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Approaches to implement safe by design in early product design through combining risk assessment and Life Cycle Assessment

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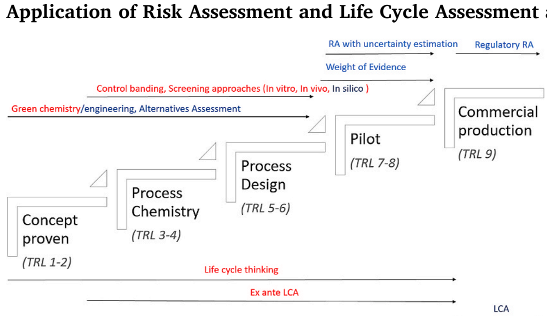
HIGHLIGHTS

- The combined use of Life Cycle Thinking (LCT) or Life Cycle Assessment (LCA) and Risk Assessment (RA) is considered suitable to operationalize Safe by Design (SbD)for product design.
- Our review of combined use of LCT/LCA and RA at Technological Readiness Levels (TRL) 1–6 found that product design teams can already perform themselves basic early-on-evaluations of safety and sustainability while collaborating with experts or value chain actors for more complex assessments (ex-ante LCA, control banding, predictive toxicology, etc).
- Studies in product design context, development of tools and databases from the product designer's perspective, collaboration between RA/LCA researchers and companies, and expansion from SbD to Safe and Sustainable by Design (SSbD) is needed for better implementation of SbD.

GRAPHICAL ABSTRACT

Application of Risk Assessment and Life Cycle Assessment along TRL



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ABSTRACT

The Safe by Design (SbD) concept aims to ensure the production, use and disposal of materials and products safely. While there is a growing interest in the potential of SbD to support policy commitments, such as the EU Green Deal and the Circular Economy Action Plan in Europe, methodological approaches and practical guidelines on SbD are, however, largely missing. The combined use of Life Cycle Assessment (LCA) and Risk Assessment (RA) is considered suitable to operationalize SbD over the whole life-cycle of a product. Here, we explore the potential of the combined use of LCA and RA at Technological Readiness Level (TRL) 1–6. We perform a review of the literature presenting and/or developing approaches that combine LCA and RA at early stages of product design. We identify that basic early-on-evaluations of safety (e.g., apply lifecycle thinking to assess risk hotspots, avoid use of hazardous chemicals, minimize other environmental impacts from chemicals) are more common,

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while more complex assessments (e.g., ex-ante LCA, control banding, predictive (eco)toxicology) require specialized expertise. The application of these simplified approaches and guidelines aims to avoid some obvious sources of risks and impacts at early stages. Critical gaps need to be addressed for wider application of SbD, including more studies in the product design context, developing tools and databases containing collated information on risk, greater collaboration between RA/LCA researchers and companies, and policy discussion on the expansion from SbD to Safe and Sustainable by Design (SSbD).

1. Introduction

There is a significant commitment to transform the EU economy to become resource efficient, climate neutral and less polluting. This is evident from recent policy commitments like the European Green Deal (COM/2019/640), the European Commission's new Action Plan for a Circular Economy (COM/2020/98), the new European Industrial Strategy and the Chemicals Strategy for Sustainability (COM/2020/667). Several emerging technologies and products are considered promising toward supporting this transition. Yet, it is widely recognized that it is challenging to evaluate the environmental risk and impacts of emerging products that are not yet produced commercially. However, during product design, there is at the same time greater flexibility and lower cost for design modification (Collingridge, 1982). Systematic evaluation of ecological and human health risks during product design can also facilitate risk governance and enhance regulatory preparedness as novel products approach commercial production (OECD, 2021a; Isigonis et al., 2020), as well as give opportunities to choose consciously where the responsibility for safety is situated in the design process (Van de Poel and Robaey, 2017).

Safe by Design (SbD) has been conceptualized in various ways across disciplines (van Gelder et al., 2021). SbD offers a solution to mediate between innovation and precaution and thereby enabling the sustainable transition envisioned in recent policy commitments. In the chemical safety context, SbD is considered a viable approach to mitigate the ecological and human health risks of products throughout their life-cycle. Based on the review of SbD research in the context of nano-enabled products in EU Horizon 2020 projects, the Organisation for Economic Co-operation and Development (OCED, 2021b) defines SbD as: "*The SbD (Safe-by-Design, Safer-by-Design, or Safety-by-Design) concept refers to identifying the risks and uncertainties concerning humans and the environment at an early phase of the innovation process so as to minimize uncertainties, potential hazard(s) and/or exposure. The SbD approach addresses the safety of the material/product and associated processes through the whole life cycle: from the Research and Development phase to production, use, recycling and disposal.*" (OECD, 2021a). Köhler and Som (2014) note that while product design teams have established processes to handle some types of risks (e.g., technical and electrical safety, fire hazards, biocompatibility), this is not the case for ecological and human health risks of novel products.

Risk assessment (RA) based approaches applying LCT (also known as Life Cycle Risk Assessment (LCRA)) are developed to ensure the safety of products. It has been extensively argued that joint application of RA and Life Cycle Assessment (LCA) can provide a comprehensive assessment of risks and impacts (Guinée et al., 2017; Subramanian et al., 2016; Shatkin, 2008). Various configurations of using these methods in combination have been reviewed (Hauschild et al., 2022; Grieger et al., 2012; Guinée et al., 2017; Harder et al., 2015; Kobayashi et al., 2015), while Linkov et al. (2017) and Guinée et al. (2017) remind us that conceptual differences between RA and LCA do not permit a complete integration of the two methods. Briefly summarized, the main reason for this lack of integration is that LCA has a global, relative and mass flow based perspective whereas RA has a highly contextual, threshold and concentration-based perspective. Nonetheless, the combination of these methods can support transparent decision making and identifies trade-offs, and could avoid problem shifting across life-cycle/risk receptors/geographical boundaries. RA has been adapted to low Technological Readiness Level (TRL) in so-called screening RA approaches (e.g., grouping, control banding (CB), predictive (eco)toxicology) that are less specific and with lower data needs (see Isigonis et al. (2020) for a review of approaches for nanomaterials). The basic principle underpinning LCA is Life Cycle Thinking (LCT), which aims at addressing environmental impacts of products, materials and resources throughout their life cycles in an integrated way (Sonnemann et al., 2018; Pennington et al., 2007). Ex-ante LCA is an adaptation of LCA using various data sources that scale-up an emerging technology using likely scenarios of future performance at full operational scale and comparing them with incumbent technology at the same point in time (Cucurachi et al., 2018). These adaptations made both the RA and LCA methods fit to future prospective assessments and, hence, can steer product design towards lower risks and environmental impacts.

The aim of this review is to synthesize literature (conceptual approaches, methods, data) on how LCT/ex-ante LCA and screening RA have been jointly used for product systems design. Product design involves imagining, creating, and iterating products that solve users' problems or address specific needs in a given market (Product Plan Website, 2022). The notion of safety in product design is currently largely focused on the use of safe chemicals and materials, ensuring benign emissions and safe disposal. SbD in a product context could also include features other than chemical, material, or process development, e.g. product architecture, circular business models, etc., but research evaluating safety of these features is scanty. Hence, the focus in this review is explicitly on the low TRLs (1–6) of a technology or product, starting from basic concept (TRL 1–4) to laboratory scale (TRL 5–6). Specifically, we seek to answer the following questions:

a) What methodological approaches for combining RA and LCA to facilitate SbD are available at TRL 1–6?
b) What gaps and challenges remain to be addressed to facilitate joint application of RA and LCA to facilitate SbD?

This review paper is organized as follows. Section 2 describes the methods used to conduct the review. Section 3 presents the key findings of the review, and Section 4 extrapolates our findings to implications for our research questions. Section 5 summarizes the key conclusions from the review.

2. Methods

The literature search was performed in June 2021 and followed a three-tiered keyword strategy to explore literature on Web of Science and Google Scholar databases. First, we sought to identify papers that combine LCA and RA in a prospective mode. Abstracts were screened manually and 255 papers were extracted. Next, we focused more broadly upon the papers actually combining RA and LCA (not just mentioning the methods). The number of papers were reduced to 35 (Appendix 1). As a final check for relevant methodological approaches, papers in LCT/ex-ante LCA and screening RA in a product design context (TRL 1–6) were identified. By specifying the product design application context, the number of papers was finally reduced to ten, and described using relevant criteria (Table 1). No publication year or geographical delimiters were used.

Table 1
Criteria to describe literature combining RA and LCA at TRL 1-6.

Criteria	Description
TRL	Scope of this review are the concept (1–4) and laboratory scales (4–6). Definitions from Fernandez-Dacosta et al. (2019) for Concept proven and initial process chemistry[a] is followed for TRL 1–4 and Lab Scale/Advanced process chemistry and Design[b] is followed for TRL 5–6. These early TRL typically fall into "material development" stage in product design.
Application Domain	What field of applied research (e.g., bio- or nanotechnology) is the product design context in?
SbD focus	Does the paper focus on the assessment of hazard, exposure or risk?
RA approach	Does the paper focus on ERA/HHRA/PHRA?
LC approach	What elements of LC (e.g. LCT, LCA) are present in the study?
Technology System	Does the paper focus on risk of a chemical or material (differs from a chemical as a material may be designed to provide certain functional characteristics), product (product including chemicals or materials and providing a desired functionality) or process (method of producing a product)?
System Boundaries	What life cycle stages does the paper focus on?

TRL: Technology Readiness Level SbD: Safe by Design ERA: Ecological Risk Assessment HHRA: Human Health Risk Assessment PHRA: Public Health Risk Assessment LC: Life Cycle LCA: Life Cycle Assessment.

[a] The idea of a new synthesis route for a chemical is determined by brainstorming of possible alternatives. The reaction is proven in the laboratory, the stoichiometry is gathered, and a rough estimation of the required technology is generated. Small amounts of purified product are obtained and data on the main reaction(s) is collected in laboratory experiments.

[b] Synthesis route is defined, and the entire production process is designed at a theoretical, commercial-scale level including main reaction and separation steps. The mass and energy balance of the production process including information on process stream composition, pressure and temperature can be obtained.

3. Results

The papers chosen for detailed review are described as per criteria in Table 2. All ten papers were found in TRL 1–4 and Fernandez-Dacosta et al. (2019) and Tan et al. (2018) were also found in TRL 5–6. Papers (column 2) are classified as per review criterion described in Table 1. Brief Description (column 3) provides a concise explanation of the main focus of the paper. More information can be found in Appendix 2. Advantages (column 10) and Disadvantages (column 11) describe the ease of application of the approach based on the typical knowledge of product design teams (lacking expertise in RA/LCA).

3.1. Application domain

Seven papers were classified as belonging to the domain of nanotechnology, two as biotechnology and one as chemistry. SbD approaches are particularly relevant for emerging technologies where the risks are poorly understood, and technology development needs to be approached with available information.

3.2. SbD approach

There are five hazard-based approaches and five risk-based approaches. Ten papers focus on HHRA (human health), five papers focus on ERA and one paper focusses on Public Health Risk Assessment (PHRA). PHRA considers hazard from HHRA (e.g. Derived No Effect Level) and exposure from exposure from ERA (e.g. Predicted Environmental Concentration), thus providing risk levels for public health.

3.3. Combining RA and LCA

Hazard-based approaches apply green chemistry metrics or check if product ingredients have been identified as hazardous in existing chemical regulations. Korevaar (2019) use green chemistry metrics recommended by Anastas and Eghbali (2009) to assess consumption of solvent, electricity, heat and emissions of pollutants and wastes. Kralisch et al. (2013) use the Environmental Health and Safety tool described by Koller et al. (1999) to estimate risks of specific volumes of chemicals. Existing chemical regulations regularly publish lists of chemicals of potential or known (eco)toxicity, as illustrated by Tan et al. (2018) in their use of a "block list" scan and by Askham et al. (2013) in their use of REACH risk phrases. The "block" list approach of Tan et al. (2018) is based on the Dutch list of "Zeer Zorgwekkende Stoffen" (ZZS, or: substances of very high concern)[1] to check product constituents. Finally, Askham et al. (2013) compare product ingredients with REACH risk phrases (now called hazard phrases).

There are also experimental approaches to predictive toxicology following the OECD guidance for *in vitro* and in vivo experimental data. An example of a study in this regards is Tan et al. (2018), which utilized zebrafish larvae (*Danio rerio*) and waterfleas (*Daphnia magna*) tests to assess ecotoxicity. While in principle such assays can provide a dose descriptor that can provide an indication of potential (eco)toxicity especially by comparing with similar chemicals, contextual features needed for a full risk assessment (i.e., ecosystem aspects in ecotoxicology) are missing.

Among risk-based approaches, risks over a product's life cycle are examined using secondary data analyses like meta-analysis and reviews (Som et al., 2010; Sweet and Strohm, 2006) for understanding risks of products through the life cycle and CB (Shatkin and Kim, 2015; Wardak, 2008; Van Harmelen et al., 2016). Song et al. (2017) and Sweet and Strohm (2006) present guidelines and case studies that guide the application of LCT to a nano-enabled product to gain insights on potential hotspots. Identified hotspots allow to be applied by product design teams to come to most optimal SbD products. An important contribution of their approach is to use state-of-the art information on e.g. hazard, fate and transport, exposure, and existing regulation to identify sources of risk. CB approach uses prior experiences on hazard and exposure to develop classification systems or bands. Combinations of hazard and exposure bands are associated with an evaluation of risk and (often) risk management that has been used successfully for the specific combination of hazard and exposure (Zalk and Nelson, 2008). Van Harmelen et al. (2016) present the software program LICARA nanoSCAN, a product design tool that uses CB based tools such as Stoffenmanager (Van der Giesen et al., 2020), Precautionary matrix (Höck et al., 2013) and Nanoriskcat (Hansen et al., 2011) for RA. Expert elicitation can also play an important role in filling knowledge gaps at low TRL, as demonstrated by Wardak (2008) and Shatkin and Kim (2015).

In terms of LCA used in the literature examined, six papers are based on LCT, and four papers include ex-ante LCA combined with RA. LICARA nanoSCAN presents a qualitative comparison of novel product with its incumbent on impacts (e.g., energy consumption, materials consumption, water use, waste generation) for each lifecycle stage. Ex-ante LCA is applied from TRL 4 onward.

3.4. Technology system

In terms of technology systems, five papers focus on the product level, four at the material level and one at the process level. The difference between chemical and product lifecycle is important in LCRA. The product life-cycle includes the life cycle of all the product constituents whereas a chemical lifecycle includes the lifecycle of a particular chemical of interest as it is included in the manufacturing, use and end of life of a product. Except for Tan et al. (2018), the four nanotechnology papers are interested only in the risks of the nanomaterials within the

[1] The ZZS list includes the most dangerous substances for the environment and human beings.

Table 2
Classification of literature based on the pre-selected criteria.

TRL	Paper	Brief Description	Application Domain	SbD Approach	Combining RA and LCA		Technology system	System boundary	Product Design context	
					RA approach	LC approach			Advantage	Disadvantage
1–4	Askham et al. (2013)	Hazard and exposure indicators of coating ingredients using REACH risk phrases[a]	Chemistry	Hazard	HHRA	Risk metrics integrating with LCI	Product	Production	Simple	Not applicable to novel chemicals, no standardized information source for risk phrases Risk phrases are obsolete [b]
	Korevaar (2019)	Decision tree for applying ex ante LCA with recommending green chemistry indicators for early stages	Nanotechnology	Hazard	HHRA	Ex-ante LCA	Product	Cradle to grave	Simple	Not applicable to novel chemicals
	Fernandez-Dacosta et al. [c](2019)	Review of toxicity and environmental impact metrics for lactic acid production at various TRLs	Biotechnology	Hazard	HHRA	LCT	Product	Production	Simple	Not applicable to novel chemicals
	Wardak (2008)	Expert elicitation based CB of nano-enabled products in the market	Nanotechnology	Risk	HHRA	LCT	Product	Use-Disposal	Simple	Laborious for design teams Variable expert input
	Van Harmelen et al. (2016)	Screening tool for product design based on LCA and RA tools	Nanotechnology	Risk	ERA, HHRA, PHRA	LCT [d]	Material	Cradle to grave	Comprehensive risk and impact metrics	Time consuming
	Som, C. et al. (2010)	Smart textile case study illustrating application of LCT to generate risk hotspots	Nanotechnology	Risk	ERA, HHRA	LCT	Material	Cradle to grave	Simple	Qualitative
	Sweet and Strohm (2006)	State of art on nanomaterial risk and discusses application of LCT	Nanotechnology	Risk	ERA, HHRA	LCT	Material	Cradle to grave	Simple	Qualitative
	Shatkin and B. Korevaar (2019)	Expert judgement on hazard and exposure criteria + a toxicology gap analysis of safety data sheets for cellulose nanomaterials	Nanotechnology	Risk	ERA, HHRA	LCT	Material	Cradle to grave	Systematic Prioritizes data gaps	Labor intensive
	Tan et al. [e](2018)	Ingredients in cellulose nanocrystal foam are scanned against substances identified in 15 environmental regulations	Nanotechnology	Hazard	HHRA	Ex ante LCA	Product	Production	Addressed hazard at product level	Not applicable to novel chemicals
	Kralisch [f](2013)	Ex-ante LCA for biodiesel production at lab scale with	Biotechnology	Hazard	ERA, HHRA	Ex ante LCA	Process	Cradle to grave	Simple	Not applicable to novel chemicals

(continued on next page)

Table 2 (*continued*)

TRL	Paper	Brief Description	Application Domain	SbD Approach	Combining RA and LCA		Technology system	System boundary	Product Design context	
					RA approach	LC approach			Advantage	Disadvantage
5–6	Fernandez-Dacosta et al. (2019)	Hazard based metrics applied Review of toxicity and environmental impact metrics for lactic acid production at various TRLs	Biotechnology	Hazard	HHRA	LCT, Ex ante LCA	Product	Production	Simple	Not applicable to novel chemicals
	Tan et al. (2018)	*In vivo* assay of product samples with zebrafish embryos (*Danio rerio*) and waterfleas (*Daphnia magna*)	Nanotechnology	Hazard	ERA	Ex ante LCA	Product	Production	Applicable to novel products	Toxicological expertise needed

TRL: Technology Readiness Level SbD: Safe by Design ERA: Ecological Risk Assessment HHRA: Human Health Risk Assessment PHRA: Public Health Risk Assessment LC: Life Cycle LCT: Life Cycle Thinking. It should be noted that LCT stands for all types of Life Cycle Thinking including LCA CB: Control Banding.

[a] R-phrases are short phrases that describe the hazard level of the substance on a mass basis.

[b] They have been replaced by hazard statements in Classification, Labelling and Packing.

[c] This review provides methods at each TRL.

[d] Relative comparisons between novel product and incumbent technology.

[e] One strategy described in this study (block list scan) is at TRL 1–4 while another (in vivo assay) is at TRL 5-6.

[f] The ex ante LCA used in this study is at TRL 5–6 but RA is at TRL 1-4.

product.

3.5. System boundary

It is noteworthy that only six out of the ten studies reviewed account for the full life cycle of the product or material. Three studies focus on the production phase and one focuses on the use-disposal phases only. Kralisch (2013) focuses on a novel production process, which includes all upstream processes of the novel production process.

3.6. Product design context

Six papers have simple methods that can be directly used by product design teams. However, even as RA/LCA methods are simplified at low TRL, several methods require expertise to apply. SbD approaches for nanotechnology and other emerging technologies may need adaptations or novel approaches to address knowledge and data gaps in physico-chemical properties, hazard, emission, fate, transport and exposure.

4. Discussion

While the concept of SbD has received increasing attention over the past years, clear methodological guidance by product design teams is missing. This review contributes to the recent interest in implementing SbD (Peijnenburg et al., 2021; Gottardo et al., 2021; Semenzin et al., 2019) by examining how RA and LCA have been combined in the product design context at TRL 1–6. Limitations of the current work and avenues for further development include: a) A small subset of papers was chosen for detailed review based on relevance to product design, b) Safety in product design may include strategies other than chemicals, materials and manufacturing processes (e.g. product architecture, circular business models, etc.) but these are not within the scope of the current paper, c) Specific gaps and challenges on combining RA and LCA that are covered in Section 4.2.

We present the findings for each research question in the sub-sections below.

4.1. Research question 1: what methodological approaches for combining RA and LCA for SbD are available at TRL 1–6?

Hazard based approaches (Askham et al., 2013; Fernandez Dacosta et al., 2019; Kralisch et al., 2013; Tan et al., 2018) can guide omission of hazardous substances to avoid or minimize concentrations of known or suspected hazardous substances. LCA can be used to identify risk hot-spots (Som et al., 2010; Sweet and Strohm, 2006). Simple metrics such as those reported by Anastas and Eghbali (2009) for consumption of solvent, electricity, heat and emissions of pollutants and wastes can also be compared to benchmarks of similar products and processes.

The results (Fig. 1) show the role for RA and LCA at various TRLs based on this review. Starting with the concept stage, application of green chemistry and green engineering principles, substituting hazardous chemicals and applying LCT is feasible. Control banding organize contextual understanding of hazard and exposure into ordinal scales that can indicate risk hotspots. Hazard screening approaches and ex ante LCA at design and laboratory stage are useful, even with simplifications and adaptations. Alternatives Assessment, in silico methods, are out of the scope of this review as they lack LCT, and methods at pilot and commercial production are also out of the scope of this review. But they have been included in Fig. 1 to indicate range of available methods.

Text in red: Method found in review Text in Blue: Not found in review but potentially useful for SbD.

The application of low TRL approaches and guidelines cannot substitute a full-fledged RA or LCA but they may pinpoint risks and impacts at an early stage of product design that otherwise are easily overlooked and cumbersome to correct at later stages.

4.2. What gaps and challenges remain to be addressed to better facilitate joint application of RA and LCA for SbD?

We find that except Van Harmelen et al. (2016) and Tan et al. (2018), the papers usually focus more on one of the methods (RA or LCA) and the full possibilities of combining them are not exploited.

While a variety of tools have been developed for screening RA, the potential of ex ante LCA has not yet been fully utilized in SbD. Ex-ante

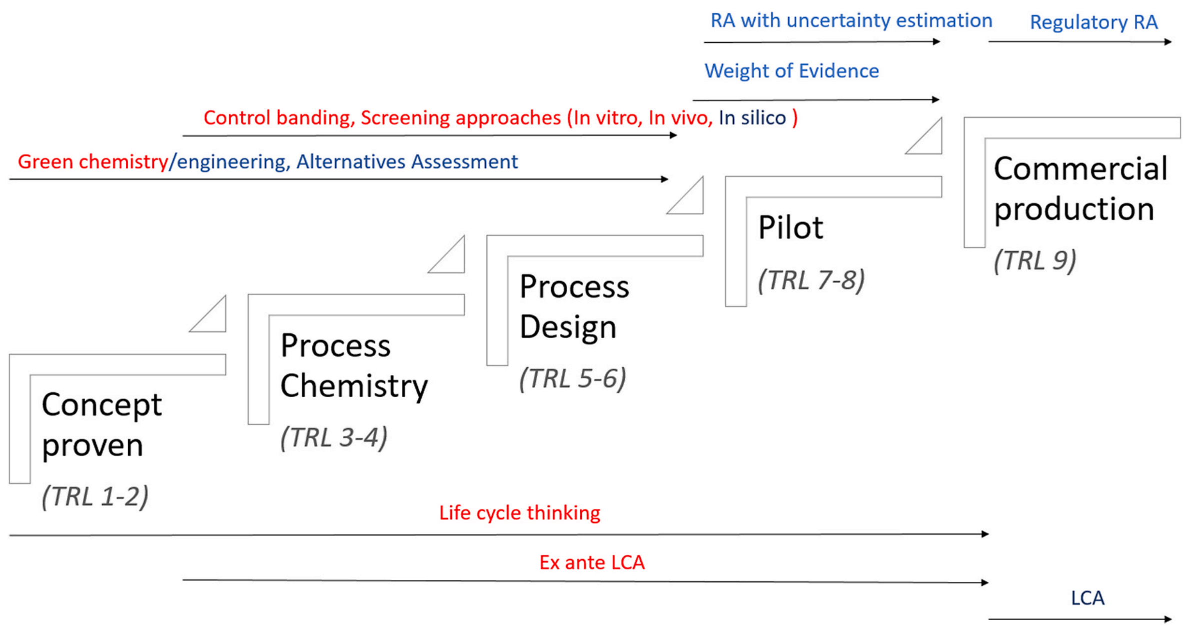

Fig. 1. Application of LCA and RA at various TRLs in a Product Design Context.

LCA in the reviewed literature is applied at TRL 4, but has outside the specific SbD literature also been applied at TRL as low as 2. Villares et al. (2017) apply e.g. ex-ante LCA to bioleaching of electronic waste to pinpoint hotspots. "Safety" in a product design context requires tradeoffs between risks, environmental impacts, functionality, costs, while meeting any applicable regulatory requirements, and involves relative assessments (OECD, 2013). The first phase within the LCA approach – the Goal and Scope Definition - at TRL 1–2 could be a good starting point for SbD via understanding technical and economic aspects of product functionality and existing product alternatives to deliver the desired functionality at various TRLs.

Most publications in the current review focus upon the risks within a product's life cycle of a single chemical or material. However, product designers should compare the risks associated with all potentially hazardous chemicals in the product system against their alternatives. A comprehensive assessment of all chemical risks in a product context is missing in the literature thus far and it should be investigated how the scope of current approaches could be expanded.

A great illustration of how early assessments can be done is given in Van Harmelen et al. (2016) who collaborated with Small and Medium Enterprises (SMEs) to develop the LICARA nanoSCAN tool. The scope of the LICARA tool has now been expanded to all novel products, and can enable more studies of combining RA and LCA in product design practice. Researchers have noted the challenges in integrating ecodesign tools in product design practice (Brones et al., 2014; Le Pochat et al., 2007). SbD can impact several product design aspects such as tradeoffs between cost, quality, safety, other environmental impacts, supply chain aspects and competitive advantage due to environmental performance. While the stage gate model has been proposed as a process model of including safety aspects in product design (Semenzin et al., 2019; Gottardo et al., 2017), more studies are needed focusing on the application of tools and implications on these cross-cutting issues.

SbD requires interdisciplinary collaboration between teams and across companies. Marcoulaki et al. (2021) emphasized the collaboration between risk assessment researchers and companies and propose a blueprint for a European Centre for Safe and Sustainable by Design (SSbD). Product designers should collaborate closely with environmental scientists and marketing teams. Similarly, many ex-ante LCA studies have emphasized this interdisciplinary collaboration too (Tsoy et al., 2020; Villares et al., 2017).

A challenge that is to be faced is on how to address the data gaps on chemical risks. The European Environmental Agency (EEA) estimated that of about 100,000 chemicals in the market, implying that hazard and exposure are characterized for about 70% of the total estimated amount of marketed chemicals (EEA, 2020). Some information exists in the ECHA website,[2] and some chemicals of concern can be screened with chemical similarity models (Wassenaar et al., 2021) and information on alternatives are available on some public databases (e.g. the SIN List[3]) for RA experts, but it is does not cater to the knowledge and perspective of the product designer (e.g., including function of chemicals, cost, example lifecycle pathways and risk identification for product types). None of the existing tools can estimate emissions of novel processes. Most of the recent early TRL projects performed experimental measurement of emissions across the life cycle. However, meeting intensive data requirements may not be feasible in the product design context due to the magnitude of information requirements, expertise needed to evaluate them, and uncertainity. RA/LCA experts address data gaps at low TRL through informatics and modelling approaches (Wassenaar et al., 2021; Tsoy et al., 2020; Song et al., 201; Ma et al., 2019). There are more tools to assess human health exposure in the manufacturing context than in the use and end of life stages of products, and this is also a knowledge gap we identify.

A challenging aspect for applying RA and LCA at different TRLs is the consistency of the results. One part of the challenge is the granularity of the low TRL RA/LCA models, whilst another part is the upscaling that occurs through the TRLs. Van Harmelen et al. (2016) report that while there is good agreement of the LiCARA screening and full RA/LCA for two case studies, positive results were exaggerated in the case of antimicrobial fiber cloth due to detailed information on the reference product) and negative results were exaggerated in the case of antibacterial coating due to magnitude of social benefit. For both LCA and RA at low TRL, results should not be considered as conclusive due to several assumptions and high uncertainty in these models. Rather, incorporating SbD within the design process should be viewed as an evaluation of a scenario based on best available knowledge and data. Such an evaluation establishes comparative benchmarks, clarifies the goal and scope of the analysis, drives data collection to build more realistic

[2] https://echa.europa.eu/information-on-chemicals.
[3] https://sinlist.chemsec.org/.

models, ultimately aiding product and technology designers to design more sustainable systems.

Finally, SbD currently focuses on risks only, while current and future policy goals - in addition to risks - also include climate neutrality, circular economy concepts and consideration of other environmental impacts, and on top of that economic and social impacts. This motivated the European Commissions' Joint Research Centre to advance the concept of SSbD (Patinha Caldeira et al., 2022; Gottardo et al., 2021). Furthermore, while the current study focusses only on chemical/material risks and impacts, it does not address risks from product architecture and larger value chain impacts. While the focus on the current paper is on reviewing existing SbD approaches, ongoing research are focusing upon SSbD approaches that can address the broader policy goals of safe, sustainable and circular products.

5. Conclusions

The current state of combined LCA and RA for SbD is that some methods and approaches are available, but application in real situations is still challenging and requires further development of all concepts involved. While hazard-based approaches and LCT that can be directly applied by product design teams, methods like ex ante LCA, expert elicitation and predictive toxicology approaches require expertise in RA/LCA.

We echo previous pleas that incorporating SbD within the design process should be viewed as an interdisciplinary collaborative process, repeated over different TRLs of a design, and ultimately driving technology and product designers and RA/LCA experts to design more sustainable technology systems. This combined use of RA and LCA in a product design context needs more comprehensive study, along with the development of data and tools in the design context, and broader inclusion of environmental impacts as envisioned in the Safe and Sustainable by Design (SSbD) concept (JRC, 2022).

Early assessment of safety issues arising during low TRLs is a precondition to improve ecology, reduce human health effects, and ensure non-hazardous material cycles for circular economy, and operationalizing SbD in the product design context is an important step toward achieving this goal.

Credit author statement

Vrishali Subramanian: Conceptualization, Methodology, Writing – original draft, Project administration, Data curation, Visualization, Willie J.G.M. Peijnenburg: Conceptualization, Methodology, Writing – review & editing, Martina G. Vijver: Conceptualization, Methodology, Writing – review & editing, Carlos F. Blanco: Conceptualization, Methodology, Writing – review & editing, Stefano Cucurachi: Conceptualization, Methodology, Writing – review & editing, Jeroen B Guinée: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2022.137080.

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