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

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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 tradeoffs.

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 analyze 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 for SoC shown in Table 1.

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)

Table 1. Classification of SoC in products, from (IenW, 2022).

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 analyzed 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 2 shows the approach for each of the elements that constitute the Safe and Circular Design Method.

Safe and Circular by Design Method elements	Approach
1. Analysis of the product-substance combination and emission-exposure scenarios.	The SoC were analyzed 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 tradeoffs found in literature. Screening RA and LCA were used to assess the effects of the strategies if data was available.

Table 2. Approach and development of the elements of the method.

Results: The Safe and Circular Design Method

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 proved 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 2 to 8). Additionally, the method suggests potential sources for the requested information on all the steps of the process. Figure 1 gives an overview of the steps of the method. First, the designer identifies and analyzes 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).

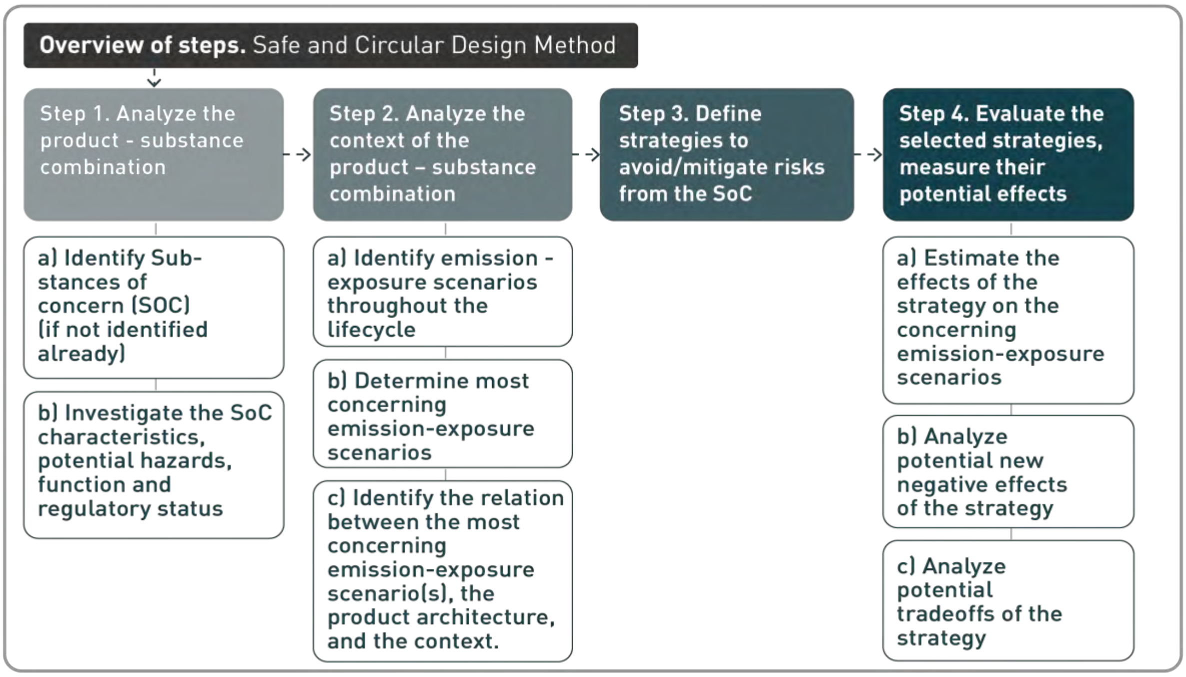

Figure 1. Overview of steps - Safe and Circular Design Method.

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 2 shows the template for this step. The method considers the classification of SoC proposed in Table 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 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. Analyze the product - substance combination

Step 1a Identify SoC (if not identified already)

ℹ Analyze your product for each type of SoC following the recommended actions

Typeof SoC	**Present in the product – intentionally added**	**Generated by the product – byproducts generated throughout their Use/EoL**	**Used or added temporarily to the product for additional functions but not intended to be present in the end- product**
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 bybproducts 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 2. Step 1a - Identify SoC. [1](European Chemicals Agency, n.d.), [2](ChemSec, n.d.), [3](Chem Forward, n.d.)

Step 1. Analyze the product - substance combination

Step 1b Investigate the SoC

ℹ 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 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 shows the template for this step with example information for the case of DEHP in vinyl flooring (for illustration purposes).

b) The designer qualitatively analyzes 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 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 analyzes 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 6 shows the template for this step with example information of a case, DEHP in vinyl flooring.

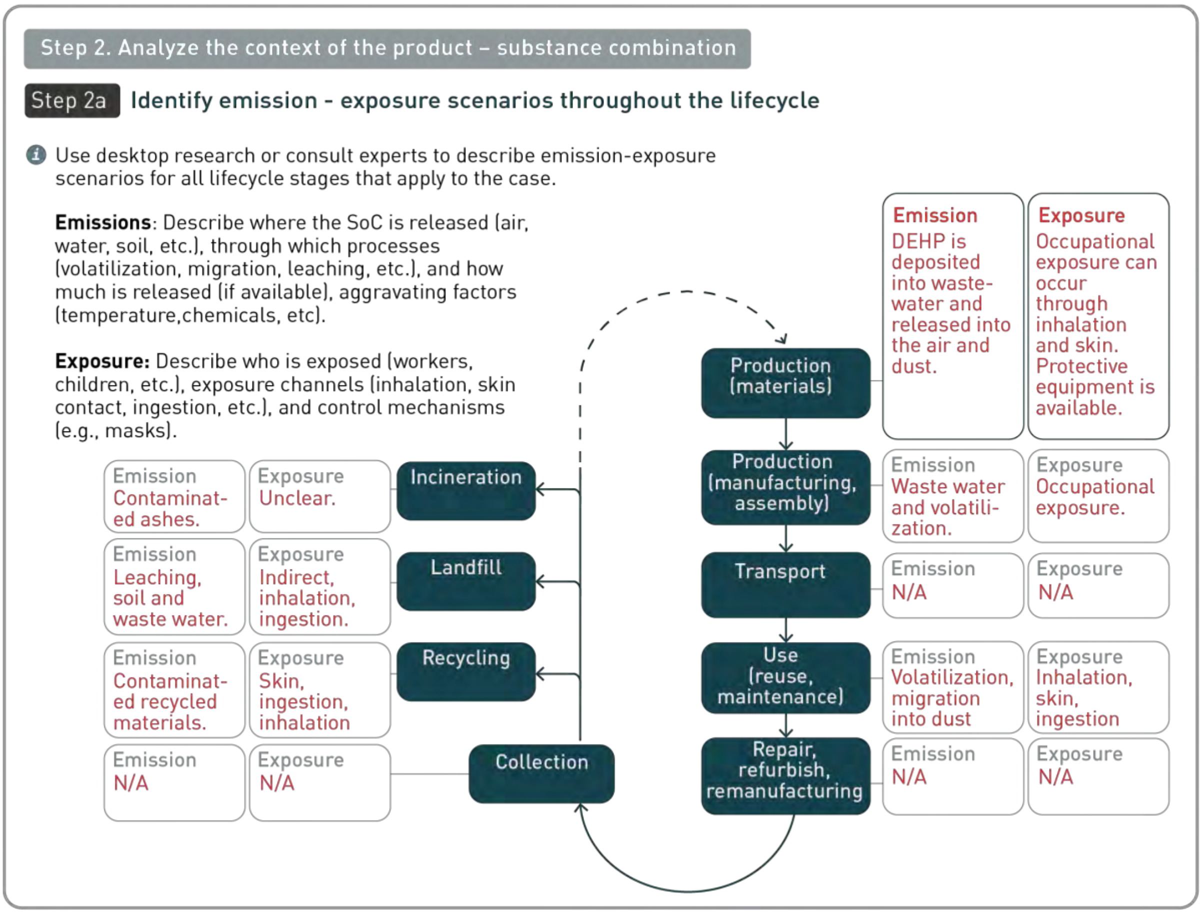

Figure 4. Step 2a – Identify emission-exposure scenarios per lifecycle stage. Example answers for the case of DEHP in vinyl flooring.

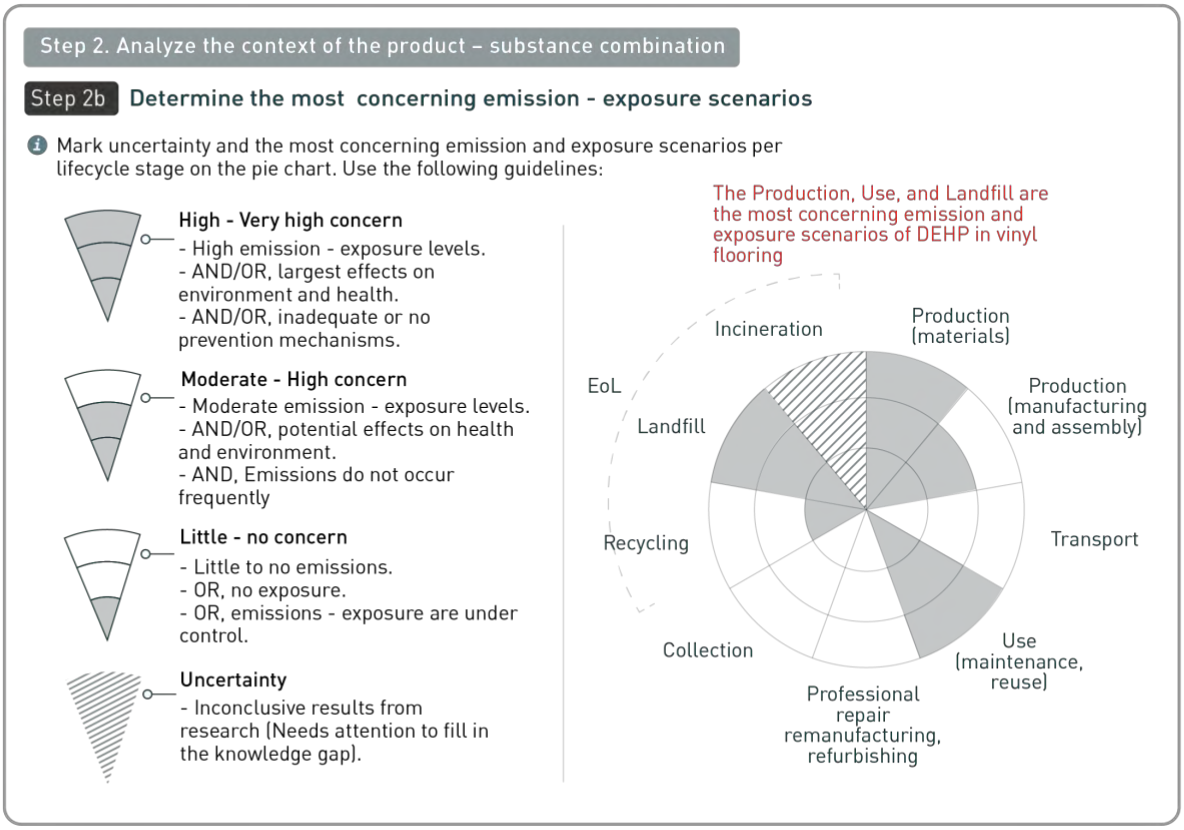

Figure 5. Step 2b, Prioritize emission and exposure scenarios. Example answer of the case of DEHP in vinyl flooring.

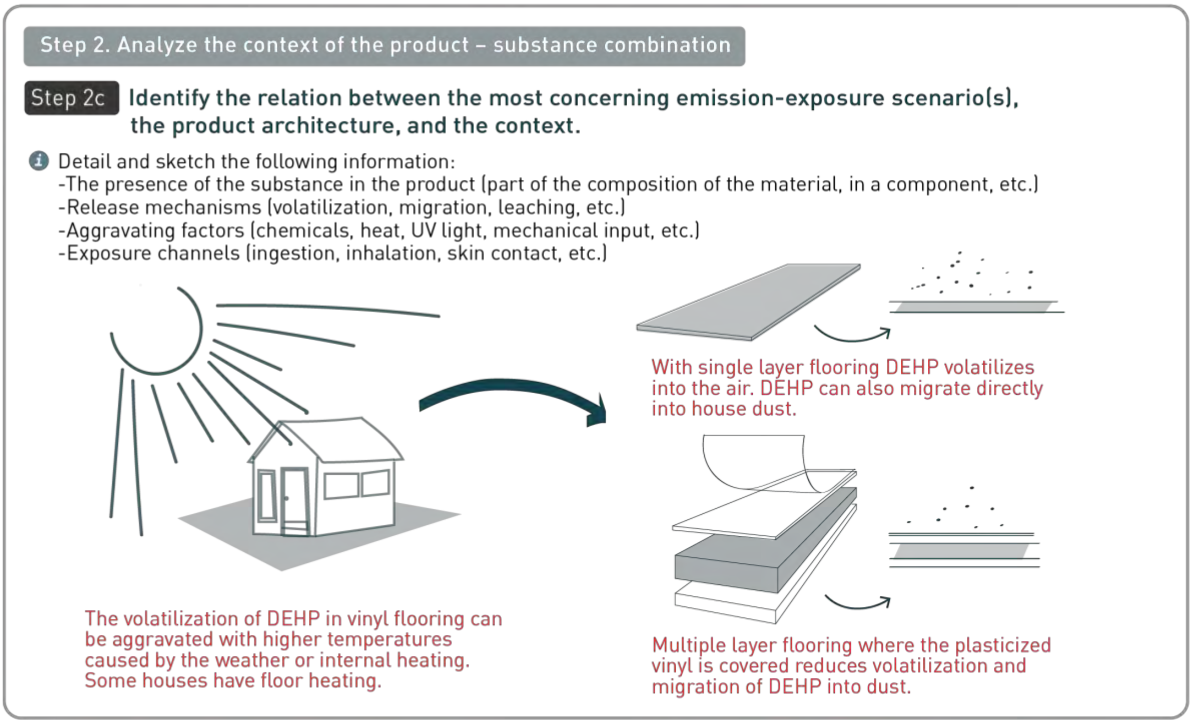

Figure 6. Step 2c, Identify the relation between concerning emission exposure scenarios, the product architecture, and the context. Example answer of the case of DEHP in vinyl flooring.

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 7).

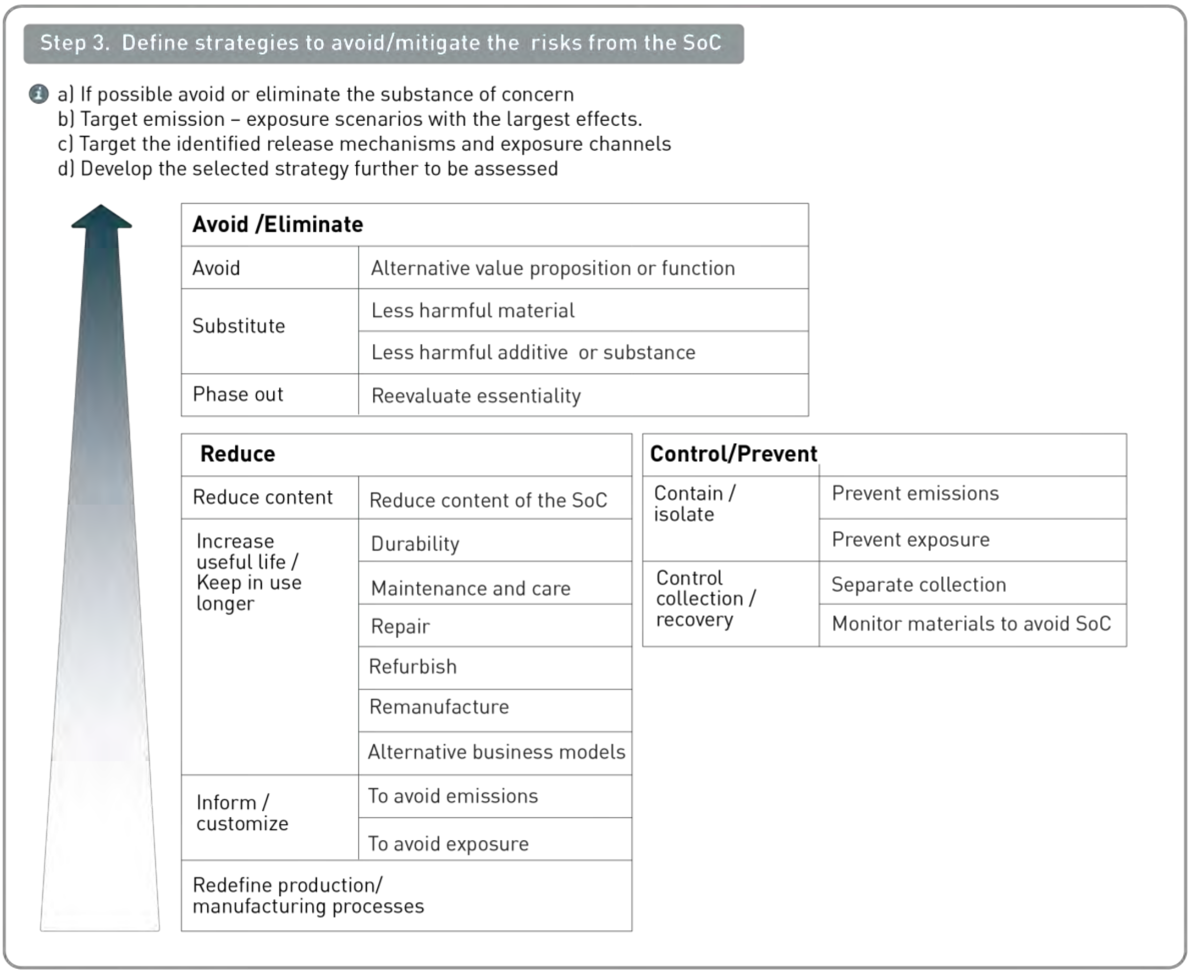

Figure 7. Step 3, List of possible design strategies to deal with SoC in products.

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

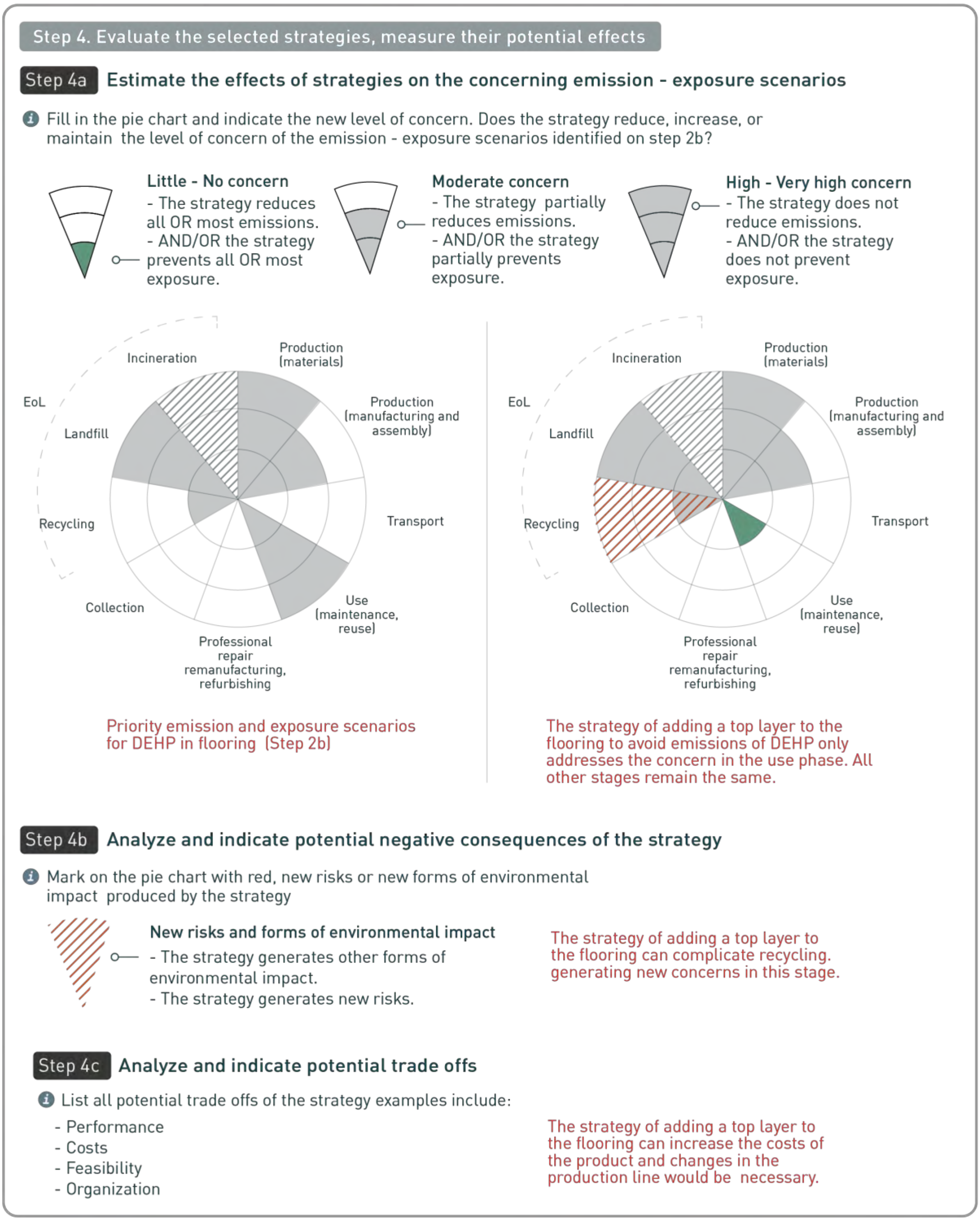

Figure 8. Step 4, Evaluation of selected design strategies. Example answer of the case of DEHP in vinyl flooring.

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 tradeoffs, 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 tradeoffs 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 further insights on data sourcing and dealing 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 tradeoffs, 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.

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