111/JIEC.13409
29. Wagner S, Schlummer M (2020) Legacy additives in a circular economy of plastics: current dilemma, policy analysis, and emerging countermeasures. Resour Conserv Recycl 158:104800. https://doi.org/10.1016/J.RESCONREC.2020.104800
30. Dumée LF (2022) Circular materials—an essay on challenges with current manufacturing and recycling strategies as well as on the potential of life cycle integrated designs. Circ Econ Sustain: Vol 2: Environ Eng 359–372. https://doi.org/10.1016/B978-0-12-821664-4.00008-X
31. Keijer T, Bakker V, Slootweg JC (2019) Circular chemistry to enable a circular economy. Nat Chem 2019 11(3):190–195. https://doi.org/10.1038/s41557-019-0226-9
32. Sánchez Jiménez A et al (2022) Safe(r) by design guidelines for the nanotechnology industry. NanoImpact 25:100385. https://doi.org/10.1016/J.IMPACT.2022.100385
33. Mech A et al (2022) Safe- and sustainable-by-design: the case of Smart nanomaterials. A perspective based on a European workshop. Regul Toxicol Pharmacol 128:105093. https://doi.org/10.1016/J.YRTPH.2021.105093
34. Caldeira C et al (2022) Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials. Luxembourg. https://doi.org/10.2760/487955

35. Commission E (2009) Directive /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, 2009, Accessed: Mar. 25, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0125
36. Commission E (2022) Communication from the commission to the European parliament on making sustainable products the norm. Accessed: Mar. 25, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0140&qid=1649112555090
37. Brezet H, van Hemel C (1997) Ecodesign: a promising approach to sustainable production and consumption. United Nations Environment Programme, Industry and Environment, Cleaner Production
38. United Nations Environment Programme (2009) Design for sustainability: a step-by-step approach. United Nations Environment Programme (UNEP). Accessed: Mar. 25, 2024. [Online]. Available: https://wedocs.unep.org/xmlui/handle/20.500.11822/8742
39. Subramanian V, Guinée JB (2021) Selection of product-chemical substance combinations for illustrating a variety of Safe by Design approaches, Leiden, Accessed: Jul. 26, 2024. [Online]. Available: https://www.safe-by-design-nl.nl/documenten/onderzoek+documenten/default.aspx
40. European Commission (2014) Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases. Accessed: Jun. 23, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0517&rid=1
41. European Commission (2008) Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods. Accessed: Jun. 30, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0068&from=EN#d1e32-59-1
42. European Commission (2008) 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. Accessed: Mar. 21, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R1272
43. European Commission (2006) Regulation (EC) 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, evaluation, authorisation and restriction of Chemicals (REACH). https://doi.org/10.4324/9781315270326-156
44. European Commission (2019) Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants. Accessed: Aug. 11, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32019R1021
45. UN Environment. About Montreal Protocol. Accessed: Jun. 23, 2022. [Online]. Available: https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol
46. European Commission (2009) Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer. Accessed: Dec. 19, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009R1005
47. European Environment Agency (2020) Fluorinated greenhouse gases 2020. 15. https://doi.org/10.2800/08599
48. Ardente F, Calero Pastor M, Mathieux F, Talens L, Peiró (2015) Analysis of end-of-life treatments of commercial refrigerating appliances: bridging product and waste policies. Resour Conserv Recycl 101:42–52. https://doi.org/10.1016/J.RESCONREC.2015.05.005
49. Velders GJM, Fahey DW, Daniel JS, Andersen SO, McFarland M (2015) Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions, *Atmos Environ*, vol. 123, pp. 200–209, Dec. https://doi.org/10.1016/J.ATMOSENV.2015.10.071
50. McCulloch A (2009) Evidence for improvements in containment of fluorinated hydrocarbons during use: an analysis of reported European emissions. Environ Sci Policy 12(2):149–156. https://doi.org/10.1016/J.ENVSCI.2008.12.003
51. Tsai WT (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
52. G. World Health Organization (1998) 1,1,1,2 Tetrafluoroethane - concise international chemical assessment document
53. Graziosi F et al (2017) European emissions of the powerful greenhouse gases hydrofluorocarbons inferred from atmospheric measurements and their comparison with annual national reports to UNFCCC. Atmos Environ 158:85–97. https://doi.org/10.1016/J.ATMOSENV.2017.03.029
54. Commission E (2012) Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), Accessed: Jun. 22, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02012L0019-20180704&from=EN
55. Koronaki IP et al (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

56. Keri C (2019) Recycling cooling and freezing appliances. Waste Electrical and Electronic Equipment (WEEE) Handbook, pp. 357–370. https://doi.org/10.1016/B978-0-08-102158-3.00013-6
57. Coste G, Negrell C, Caillol S (2020) From gas release to foam synthesis, the second breath of blowing agents. Eur Polym J 140:110029. https://doi.org/10.1016/J.EURPOLYMJ.2020.110029
58. Harby K (2017) Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: An updated overview, *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 1247–1264, Jun. https://doi.org/10.1016/J.RSER.2017.02.039
59. Vuppaladadiyam AK et al (2022) Progress in the development and use of refrigerants and unintended environmental consequences. Sci Total Environ 823:153670. https://doi.org/10.1016/J.SCITOTENV.2022.153670
60. European Commission. Climate-friendly alternatives to HFCs. Accessed: Jul. 06, 2022. [Online]. Available: https://ec.europa.eu/clima/eu-action/fluorinated-greenhouse-gases/climate-friendly-alternatives-hfcs_en
61. McCulloch A, Midgley PM, Lindley AA (2006) Recent changes in the production and global atmospheric emissions of chlorodifluoromethane (HCFC-22). Atmos Environ 40(no. 5):936–942. https://doi.org/10.1016/J.ATMOSENV.2005.10.015
62. Tassou SA, Grace IN (Aug. 2005) Fault diagnosis and refrigerant leak detection in vapour compression refrigeration systems. Int J Refrig 28(5):680–688. https://doi.org/10.1016/J.IJREFRIG.2004.12.007
63. Brutus J, Calero J, Corden C, Esparrago J, Mackay C (2013) Analysis of alternatives for a group of phthalates. Available: https://www.rivm.nl/nieuws/onderzoek-naar-alternatieven-voor-ftalaten. Accessed 19 Dec 2023
64. European Commission (2019) Impact assessment study on common chargers of portable devices. [Online]. Available: https://circabc.europa.eu/ui/group/43315f45-aaa7-44dc-9405-a86f639003fe/library/d0737bf2-7738-4073-9ba0-1eb681e893eb/details
65. Danish Environmental Protection Agency (2022) Optimization of PVC-free materials in cables. Accessed: Mar. 21, [Online]. Available: https://www2.mst.dk/udgiv/Publications/1999/87-7909-561-5/html/helepubl_eng.htm#6.1
66. Jeon S, Kim KT, Choi K (Mar. 2016) Migration of DEHP and DINP into dust from PVC flooring products at different surface temperature. Sci Total Environ 547:441–446. https://doi.org/10.1016/J.SCITOTENV.2015.12.135
67. Kashyap D, Agarwal T (2018) Concentration and factors affecting the distribution of phthalates in the air and dust: a global scenario. Sci Total Environ 635:817–827. https://doi.org/10.1016/j.scitotenv.2018.04.158
68. Günther A, Langowski H-C (1997) LCA Case studies - life cycle assessment study on resilient floor coverings. Int J Life Cycle Assess
69. Grossman RF (2008) Handbook of vinyl formulation. Accessed: Jun. 09, 2022. [Online]. Available: https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/reader.action?docID=469476&ppg=3
70. Tarkett Environmental product declaration. Accessed: Jun. 12, 2022. [Online]. Available: https://media.tarkett-image.com/docs/EPD_Premium_Plus.pdf
71. Tarkett Material Health Declaration. Accessed: Jun. 12, 2022. [Online]. Available: https://media.tarkett-image.com/docs/MHS_Acczent.pdf
72. Miliute-Plepiene J, Fråne A, Almasi AM (2021) Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries, Oct. 01, *Elsevier*. https://doi.org/10.1016/j.clet.2021.100246
73. European Commission (2008) Priority list European union risk assessment report bis(2-ethylhexyl) phthalate (DEHP). https://doi.org/10.2788/80862
74. 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
75. Shah F, Wu W (Jan. 2020) Use of plastic mulch in agriculture and strategies to mitigate the associated environmental concerns. Adv Agron 164:231–287. https://doi.org/10.1016/BS.AGRON.2020.06.005
76. Kasirajan S, Ngouajio M (2012) Polyethylene and biodegradable mulches for agricultural applications: a review. Agron Sustain Dev 32(no. 2):501–529. https://doi.org/10.1007/S13593-011-0068-3
77. Huang Y, Liu Q, Jia W, Yan C, Wang J (May 2020) Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ Pollut 260:114096. https://doi.org/10.1016/J.ENVPOL.2020.114096
78. 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
79. Sorema. Agricultural film recycling. Accessed: Jul. 10, 2022. [Online]. Available: http://sorema.it/en_US/applications/plastic-film-recycling/agricultural-film-recycling/

80. Madrid B et al (2022) End-of-life management options for agricultural Mulch films in the United States—a review. Front Sustain Food Syst 0:282. https://doi.org/10.3389/FSUFS.2022.921496
81. Hoidal N (2021) Exploring alternatives to plastic mulch, Accessed: May 12, 2022. [Online]. Available: https://blog-fruit-vegetable-ipm.extension.umn.edu/2021/01/exploring-alternatives-to-plastic-mulch.html
82. Whiting R et al (2020) The use of PFAS and fluorine-free alternatives in textile, upholstery, carpets, leather and apparel. [Online]. Available: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=
83. Ellen MacArthur Foundation (2017) A new textiles economy: redesigning fashion's future. [Online]. Available: https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future
84. Patagonia. Worn wear - used patagonia clothing & gear. Accessed: Aug. 18, 2022. [Online]. Available: https://wornwear.patagonia.com/
85. Patagonia. Repairs - Patagonia. Accessed: Aug. 23, 2022. [Online]. Available: https://eu.patagonia.com/nl/en/repairs.html
86. Hill PJ, Taylor M, Goswami P, Blackburn RS (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
87. Park S, Kim J, Park CH (2015) Superhydrophobic textiles: review of theoretical definitions, fabrication and functional evaluation. J Eng Fiber Fabr 10(4). https://doi.org/10.1177/155892501501000401
88. Cousins IT et al (2019) The concept of essential use for determining when uses of PFASs can be phased out. Environ Sci Process Impacts 21(no. 11):1803–1815. https://doi.org/10.1039/C9EM00163H
89. NRDC (2021) A review of PFAS as a chemical class in the textile sector
90. Schellenberger S et al (2019) Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. J Clean Prod 217:134–143. https://doi.org/10.1016/J.JCLEPRO.2019.01.160
91. European Commission (2020) Chemicals Strategy for Sustainability Towards a Toxic-Free Environment SWD(2020). Accessed: Dec. 19, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN
92. Hendershot DC (2012) Inherently Safer Design: the fundamentals. Chem Eng Prog 108(1):40
93. Anastas PT, Zimmerman JB (2003) Design through the 12 principles of Green engineering. Environ Sci Technol 37(no. 5):94A–101A. https://doi.org/10.1021/ES032373G
94. Anastas PT, Warner JC (1998) Green chemistry: theory and practice. Oxford University Press