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“Avoid” is not enough – An overview of approaches to substance safety in sustainable material selection methods for product development

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ABSTRACT

Existing material selection methods seem to offer limited support for addressing substance safety in practice, as the focus remains on intrinsic material properties and less on exposure risk. This hinders Safe and Sustainable by Design (SSbD) efforts that can prevent use and accumulation of substances of concern (SoCs) across product lifecycles in a circular economy. This study reviews 29 sustainable material selection methods to evaluate how they do support substance safety. Results show that substance safety is generally embedded within the broader sustainability realm without explicit risk or lifecycle-based assessment. Of the four steps that can be distinguished in material selection, most methods support the steps ‘Establishing a set of candidates’ and ‘Comparing candidates’ but the steps ‘Formulating selection criteria’ and ‘Choosing suitable candidates’ are often unsupported, leaving critical substance safety trade-offs unaddressed. The importance of mindsets such as systemic thinking and iterative reflection is recognized but underrepresented. The findings highlight the need to adapt existing methods with better guidance and risk integration to advance SSbD in material selection.

1. Introduction

The circular economy addresses the ongoing and escalating depletion of energy and material resources (Richardson et al., 2023; OECD, 2019). It implies a systems perspective, in which production and consumption systems are redesigned to eliminate waste, minimize pollution, and retain the value of products for longer (Kirchherr et al., 2017; Ellen MacArthur Foundation, n.d). A key challenge within this framework is material selection, as it directly influences a product's environmental impact and circular potential. Product developers play a central role here, as they determine product architecture and its materials (den Hollander et al., 2017). In the circular economy, hazardous substances—referred to as substances of concern (SoC)—may accumulate or intensify in risk across multiple lifecycle stages and consecutive lifecycles. These risks can arise through e.g. extended use, repeated lifecycles, or occupational exposure during remanufacturing. Hence, the material selection process becomes more complex (Beekman et al., 2020).

In this study, we define SoC as substances emitted during the product lifecycle that are harmful to human health or the environment upon exposure (Bolaños Arriola et al., 2023). These substances hinder the circular economy by making “contaminated” materials less suitable for reprocessing due to diminished physical performance, while also preventing loop closure because of health and safety concerns related to their recovery and reuse (Bodar et al., 2018). However, the presence of SoC rarely is coincidental; they are either added for functionality, generated during use (e.g. wear) or added for manufacturability (Bolaños Arriola et al., 2023).

The materials of a product largely determine the environmental impact and safety risks associated with resource extraction, processing, and achievable performance — including end-of-life options (Ashby, 2013). Methods that integrate the assessment of sustainability and associated hazards, risks, and lifecycle impacts, fall under the safe-and-sustainable-by-design (SSbD) umbrella. This concept was first operationalized by the EU's Joint Research Centre (JRC) in 2022 for the development of new chemicals and processes (Caldeira et al., 2022). The transition from Safe by Design (Sbd) to SSbD aims to integrate health, safety as well as socioeconomic aspects and sustainability as central values during early-stage innovation processes for chemicals assessment and development, so that the resulting chemicals and processes are safer for people and the environment (Apel et al., 2024; Sudheshwar et al., 2024).

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In product development, SSbD is still an understudied subject. Existing approaches for sustainable product development, like Ecodesign methods such as the Ecodesign Strategy Wheel (den Hollander et al., 2017; Rossi et al., 2016; Wever and Vogtländer, 2014) or the Cradle-to-Cradle approach (Braungart et al., 2007), offer high-level guidance in selecting sustainable materials. These methods encourage avoiding harmful substances, but they lack specific procedures for evaluating substance safety during material selection. They also provide limited support to deal with inherent uncertainty related to early development stages as well as the lack of transparency along the value chain (Apel et al., 2024), or when SoC cannot be fully eliminated (essential use). This lack of integrated support can lead to unintended consequences like product lifetime extension at the cost of safety, accumulation of SoC in the environment or regrettable substitutions (Feuilloley et al., 2005; Blum et al., 2019; Glüge et al., 2020). Past research on material selection methods for product development offers valuable insights into sustainability; this includes reviews of available methods, their strengths and limitations, and relevant selection guidelines (Rahim et al., 2020; Jahan et al., 2010; Ashby et al., 2004; Italia et al., 2023). Some methods occasionally include guidelines to reduce toxic impacts by considering material properties and environmental legislation — often addressing substance safety aspects such as minimizing hazardous substances or incorporating separable materials (Lin and Lin, 2003; Italia et al., 2023; Stuart and Sommerville, 1998). However, these studies have not examined how material selection methods explicitly support decisions that integrate both SoC management and sustainability within circular product design, nor how they handle uncertainty or lifecycle exposure risks. This reveals a twofold research gap: current methods neither explicitly operationalize the SSbD concept nor have been examined from an SSbD perspective.

Accordingly, we address the following research question: How do material selection methods support addressing substance safety and sustainability, while accounting for the complete product lifecycle? We distinguish four specific objectives: (1) reviewing academic and grey literature to identify existing methods, (2) classifying them according to procedure and nature, (3) assessing how they incorporate substance safety and uncertainty management, and (4) identifying gaps in support, informing future method development. For our analysis, a novel analytic framework was developed where we integrate method content theory and standard classifications of material selection procedures (Italia et al., 2023; Van Kesteren et al., 2008; Daalhuizen and Cash, 2021; Cash et al., 2023).

This paper contributes to sustainable design and material selection literature as well as safe and sustainable by design literature. More specifically, it contributes to the evolving field of SSbD in general, and SSbD from a product perspective in particular, by identifying opportunities to integrate substance safety with sustainability in material selection. This is crucial for future method development and to carve out the role of product developers in SSbD.

2. Background

2.1. Safe and sustainable by design at the product level

SSbD is defined by the JRC as "*a pre-market approach to chemicals and materials design that focuses on providing a function (or service), while avoiding volumes and chemical and material properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco)toxic, persistent, bio-accumulative or mobile*" (Caldeira et al., 2022). The definition reveals that the product development perspective is not considered when establishing risks, nor leveraged to avoid harmful exposure. Consequently, methods within the JRC framework and similar approaches (e.g. those of CEFIC or ChemSec (CEFIC, 2024; ChemSec, 2021)) focus on avoiding hazardous substances and processes and substituting them with safer alternatives. They do not address how substances behave throughout product lifecycles. As a result, environmental and social lifecycle impacts, exposure scenarios, associated uncertainty and trade-offs are not fully integrated into substance safety assessments (Bolaños Arriola et al., 2023; Apel et al., 2024). In contrast, a product development perspective could enable context-sensitive and systemic assessment for specific applications. For example, certain plasticizers may be acceptable in industrial cable coatings but not in household ones, where a child could ingest the harmful substances. Similarly, trade-offs resulting from SSbD decisions are best evaluated from the product developer's perspective: PFAS in synthetic textiles can be replaced with weaving methods that provide waterproofing without additives, though this might increase textile stiffness that is unsuitable for some applications. Finally, product developers' iterative, learning-by-doing approaches (Cross, 2001) are key under SSbD's uncertainty.

Bolaños Arriola et al. (2024) proposed a product-level framework that integrates substance safety and sustainability. This framework offers a general product development workflow as well as general design strategies. It adds two strategies beyond avoidance: control (preventing emissions or exposure through design) and reduce (minimizing SoC quantity or impact, e.g., by extending product lifetime). This strategy-based framing supports decision-making through relative assessment and identification of trade-offs. It does not explicitly support material selection and needs further integration of specific tools, such as one for material selection.

2.2. The circular economy and SoC

Contrary to the linear economy, with a take-make-use-dispose model, the circular economy aims to preserve the value of products and materials for as long as possible through closing, slowing, and narrowing resource loops (Bocken et al., 2016). The circular economy is based on three design-driven principles: eliminate waste and pollution, circulate products and materials and regenerate nature (Ellen MacArthur Foundation, n.d.). Theoretically, circularity aligns with SSbD principles: reducing environmental impacts, eliminating pollution, and maintaining control over material flows, thereby minimizing material-related hazards and risks. In practice, however, the lack of comprehensive substance safety and sustainability data, combined with limited data sharing, means that closing material loops may introduce unintended hazards (Beekman et al., 2020). Only a small proportion of chemicals in use have been rigorously assessed for hazards, and even fewer are regulated for specific applications (European Environment Agency, 2019). For instance, a 2025 study of 16,325 chemicals used in plastics found that 10,726 (65.7 %) lacked sufficient safety data. 4219 (25.9 %) were identified as SoC (Monclús et al., 2025). Consequently, SoC can both hinder the implementation of circular strategies and create unsafe scenarios when such strategies are applied. Beyond obvious SoC risks, lifetime extension strategies—reuse, repair, remanufacturing—may create exposure environments not considered in first use. For example, large volumes of expandable polystyrene in constructions containing hazardous flame retardants that hinder reuse as exposure might be harmful (Bodar et al., 2018), or the potentially unsafe recycling of flame-retardant mattresses into playground surfaces where toxic substances leach out (Faber et al., 2021). Finally, it is important to note that the transition to the circular economy requires innovative product development, potentially creating new substance-application combinations, which may lead to new applications of SoC (Beekman et al., 2020).

2.3. Method content theory and material selection methods

Since this study focuses on evaluating methods, we draw on Daalhuizen and Cash's Method Content Theory (MCT) and its extended assessment framework (Daalhuizen and Cash, 2021; Cash et al., 2023). MCT describes the five essential elements that constitute a high-quality design method. The *assessment framework* extends MCT and adds four elements that evaluate the rationale for selecting the method content, the key decisions made during its development, the scope and evidentiary basis of the claims it makes.

Nine elements are used to evaluate methods in MCT and the accompanying assessment framework:

(1) *Method goal:* the aim of using the method and its scope.
(2) *Method rationale:* The relationship between user performance and the goals of the method, enabling the user to evaluate when they have "succeeded".
(3) *Method procedure:* The prescribed steps and criteria to reach the goal.
(4) *Method mindset:* Required values, principles, and beliefs to use and interpret the method.
(5) *Method framing:* Information that composes the method, consisting of four sub-elements: (5a) *Context:* Relevant context of use, i.e. organizational structure, type of project, and situating in the wider development process. (5b) *Pre-requisites:* Resources or knowledge necessary to use the method. (5c) *Positioning:* Where in the process to apply the method. (5d) *Task:* Types of activities prescribed, e.g. calculations, visualization.
(6) *Method motivation:* Why it was needed to develop this method and where the need originated.
(7) *Method nature:* What type of method it is and the purpose of the support, e.g. a template for students or a general approach for design practitioners.
(8) *Method development:* The processes underlying the development of the method.
(9) *Method claims:* The outcome claims and the type of evidence these are based on.

Of these nine elements, we further specify the element *Method procedure.* We structure this element using van Kesteren et al.'s material selection process model (Van Kesteren et al., 2008), which distinguishes four standard steps: (1) *Formulating selection criteria*: Defining the required material properties and set or revise search boundaries, (2) *Establishing a set of candidates*: Compile a shortlist of suitable material options, (3) *Comparing candidates*: Evaluate how well each option meets the criteria, and (4) *Choosing suitable candidates*: Narrowing down the options by eliminating less suitable materials. For sustainable material selection, criteria extend beyond traditional cost and performance to include regulation compliance, environmental impact, recycled content, renewability, and recyclability (Ashby, 2013; Ashby and Johnson, 2003). To classify the support given for each of those steps, we draw on two previous studies (Rossi et al., 2016; Rahim et al., 2020), that identify five method classes supporting these steps: (1) *Lifecycle assessment*: Quantification of a product's environmental performance across its full life cycle, following ISO LCA standards, (2) *Computer-aided design (CAD):* Integration of CAD to quantify performance of a material, (3) *Diagram tools*: Assessment of material attributes not based in LCA, (4) *Checklists and guidelines*: Textual descriptions and prescriptions considering favourable material attributes and (5) *Multi-criteria methods*: Evaluate alternatives against weighted and potentially conflicting criteria.

3. Method

To identify current available material selection methods, a literature search was performed in combination with expert consultation. A selection of 29 methods was identified and analyzed - using method typologies, method procedure, and a method assessment framework - to understand how they support substance safety and sustainability of products.

3.1. Academic literature search

In January 2024, we conducted a search for material selection methods focusing on sustainability and substance safety. In May 2025, the process was repeated but no additional methods were identified. As very few methods explicitly address both sustainability and substance safety, we decided to take sustainable material selection methods as a starting point. The search string used was *material AND select AND (circular* OR sustainab*) AND product AND design AND method**. The search was performed across three databases: Web of Science, Scopus, and Google Scholar (the latter limited to the first 20 pages), yielding 1358 results. After removing duplicates (299), we screened titles and abstracts based on three criteria: (1) focus on material selection, not retrospective assessment; (2) applicability to general product development, not specific products; and (3) addressing sustainability goals. This resulted in 42 methods, which were further assessed for addressing substance safety criteria. After this final screening, 20 methods remained that addressed both sustainability and substance safety. An overview of the screening process is shown in Fig. 1.

3.2. Grey literature and expert consultation

To also include methods developed outside academia, we performed an additional two-stage search: a Google Search followed by an expert query. Based on authors' knowledge of the field and desk research, a basic Google search (querying specific keywords i.e., sustainability*, material*, selection*, circular* economy in different combinations) resulted in 5 additional methods.

To reach higher levels of representation, four material experts from Delft University of Technology's Faculty of Industrial Design Engineering were consulted. The four experts were selected because of their expertise in CE and materials. The experts were contacted via email by the authors. They were asked to: (1) review the authors' compiled list and (2) suggest any additional methods encountered in practice. The experts listed ten additional industry-developed methods, that did not overlap with the already obtained results. Two of those were mentioned by two of the experts. Six methods were excluded for failing to meet the criteria. Ultimately, four additional methods were identified and included in the study.

Altogether, a representative, although likely not exhaustive, set of methods was achieved from the systematic literature search and the expert query. The 29 material selection methods for sustainable design that also address substance safety make up the final analyzed set.

3.3. Data analysis

The methods were analyzed using an analysis framework based on the frameworks and definitions introduced in Section 2; the design method assessment framework of Cash et al. (Cash et al., 2023), a set of method typologies by Rahim et al. and Rossi et al. (Rossi et al., 2016; Rahim et al., 2020), and the standard procedural steps in material selection as identified by van Kesteren et al. (Van Kesteren et al., 2008). Drawing on the work of these researchers, we identified six analytical elements (Elements 1–6). From (Cash et al., 2023), we adopted the method evaluation elements: Method Procedure, Method Nature, Method Context, Method Prerequisite, Method Motivation, and Method Mindset, which we tailored to suit the current review.

The first four elements typify the methods and their procedures, whereas elements 5 and 6 are more contextual characteristics of the methods.

Three additional, in-depth elements were inductively identified after the initial coding process (element 7–9). These three additional elements further clarify the support offered. Together, the nine elements constitute the analysis framework, shown in Table 1.

This integrated analysis approach was necessary because the study bridges design, engineering, and material science, and no single framework could address all relevant aspects. Fig. 2 illustrates how elements were integrated and how they relate to each other.

We performed a content analysis of the 29 sustainable material selection methods through the analysis framework consisting of the nine

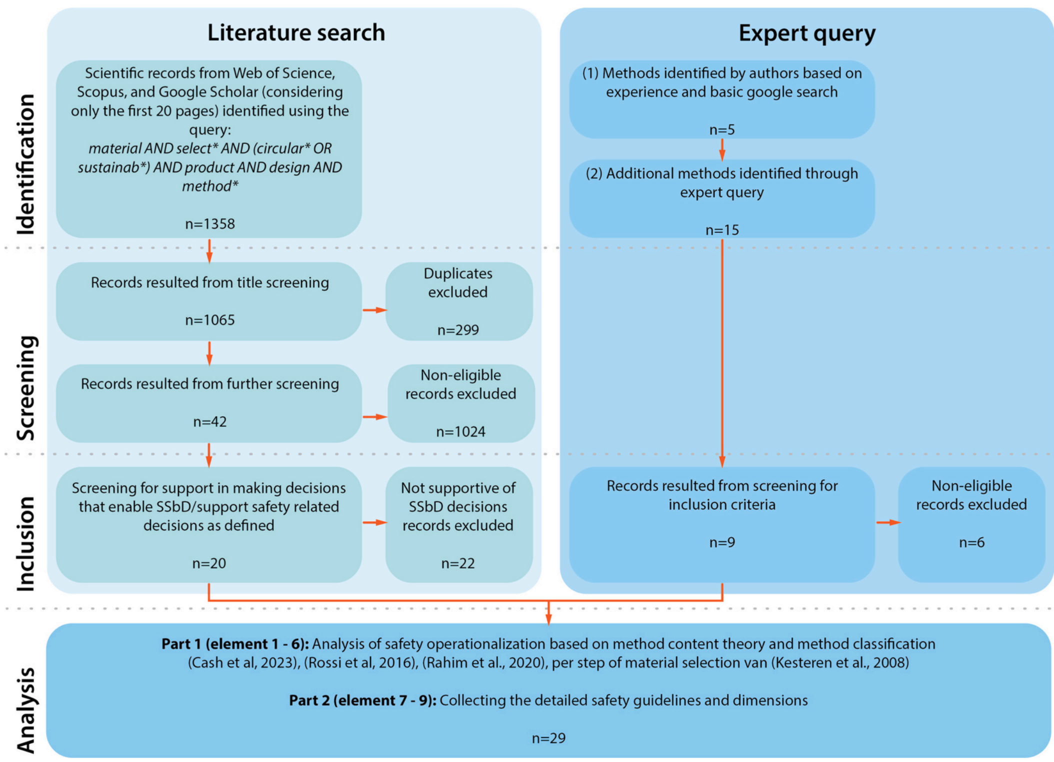

Fig. 1. Overview of the data collection approach.

Table 1
The nine elements of the analysis framework and their purpose. The purpose also indicates the codes used during analysis (if applied) and indicates between brackets on which element in the original MCT framework the current element is based.

Framework elements:	Purpose:
(1) Method procedure	To analyse which step(s) of the four procedural steps; formulating selection criteria, establishing a set of candidate materials, comparing candidates, and choosing, are supported. For each of these steps that is addressed by a method, the method type is identified (LCA-; CAD integration-; Diagram tool-; Checklists and guidelines-; Multi-criteria-type). (same in Cash et al. (2023) and Daalhuizen et al. (2021)).
(2) Professional field	To describe if the method nature is related to engineering or design practice according to the record. Codes: developed/made/intended for design, designer, engineering, engineer (Method Nature in Cash et al. (2023)).
(3) Use context	To analyse in which context the method is used. Codes: team, company size, SME, interdisciplinary, multidisciplinary, workshops, collaboration (Method Context in Cash et al. (2023)).
(4) Data sources	To analyse which data prerequisites are present in the method record and how they should be met. Codes: data sources, databases, input, resources (Method prerequisite in Cash et al. (2023)).
(5) Substance safety motivation	To describe why the method addresses substance safety (Method Motivation in in Cash et al. (2023)).
(6) Mindset	To describe the interpretative lens through which the methods user is ought to view and approaches problems. (same in Cash et al. (2023) and Daalhuizen et al. (2021)).
(7) Guidelines for substance safety	To identify qualitative phrases that guide a method user into making specific choices in selecting materials for substance safety. Guidelines were extracted after analyzing the complete method records, then grouped into three application levels: (1) material, (2) product, and (3) process. Redundant guidelines across methods were consolidated. Authors looked for phrasings in imperative form or offered as optional strategies.
(8) Substance safety scores	To identify which scores are used to represent data that allow for quantitative guidance. These were identified by analyzing the complete method records then grouped into three types: (1) LCA impact categories and (2) other, e.g. scoring on scales.
(9) Strategies to deal with uncertainty	To identify operationalization of uncertainty. We looked for instances where types of uncertainty in the material selection procedure where mentioned. Consecutively, we evaluated whether the method offered support to deal with this uncertainty. Codes: data, data gaps, data lack, estimation, proxy, substitute, assumption.

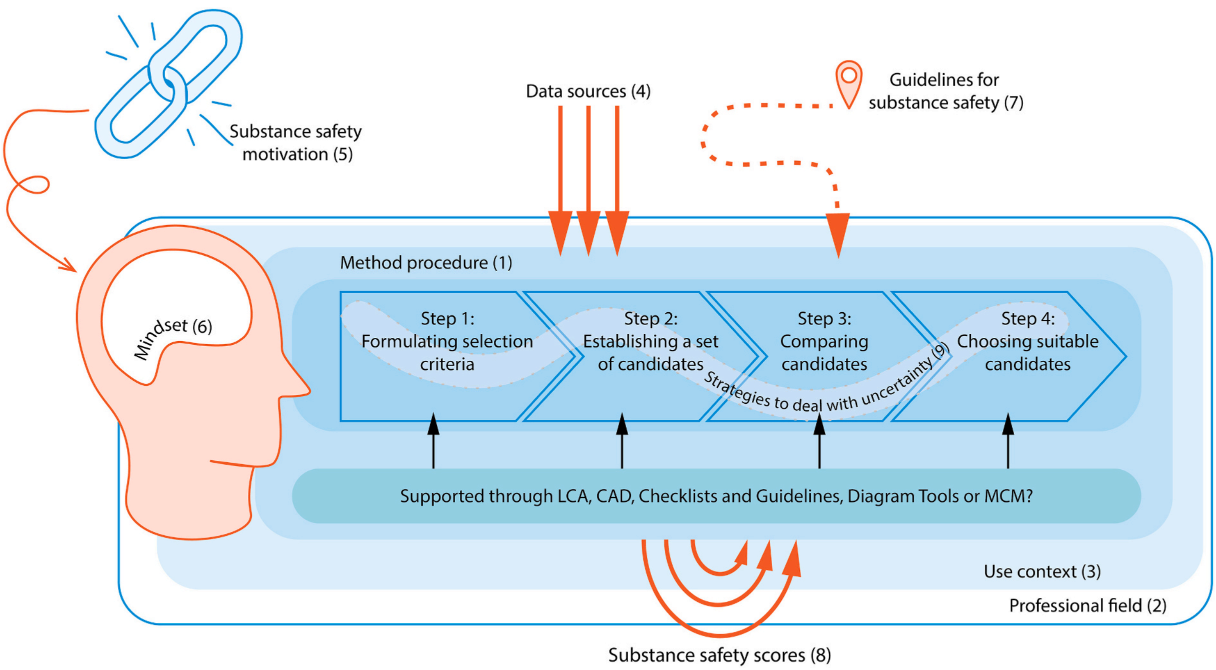

Fig. 2. Representation of how the nine framework elements are integrated in the analysis framework.

elements presented in Table 1 and Fig. 2 (Elo et al., 2014). Assessing the methods for elements 1, 2, 3, 4 and 9 and thereby assigning aspects such as the specific Field was done by coding the method records using the codes introduced in Table 1. To assess elements 5, 6, 7 and 8, for instance the substance safety motivation described in the various methods, a strict coding scheme was not suitable and rather the records were analyzed for the broader concepts. The first author conducted the coding, which was then extensively discussed and iterated with the full research team.

Through these discussions, we aggregated results for each framework element, integrating insights from all methods into the various subsections of Section 4. Depending on the nature of the framework element, the findings are presented in a more quantitative or more descriptive manner.

4. Results

This section presents the results from the analysis of the 29 material selection methods. This section is divided in 6 parts, based on the analysis framework as shown in Table 1.

In Table 2, the main findings for the first five elements of the analysis framework (method procedure, method field, use context, data sources referenced and safety motivation) are provided. The other four elements are elaborated on thereafter.

4.1. Method procedure, nature, context of use and data sources

For the first element of analysis, the procedures, we find that different types of methods each support one or more steps in the selection process in different ways:

- *Checklists and guidelines* highlight relevant material attributes;
- *LCA-methods* score material alternatives and identify materials with the lowest environmental and toxicity-related impacts;
- *Diagram tools* help organize material options and score them for substance safety;
- *CAD-based methods* generate adaptable models to explore alternatives during early design;
- *Multi-criteria methods* support (weighted) comparisons through scoring to balance different interests, of which safety of the material and its substances is one.

Further, as is evident from Table 2, we find that most of the 29 methods support step 2 ‘Establishing a set of candidates’ and step 3 ‘Comparing candidates’. However, few provide guidance on step 1 ‘Formulating selection criteria’ or step 4 ‘Choosing suitable candidates’.

Regarding the second and third elements of analysis—the field of the methods and their context of use—we observe that this information is not consistently reported across all methods. The majority are intended for use in professional “design” contexts, with a smaller portion applied in “engineering” contexts. Method 5 and method 27 are exceptions, where method 5 is also intended for education and method 27 is intended for consumers as well as product developers (Omodara et al., 2022; Rocha et al., n.d.). Approximately half of the methods explicitly support collaborative activities through collaborative tools such as workshop templates.

The fourth element of analysis is the data sources referenced. Availability of reliable data is critical to material selection. We find that there are four ways that methods facilitate acquiring the necessary data to support substance safety and sustainability evaluation during material selection. First, and this is most common, there are methods that refer to external databases. However, they do not always motivate why that database is referred to, and they do not support familiarizing with that database. Second, there are methods that provide the data, in which case no external data sourcing is needed. Third, there are methods that point the user to scientific literature to use published results from assessments of similar products. Finally, there are methods that refer the user to experts for data input. A full list of the external databases used as sources in the different methods can be found in Appendix A.

4.2. Safety motivation

The motivation to address substance safety (element 5 in the assessment framework) as part of sustainable or circular material selection by the methods was analyzed, to understand the role of this value within the selection procedure. The motivation to consider substance safety is explicitly described in 12 of the 29 methods and is generally

Table 2
Assessment of elements: (1) the method procedure per selection step, (2) method nature, (3) context of use, (4) data sources and (5) safety motivation. A blank cell indicates that the method did not report on this element. Abbreviations: LCA = lifecycle assessment related tools; CAD = computer aided design integrated tools; DT = diagram tools; CG = checklists and guidelines; MCM = multi-criteria or multi-attribute methods.

Method	Procedure (1)				Field (2)		Use context (3)		Data sources (4)				Motivation (5)
	Step 1: Formulating selection criteria	Step 2: Establishing a set of candidates	Step 3: Comparing candidates	Step 4: Choosing suitable candidates	Design	Engineering	Non collaborative	Collaborative	Provided by method	External Database	Scientific literature	Experts	
(1) A metrics-based framework to evaluate and assist sustainable product design for the circular economy			DT	CG	●		●	●		●			
(2) An eco-design methodology based on a-LCA and TRIZ		DT	LCA		●	●	●			●			
(3) Ansys GRANTA EduPack		DT	DT		●	●	●		●				
(4) Assessment of sustainability issues for the selection of materials and technologies during product design			LCA		●	●	●			●			
(5) CE Designer			DT	DT	●			●					Avoid toxic materials
(6) Circular Design Guide - Material selection methods		CG	CG/DT	CG	●		●	●		●			Lifecycle perspective
(7) Combining Stage-Gate™ model using Set-Based concurrent engineering and sustainable end-of-life principles in a product development assessment tool		DT	DT	DT	●	●		●		●			
(8) Design for and from Recycling: A Circular Ecodesign Approach to Improve the Circular Economy		CG/DT	DT		●					●	●		Lifecycle perspective
(9) Design for Remanufacturing and Remanufacturability Assessment (DRRA)		CG	MCM/DT	MCM/DT	●		●						
(10) Design guidelines based on the circular strategy scanner	CG	CG			●			●					
(11) Design Method for Improving Product Recoverability			DT		●		●						Lifecycle perspective
(12) Ecolizer		CG	LCA		●		●	●	●				
(13) Extended Material Circularity (EMC)			DT		●	●	●			●	●		Lifecycle perspective
(14) Green CAD		CAD	LCA	MCM	●		●			●			
(15) Greener Materials	CG	CG	CG		●	●				●			
(16) Healthy materials method cards	CG	CG			●			●					Avoid toxic materials
(17) IDEMAT app		DT	DT		●		●		●				
(18) Integrated model for the analyses of environmental impact and market value			DT		●	●	●						Avoid toxic materials
(19) Integrated model for the environmental assessment of industrial products during the design process		LCA	MCM	DT	●			●		●			Attribute trade-off process
(20) Interval 2-tuple linguistic intuitionistic fuzzy numbers (I2LIFNs)			MCM	MCM			●	●				●	
(21) Material pathways	CG	CG			●			●					Lifecycle perspective
(22) Material selection expert system for sustainable product design (MSESPD)		CG/DT			●	●	●						Avoid toxic materials
(23) Materials selection in eco-design		CG	DT		●		●	●	●				Lifecycle perspective
(24) Method to construct and capitalize eco-design knowledge			DT		●	●	●	●				●	
(25) An eco-design methodology based on a-LCA Methodical Approach for robust Surrogate modelling for material selection in Sustainable Design Of Products (MASSDOP) and TRIZ		DT	MCM	MCM	●		●			●			
(26) Obtaining sustainable production from the product design analysis			LCA	CG	●		●			●			
(27) Product sustainability assessment tool (PSAT)			DT/CG		●		●				●		
(28) SPICE model	CG	CG			●			●				●	Avoid toxic materials
(29) Using life cycle costing (LCC) to select circular measures		DT	DT					●					
Sums	5	19	25	10	27	9	19	13	4	12	3	3	
LCA		1	5	1									
CAD		1											
DT		8	15	4									
CG	5	11	3	3									
MCM			4	4									

(Lifecycle perspective symbol) = Lifecycle perspective
(Avoid toxic materials symbol) = Avoid toxic materials
* = Attribute trade-off process

References per method: (1) Hapuwatte and Jawahir (2021); (2) Bersano et al. (2017); (3) Inc. ANSYS (2024); (4) Reuter (2016); (5) Rocha et al. (n.d.); (6) Ellen MacArthur Foundation (2016); (7) Miranda De Souza and Borsato (2016) ; (8) Leal et al. (2020); (9) Yang et al. (2016); (10) Shahbazi and Jönbrink (2020); (11) Cong et al. (2019); (12) Ovam (2009) ; (13) Mesa (2023); (14) Gaha et al. (2014); (15) Faludi (2015); (16) Healthy Materials Lab (n.d.); (17) Meursing and Vögtlander (2024); (18) Vögtlander et al. (2001); (19) De Napoli et al. (2017); (20) Wang et al. (2021); (21) Hasling (2020); (22) Zarandi et al. (2011); (23) Philips Design (n.d.); (24) Rossi et al. (2022); (25) Eddy et al. (2015); (26) Lacasa et al. (2016); (27) Omodara et al. (2022); (28) Prendeville (2014); (29) Kambanou and Sakao (2020) explained as *the need to avoid toxicity* (e.g. method 16, 18) (Prendeville et al., 2014; Healthy Materials Lab, n.d.). This is argued without further argumentation, or based on a *lifecycle perspective*, see Table 2 for the overview. From a lifecycle perspective, substance safety aims to prevent toxic material flows from entering new cycles (methods 6, 21, 23) and to avoid hidden toxicity and pollution (Hasling et al., 2020; Ellen McArthur Foundation, 2016; Philips Design, n.d). An end-of-use perspective is considered in methods 8, 11, 13, and 21 to prevent contamination during recycling or biodegradation (Cong et al., 2019; Leal et al., 2020; Mesa, 2023). Method 19 addresses substance safety after performing a trade-off process to determine which material selection criteria to use, based on factors such as literature relevance and data availability (De Napoli et al., 2017).

The other 17 methods seem to consider substance safety as an aspect of environmental sustainability, next to other environmental dimensions like e.g. global warming potential, water use, and eutrophication (e.g. method 15, 20) (Wang, 2021; Faludi, 2015). We refer to this as implicit motivation. In these methods substance safety is presented in the context of general environmental impact assessment or mentioned in a set of guidelines for circular design, without specific reasoning, for example in LCA methods, where the use of specific end- or midpoints is not separately motivated (e.g. method 2) (Bersano et al., 2017).

4.3. Method mindsets in material selection

We analyzed the methods for the required mindset (element 6 in the analysis framework) to understand the interpretative lens through which a method user is ought to view and approach problems. Only in a minority of the methods (8/29), such a lens is offered to the method users. We identified four general themes in the method mindsets: (1) Systemic, (2) Iterative, (3) Envisioning, and (4) Trade-off Balancing, which cannot always be clearly separated. Some address substance safety specifically, while others take a broader perspective.

A systemic mindset emphasizes the importance of considering the needs not only of direct users but also of everyone interacting with the material across its lifecycle. Method 6 highlights this by including the full value chain, and Method 1 explicitly frames society as a stakeholder (Hapuwatte and Jawahir, 2021). This broader view aims to reduce (potentially harmful) waste by involving all actors—from extraction to disposal. Method 21 introduces the concept of “material transparency”, encouraging product developers to reflect on the economic and ethical consequences of their material choices, and how these relate to global material flows. This reflection supports more responsible sourcing and practices that better align substance safety with sustainability goals.

An iterative mindset promotes reassessing materials as the design process progresses. Method 7 uses a stage-gate approach to reinforce continuous evaluation (Miranda De Souza and Borsato, 2016). Method 6 views products as evolving systems, encouraging the incorporation of feedback throughout development. This mindset recognizes that circular strategies can sometimes conflict: substance safety measures may complicate recyclability, or design priorities may shift over time.

Envisioning mindsets involve proactive thinking. Method 18 encourages asking “what if” questions early in the design process—before costs, pollution, or resource demands arise (Vogtländer et al., 2001). Method 8 invites developers to see themselves as the user and consider integrating recycled materials into their designs—especially those less understood in terms of substance safety. Method 11 makes the method user keep in mind during product development that design impacts 70–80 % of the downstream activities.

Finally, a trade-off balancing mindset helps navigate competing requirements. Method 10 emphasizes that no material is inherently sustainable or “green” in isolation (Shahbazi and Jönbrink, 2020). Method 15 adds that sustainability depends on how well a material fits its function, its environmental impact, including toxicity, and its role within the full system and product lifecycle.

4.4. Guidelines for substance safety

The methods were analyzed for material selection guidelines for substance safety (Element 7 in the analysis framework), as guidelines provide more detailed insight into how users are guided in making informed choices regarding substance safety in sustainable material selection. The identified guidelines are targeting three different levels; 1) material level: referring to all guidelines that provide guidance on what material or compound is most suitable or should be avoided, 2) product level: referring to all guidelines that provide guidance on making the product safer, going hand-in-hand with or beyond the substance safety inherent to the composition of the materials used, and 3) process level: all guidelines that provide guidance on making the processes necessary to create the product safer, regardless of the specific material that was selected. This categorization reflects the levels at which product developers can intervene to enhance substance safety—often resulting from, but not limited to, material choices.

There are two ways in which the guidelines are expressed. The first is guiding or provoking specific lines of thought, e.g. “when addressing topic x, consider y”. The second is more imperative or prescriptive, discouraging specific choices, e.g. “Avoid or reduce the use of toxic materials or components” (method 11). Prescriptive guidelines are most often given for the material level, suggesting to “avoid or reduce toxicity” in various wordings, sometimes specified for the material class or the application of the material (e.g. method 12, 22) (Ovam, 2009; Zarandi et al., 2011). An overview of all guidelines is provided in Appendix B.

4.5. Substance safety scores

The methods were analyzed for their use of a safety scoring (element 8 in the analysis framework) to identify which scores are used to represent data that allow for quantitative guidance or ranking. In 20 methods, substance safety scores are used to aid material selection through quantifying substance safety aspects. We distinguish two main approaches: (1) life cycle assessment (LCA) and (2) non-LCA scoring systems.

Six methods integrate LCA into the material selection process (methods 2, 4, 12, 14, 19, 26), while three apply life cycle costing based on LCA (methods 17, 18, 29) (Gaha et al., 2014; Kambanou and Sakao, 2020; Lacasa et al., 2016; Reuter, 2016; Meursing and Vögtlander, n.d). The impact categories used are summarized in Table 3. In LCA, midpoint indicators represent specific environmental issues (e.g., climate change), while endpoint indicators aggregate multiple midpoint indicators to reflect the potential damage to broader areas of protection: human health, ecosystem health, or resource depletion (European Commission, 2010). Several methods rely on older methodologies, such as the CML method (e.g., methods 2, 24) or Eco Indicator versions EI ‘95 and EI ‘99 (e.g., Methods 19, 26) (Rossi et al., 2022). Substance safety midpoint indicators related to human health are common, whereas ecosystem health midpoint indicators are rarely used — only methods 14 and 27 address them. Methods 7 and 24 apply endpoint assessments, aggregating midpoint indicators for human and ecosystem health. Method 7 uses both endpoints and a single score, which combines all environmental impacts into one overall score.

4.5.1. Non-LCA scoring

Besides LCA impact categories, a range of alternative methods are used to evaluate substance safety aspects. These were categorized as either diagram tools or multi-criteria evaluation frameworks, or both (e.g. method 9, 25), see Table 2 (Eddy et al., 2015; Yang et al., 2016). These methods rely on structured scoring systems, rule-based logic, or expert judgment rather than impact modeling. We identified 5 categories based on their main characteristics. The general approach, key substance safety scores and scoring logic of these methods using non-LCA safety scoring are summarized in Table 4.

Table 3
Overview of substance safety related midpoints and endpoints used in the methods. Midpoints are grouped by endpoint category.

	Endpoints	Midpoints
Human health	Damage to human health; Human Health Impact (7)	Human Toxicity (non-cancer effects) (14, 17, 24, 27)
		Human Toxicity (cancer-effects) (18, 27)
		Photochemical ozone creation (2, 4, 27)
		Particulate Matter Formation (18, 27)
		Ionizing Radiation (27)
Ecosystem health	Damage to ecosystems; Ecosystem quality (7, 29)	Freshwater Ecotoxicity; Aquatic Ecotoxicity (14, 27)
Single score	ReCiPe indicator; Eco Indicator '95 or '99 (7, 12, 19, 26).	

Table 4
Overview of other safety scoring systems used in the method reports and their key characteristics.

Category	Approach	Determinants of the safety scores	Quantification	Methods
(1) Questionnaire - based scoring	Predefined questions and rule-based logic	Presence of hazardous/restricted substances, recyclability, working conditions, safe and ethical sourcing	Letter grades (5), point-based scoring (27), exclusion criteria (22)	5, 27, 22
(2) Expert judgment & decision models	Multi-criteria decision-making, expert scoring	Material toxicity, emissions, waste, legal compliance	Scales (0–6 in 20), qualitative scale in 9; weighted by user or model	20, 9
(3) Attribute - specific scoring	Direct scoring of material properties	Toxicity (incl. recycling), food safety, RoHS/REACH/SIN compliance	1–5 scale (23), risk and compliance ratings (3)	23, 3
(4) Circularity & end-of-life focus	Index-based or quantitative assessment	Biodegradability, hazardous waste, material mass, recyclability	Loop-life index (1 of 6 attributes) (13), material mass and cost factors (11, 19)	13, 11, 19
(5) Gate-based screening	Stage-gate filtering	Toxic substance thresholds, traceability of parts	Pass/fail criteria at decision gates	7

These methods provide structured, often semi-quantitative means to evaluate substance safety in material selection. While they vary in scope and complexity, they share a common focus on assessing human health, environmental, and regulatory risks (e.g. RoHS compliance, method 3) without relying on LCA modeling and by considering other determinants than LCA impact categories (Inc. ANSYS, 2024).

4.6. Uncertainty and substance safety

How the methods deal with uncertainty (element 9 in the analysis framework) was analyzed because this is a crucial part of product development within the SSbD approach. Data on materials and substances is often limited, and the risks of most substances are rarely assessed for the specific (new) application a product developer is working on. Of the 29 methods, 15 address uncertainty. The other 14 methods do not mention uncertainty or lacking data and do not offer support in dealing with it. We found two ways uncertainty is dealt with: 1) methods that acknowledge uncertainty but provide limited or no explicit support in managing uncertainty, and 2) methods that advice specific strategies, such as expert input, collaborative approaches, or alternative frameworks, to address uncertainty.

When uncertainty is merely acknowledged as part of the sustainable material selection process, the methods mention challenges in obtaining material data due to confidentiality or due to data simply not existing (methods 11, 27). Method 25 notes that assumptions are often necessary, introducing uncertainty into results; product developers are advised to assess such decisions case by case.

When strategies to address uncertainty are also given, methods propose strategies to manage uncertainty directly. The strategies are summarized in Table 5. Some methods apply more than one strategy.

5. Discussion

This review examined 29 sustainable material-selection methods to evaluate how current sustainable material selection methods integrate substance safety across all stages of the material selection process. Support for integrating substance safety across the four steps of the sustainable material selection process varies among the methods. Most

Table 5
Overview of approaches to uncertainty in the material selection methods.

Category	General approach	Methods
(1) Stakeholder consultation	Collaboration during method use with upstream stakeholders or experts (e.g. chemists or toxicologists) is supported to fill in data gaps. Transparency toward downstream stakeholders is also encouraged.	6, 15, 16, 20, 22, 28
(2) Ordinal assessment	The methods offer ordinal scoring/scales (e.g. a 7 point scale where 0 = extremely terrible and 6 = extremely fine) of attributes over objective/exact scores.	20, 22, 13
(3) Proxies	Guidance for substitute data used to represent a process, material, or product when specific data are unavailable.	12, 18
(4) Frameworks for system simplification	Uses standardized frameworks to be able to monetize social health and safety effects. Simplification tools—such as product archetypes—enable LCAs using rough or limited data.	4, 19
(5) Error variables	Variable as a parameter in the optimisation formulation, the designer can assess the significance, confidence, and risk posed by it in each individual case.	25

provide some level of assessment and comparison of material alternatives for substance safety criteria and offer guidelines to avoid hazardous substances. None of the methods explicitly address substance safety as SSbD frameworks suggest, by integrating environmental and social impact assessment with risk assessment, nor do they articulate the need for or underlying mindset behind this approach. By treating safety as a subset of sustainability, they neglect the necessary balance between reducing sustainability impacts and minimizing SoC exposure risks.

5.1. Substance safety in material selection methods: gaps and implications

First, this study showed that the first and fourth steps of the material selection process—formulating selection criteria and choosing suitable candidates, respectively—are the least supported. This aligns with prior findings indicating that early and final stages of material selection are generally less well-supported (Rahim et al., 2020; Shaharuzaman et al., 2021). Methods that do support step 1, typically provide explicit motivation for addressing substance safety, which informs users of its necessity. However, in half of these methods, the focus is on *avoiding material toxicity* regardless of application context, implying that inherently safe alternatives always exist (Daalhuizen et al., 2009). This overlooks the reality that most SoCs serve a function in products that cannot always be fulfilled by a safer alternative, making simple avoidance strategies insufficient (Bolaños Arriola et al., 2024; Cousins et al., 2019). Without lifecycle-informed guidance in step 1, developers may fail to consider how manufacturing conditions, use contexts, and end-of-life treatment should shape material selection from the outset. Similarly, lack of support during the final step could lead to oversights, where the absence of hazard data may be misinterpreted as indicating safety. To address this gap, future methods should support both identifying context-appropriate safety criteria (step 1) and verifying the safest alternative (step 4) by building on the systemic mindset found in eight methods. This mindset moves decision-making toward integrated, timeframe-aware approaches essential for SSbD products (Bodar et al., 2018). Specifically, methods should guide developers to consider substance safety from a lifecycle perspective—where intended end-of-life treatment, manufacturing conditions, and use contexts inform material selection. For example, a product intended for use in water should not contain water-soluble SoCs, even if those substances might be acceptable in other contexts. This lifecycle perspective offers more compelling motivation for product developers and enables context-sensitive decisions across both early and final selection stages.

Second, methods depend on externally sourced data, which are often scarce, and especially uncertain in the first selection step (Apel et al., 2024). Little support is offered to identify data gaps that might be present, nor is there support on how to identify and integrate diverse data sources to fill those gaps. Since substance safety data are so specific to a material and application, this is problematic. Methods that use scientific literature, offer high specificity but limited generalizability, while (open access) databases provide broader scope with less detail. In the case of databases, there is another looming disadvantage; at some point, they seize to be updated or are retired altogether (ChemForward, n.d.). In the absence of data, expert consultation is recommended. However, this approach, in combination with the identified lack of tools that support collaboration to make decisions surrounding SoC, raises a key concern: it assumes users can critically assess expert input. Without sufficient structure, this approach risks becoming too open-ended. Future method development should offer tools for identification and scrutinization of data and for collaboration with relevant stakeholders; those along the value chain that are responsible and those affected by the product. To do so, future method development should align with the Ecodesign for Sustainable Products Regulation's information rules for value chain collaboration and data transparency (European Parliament and Council of the European Union, 2024).

Third, methods lack integration between LCA, diagram tools and guidelines, risking decontextualized LCA results that fail to account for critical factors such as emissions and exposure scenarios. Conversely, methods relying solely on guidelines often must default to the precautionary principle (Hansson, 2018), which can lead to overly absolute conclusions regarding risks (e.g. avoiding a specific material, while preferring an alternative with yet unknown risks). Regarding implications for future method development, addressing this lack of explicit, balanced integration of environmental and risk assessment is critical. Prior research suggests that product development methods should be treated as an *ecosystem*, where multiple methods can address different aspects of a project (Gericke et al., 2022). For the implementation of material selection for safe and sustainable design, this could mean integrating LCA tools with checklists and guidelines. For example, a tool that ranks materials by eco-costs (Meursing and Vögtlander, n.d), may highlight impacts to human health and eco-toxicity, requiring guidelines to contextualize the decision based on e.g. intended use context and multi-criteria decision tools to support final choosing. Furthermore, a form of risk assessment suitable for product development practice is needed, particularly toward considering emissions and exposure scenarios for substances used in products.

Fourth, the methods often lack strategies for trade-off operationalization. While most methods score material alternatives on substance safety, such scoring often produces conflicting outcomes that must be resolved. Yet guidance becomes more limited as the selection process becomes more specific, despite trade-offs becoming most evident toward the end—a limitation also identified by Italia et al. (Italia et al., 2023). Where present, trade-off support relies on optimization using (semi-) quantitative tools or holistic approaches using qualitative tools. Optimization approaches are efficient for well-defined problems but unsuitable when uncertainty is high or objectives conflict (Sirisalee et al., 2003), risking critical oversights. Holistic approaches offer greater adaptability under uncertainty but tend to be more time-consuming and ambiguous (Taramsari et al., 2025). Therefore, future methods require pragmatic support for addressing uncertainty and trade-offs systemically, building on the error variable identification, system simplification frameworks, and multi-criteria decision tools identified in this review—tailored to address the lifecycle perspective for criteria formulation (gap 1), data identification (gap 2), and risk assessment integration (gap 3) identified above.

5.2. Situating SSbD material selection for product development

The complexity and context-sensitivity of material selection for substance safety, involving social, performance, and sustainability trade-offs across lifecycles and inherent uncertainties, demands a systemic approach rather than linear solutions. We introduce two approaches where SSbD material selection methods could be situated.

The Value Sensitive Design (VSD) approach provides a theoretical grounding for reflecting on how decisions are influenced by, and influence, values in social and technical contexts (Friedman and Hendry, 2019). The *early steps* of material selection methods are where diverse values can be investigated: Which stakeholders' concerns about substance hazards are represented? Whose assumptions about acceptable trade-offs are embedded in the method? VSD has already been applied in other fields to enable e.g. *safe by design* nanotechnology, where starting from the value *safety* helps to identify and anticipate risks associated with the emerging applications (van de Poel and Robaey, 2017). Applied to material selection, this means recognizing that the criteria used to evaluate materials are not objective but reflect stakeholder priorities and balancing risks with other values, like sustainability. Similarly, Systemic Design has emerged as a response to the increasing complexity and interdisciplinarity of product development, offering means to navigate the complexity and uncertainty inherent in material selection decisions (Jones and Van Ael, 2022). Critically, this approach makes the trade-offs and uncertainties structurally visible during the *later steps* of material selection: How do choices in early lifecycle phases constrain or enable options in later ones? Where do uncertainties accumulate across the system? What unintended consequences might emerge from prioritizing particular substances or processes, how might we anticipate those and how might we adapt (Jones and Upward, 2014)? SD encourages mapping the interactions within the system—across stakeholders, lifecycles, and unintended consequences (Jones and Van Ael, 2022; Ryan, 2014), additionally enabling inclusive collaboration, providing means to involve diverse actors in decision-making, which directly addresses the reviewed methods' identified lack of support for collaboration (Ryan, 2014).

The integration of VSD and SD would frame material selection as a situated practice that should relate to other product development processes and support the identification of criteria that evolve across lifecycle phases and stakeholder contexts, and decision-making processes that render trade-offs and their justifications transparent.

5.3. Limitations and future research

This study focused on general sustainable material selection methods, which might have affected our conclusion that these methods offer limited and generic support at the end of the selection process. Including methods aiming at specific material classes, such as composites, or dedicated domains, like automotive applications might be more dedicated. Future research could examine such specialized approaches to assess whether they offer novel or complementary insights for SSbD material selection.

To create a usable overview of the methods, the analysis framework necessarily simplified and generalized both the tools and their underlying principles. For example, by dividing material selection into four distinct steps, methods offering continuous or integrated support may be misrepresented. Likewise, in examining the reported method mindsets and their connection to values relevant for circular economy design, we observe that while a holistic mindset is important for addressing the complex demands of sustainable material selection, it is not always necessary to explicitly label a method as such—similar values can still be conveyed implicitly, which are then overlooked in the framework.

Material selection is foundational to SSbD, yet represents only one component of a comprehensive strategy that must encompass multiple design stages and the complete lifecycle. When isolated, material selection becomes difficult to evaluate and limits exploration of alternatives or other intervention levels. Research in real-life setting should point out how future methods that integrate guidelines, environmental assessment and risk assessment elements best relate to other product development processes, using VSD and SD as grounding theories.

6. Conclusion

This review analyzed 29 sustainable material selection processes and how the methods address substance safety. Our analysis confirms that substance safety is often treated as a subset of sustainability, without offering practical procedures for its assessment. Additionally, it demonstrates that the methods insufficiently integrate substance safety with sustainability. They also insufficiently support dealing with uncertainty and in turn insufficiently addressing potential trade-offs.

This study contributes to both the field of material selection methods and the emerging area of SSbD by identifying how and where existing approaches fall short in supporting substance safety throughout the selection process. The findings point to the need for methods that more explicitly integrate both sustainability and substance safety, grounded in lifecycle thinking and aligned with the realities of product development. Most importantly, there is a need for material selection methods that deal with the different types of uncertainty that occur along the selection process, and that combine risk information with environmental impact assessment, from a lifecycle perspective.

CRediT authorship contribution statement

M.M. Weber: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **J.I.J.C. de Koning:** Writing – review & editing, Supervision, Conceptualization. **A.R. Balkenende:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT to improve readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Declaration of competing interest

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Appendix A

- Materials Sustainability Index
- Okala Practitioner and Ecolizer
- SA8000 Certified Facilities List by Social Accountability International (free access; lists all companies/factories SA8000 certified)
- MiniWiz material upcycling database (free access; furniture, architectural, & textile products)
- Environmental Working Group's database of cleaning chemicals (free access; lists EWG-certified and scores non-certified)
- EcoSpecifier (free access; architectural, cleaning products, personal care products; includes certification data)
- Cleangredients (free access; lists chemicals meeting US EPA Safer Choice standard; largely cleaning products)
- Sustainable Packaging Coalition library (members only)
- MaterialDistrict.com (free access; only some materials are green)
- Material Connexion (only some materials are green; has physical libraries in several cities)
- Transmaterial (only some materials are green)
- Materiom (free access; do-it-yourself local renewable biomaterial recipes)
- Granta CES Selector (expensive offline software; mostly physical properties, but some environmental/LCA data)
- Paid LCA software (e.g. SimaPro desktop, GaBi desktop, SustainableMinds online, etc.)
- Ecolizer LCA software (free online; in English, Dutch, German, or French)
- Ecolizer LCA lookup table (free PDF, but limited data)
- Idemat LCA phone app (free app, extensive data)
- SolidWorks Sustainability (free & pro LCA-light plugins for SolidWorks CAD software)
- Sustainable Apparel Coalition's Materials Sustainability Index (free access; fabric/soft goods list with non-LCA sustainability scores)
- MatWeb (free access; no sustainability data, but detailed mechanical & other data)
- Plastic Fantastic Library (via the Internet Archive, may be slow or non-functional; plastics only; only some materials are green; sophisticated filtering and charting).

Appendix B

Table 6
Material selection guidelines for safety on the three intervention levels: material-, product- and process level extracted from the method records.

Intervention level		Guidelines	Methods
Material	Generally applicable	1. Reduce toxicity	8, 9, 28
		2. Avoid hazardous/toxic substances	8, 15, 16, 22
		3. When designing for material degradation, consider the potential environmental impact of materials breaking down into persistent particles like microplastics, which can harm organisms.	21
		4. Consider benefits of experimental practice in discovering material properties and repurposing waste streams but also notes the risks of toxic exposure during direct experimentation.	21
		5. Consider how lifecycle aspects (e.g. recycling, reuse) influence material choices, including risks like contamination and material separation.	6, 16, 21
		6. "Avoid materials that emit toxic or harmful substances, during pre-production, usage or disposal."	22
		7. "Do not go for acceptable limits (but use less)"	23
		8. "Avoid toxic or harmful surface treatments."	22
		9. "Circular sourcing: Using resources as production inputs that are renewable, recoverable, bio-based, less resource intensive or recovering existing pollutants from the biosphere, such as ocean plastics."	5
		10. "Rethink the chemical: Explore the possibility of removing it from the material or product or substitute it with a safer one with similar or better features."	6
		11. "Remain vigilant: Define substitution criteria to avoid regrettable substitutions"	16
		12. "Get to know the material and the best use for it."	23
	Material specific	13. For plastics: "Ensure the material doesn't contain any toxic or 'suspicious' substances."	12
		14. For wood: "Try to avoid polluting the wood too much by applying harmful coatings."	12
		15. For chemicals (e.g. detergents, spin finishes): "Avoid harmful substances in a product as well as harmful processing substances."	12
		16. "Do not use any form of heavy metal"	23
Product		17. Design for people with allergies	16
		18. Design safeguards around the substance/reduce exposure	6, 15
		19. Reduce material joining method toxicity	9
		20. If you must use hazardous substances, label the product	15
		21. Address the highest volume materials used first	6
		22. "Avoid toxic substances, but use closed loops when necessary to do so"	22
		23. "Redesign the part: Improve the component by designing out the chemical, while redesigning the structure and the shape to retain or improve functionality."	6
		24. "Redefine the product: Consider the functional and emotional needs the product fulfills and the design requirements to achieve them."	6
		25. "Reimagine proposition: Design out chemicals of concern by exploring new ways to deliver the value of the product to the user."	6
Process		26. Reduce air emissions and waste disposal during remanufacturing	9
		27. Consider current and upcoming laws and regulations for substances	9, 10
		28. Use other's work (refer to certifications and evaluation tools)	16
		29. Prioritize transparency	16
		30. Propose NDAs for suppliers that are hesitant to share material data	6
		31. Use suppliers to gather information about chemical composition of their materials and components, restricted substances or chemicals of concern in their materials	6
		32. Use suppliers with high safety standards	15
		33. "Favor cleaner production, processes, machines and equipment."	10
		34. "Treat production (pre-consumer) wastes appropriately."	10

References

Apel, C., et al., 2024. Safe-and-sustainable-by-design: State of the Art Approaches and Lessons Learned From Value Chain Perspectives. Elsevier B.V. https://doi.org/10.1016/j.cogsc.2023.100876 (Feb. 01).
Ashby, M.F., 2013. Materials and the Environment. Elsevier. https://doi.org/10.1016/C2010-0-66554-0.
Ashby, M., Johnson, K., 2003. The Art of Materials Selection.
Ashby, M.F., Bréchet, Y.J.M., Cebon, D., Salvo, L., 2004. Selection strategies for materials and processes. Mater. Des. 25 (1), 51–67. https://doi.org/10.1016/S0261-3069(03)00159-6.
Beekman, M., et al., 2020. Coping With Substances of Concern in a Circular Economy. Bilthoven. https://doi.org/10.21945/RIVM-2020-0049.
Bersano, G., Fayemi, P.E., Schoefer, M., Spreafico, C., 2017. An eco-design methodology based on a-LCA and TRIZ. In: Smart Innovation, Systems and Technologies. Springer Science and Business Media Deutschland GmbH, pp. 919–928. https://doi.org/10.1007/978-3-319-57078-5_86.
Blum, A., et al., 2019. Organophosphate ester flame retardants: are they a regrettable substitution for polybrominated diphenyl ethers? Am. Chem. Soc. https://doi.org/10.1021/acs.estlett.9b00582 (Nov. 12).
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33 (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124/ASSET/F082D9C5-4B03-450B-B8B1-B30B09625200/ASSETS/IMAGES/LARGE/TJCI_A_1172124_F0002_OC.JPG (Jul.).
Bodar, C., et al., 2018. Risk Management of Hazardous Substances in a Circular Economy. https://doi.org/10.1016/j.jenvman.2018.02.014.
Bolaños Arriola, J., Subramanian, V., Bakker, C., Balkenende, R., Niinimäki, K., Cura, K., 2023. Safe and circular design – a design method for dealing with substances of concern in products. In: 5th PLATE Conference Proceedings 2023. Available: https://kth.diva-portal.org/smash/get/diva2:1795825/FULLTEXT01.pdf. (Accessed 8 November 2023) (Espoo, Online).
Bolaños Arriola, J., Aghaeian, S., Bakker, C., Balkenende, R., 2024. Strategies for dealing with substances of concern in product design – a review of five cases. Circ. Econ. Sustain. https://doi.org/10.1007/s43615-024-00449-4.
Braungart, M., McDonough, W., Bollinger, A., 2007. Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. J. Clean. Prod. 15 (13–14), 1337–1348. https://doi.org/10.1016/j.jclepro.2006.08.003.
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. https://doi.org/10.2760/404991.
Cash, P., Daalhuizen, J., Hekkert, P., 2023. Evaluating the efficacy and effectiveness of design methods: a systematic review and assessment framework. Des. Stud. 88. https://doi.org/10.1016/j.destud.2023.101204 (Sep.).
CEFIC, March 2024. Safe and Sustainable-by-Design: a guidance to unleash the transformative power of innovation. https://cefic.org/resources/safe-and-sustainable-by-design-a-guidance-to-unleash-the-transformative-power-of-innovation/ (Accessed on 28 November 2025).
ChemForward, n.d. Materialwise.org has evolved into ChemForward, a safer chemistry resource. Available: (Online) https://www.chemforward.org/materialwise. (Accessed 20 May 2025).
ChemSec, 2021. Our view on Safe and Sustainable by Design criteria. https://chemsec.org/reports/our-view-on-safe-and-sustainable-by-design-criteria/ (Accessed 28 November 2025).
Cong, L., Zhao, F., Sutherland, J.W., 2019. A design method to improve end-of-use product value recovery for circular economy. J. Mech. Des. 141 (4). https://doi.org/10.1115/1.4041574 (Apr.).
Cousins, I.T., et al., 2019. The Concept of Essential Use for Determining When Uses of PFASs Can be Phased Out. Royal Society of Chemistry. https://doi.org/10.1039/c9em00163h (Nov. 01).
Cross, N., 2001. Designerly ways of knowing: design discipline versus design science. Cross Source Des. Issues 17 (3), 49–55 (doi:154.59.124.113).
Daalhuizen, J., Cash, P., 2021. Method content theory: towards a new understanding of methods in design. Des. Stud. 75. https://doi.org/10.1016/j.destud.2021.101018 (Jul.).
Daalhuizen, J., Badke-Schaub, P., Batill, S., 2009. Dealing with uncertainty in design practice: issues for designer-centered methodology. In: ICED 09 - The 17th International Conference on Engineering Design, Vol 9: Human Behavior in Design. Design Society, pp. 147–158.
De Napoli, L., Rizzuti, S., Rocco, C., 2017. An integrated model for the environmental assessment of industrial products during the design process. Concurr. Eng. Res. Appl. 25 (4), 360–380. https://doi.org/10.1177/1063293X17729000 (Dec.).
den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product design in a circular economy: development of a typology of key concepts and terms. J. Ind. Ecol. 21 (3), 517–525. https://doi.org/10.1111/jiec.12610.
Eddy, D.C., Krishnamurty, S., Grosse, I.R., Wileden, J.C., Lewis, K.E., 2015. A predictive modelling-based material selection method for sustainable product design. J. Eng. Des. 26, 365–390. https://doi.org/10.1080/09544828.2015.1070258.
Ellen MacArthur Foundation. What is a circular economy? Available: https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview. (Accessed 29 May 2024) (Online).
Ellen McArthur Foundation, 2016. The circular design guide. Available: (Online). https://www.ellenmacarthurfoundation.org/circular-design-guide/overview (Accessed 23 August 2024).
Elo, S., Kääriäinen, M., Kanste, O., Pölkki, T., Utriainen, K., Kyngäs, H., 2014. Qualitative content analysis: a focus on trustworthiness. SAGE Open 4 (1). https://doi.org/10.1177/2158244014522633 (Jan.).
European Commission - JRC-IES, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps, First edition March 2010. Publications Office of the European Union, Luxembourg. EUR 24378 EN.
European Environment Agency, 2019. The European Environment – State and Outlook 2020 – Knowledge for Transition to a Sustainable Europe. Publications Office. https://doi.org/10.2800/96749.
European Parliament and Council of the European Union, 2024. Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (Text with EEA relevance). Available: (Online). http://data.europa.eu/eli/reg/2024/1781/oj (Accessed 12 December 2025).
Faber, M., Heens, F., Spanbroek, N., Lijzen, J.P.A., van Drongelen, A.W., 2021. Recycling van matrassen: analyse van risico's van verwerking en nieuwe toepassingen. Available: https://www.rivm.nl/bibliotheek/rapporten/2021-0131.pdf. (Accessed 27 November 2023).
Faludi, J., 2015. Greener materials. Available: https://venturewell.org/tools_for_design/greener-materials/. (Accessed 28 May 2024) (Online).
Feuilloley, P., et al., 2005. Degradation of polyethylene designed for agricultural purposes. J. Polym. Environ. 13 (4), 349–355. https://doi.org/10.1007/s10924-005-5529-9 (Oct.).
Friedman, B., Hendry, D.G., 2019. Value Sensitive Design. The MIT Press. https://doi.org/10.7551/mitpress/7585.001.0001.
Gaha, R., Yannou, B., Benamara, A., 2014. A new eco-design approach on CAD systems. Int. J. Precis. Eng. Manuf. 15 (7), 1443–1451. https://doi.org/10.1007/s12541-014-0489-4.
Gericke, K., Eckert, C., Stacey, M., 2022. Elements of a design method - a basis for describing and evaluating design methods. Des. Sci. 8. https://doi.org/10.1017/dsj.2022.23 (Dec.).
Glüge, J., et al., 2020. An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environ. Sci. Process Impacts 22 (12), 2345–2373. https://doi.org/10.1039/d0em00291g (Dec.).
Hansson, S.Ove., 2018. The precautionary principle. In: Möller, N., Hansson, S.O., Holmberg, J.-E. (Eds.), Handbook of Safety Principles. John Wiley & Sons, Inc.
Hapuwatte, B.M., Jawahir, I.S., 2021. Closed-loop sustainable product design for circular economy. J. Ind. Ecol. 25 (6), 1430–1446. https://doi.org/10.1111/jiec.13154 (Dec.).
Hasling, K.M., Ræbild, U., Patel, A., Herttua, I., Casellas Vila, C., 2020. Material Pathways. Design School Kolding.
Healthy Materials Lab. "Healthy Materials Method Cards." Parsons.
Inc. ANSYS, 2024. Ansys GRANTA EduPack Software (Cambridge, UK).
Italia, M., Papile, F., Santi, R., Del Curto, B., 2023. Sustainable material selection framework: taxonomy and systematisation of design approaches to sustainable material selection. Sustainability 15 (24), 16689. https://doi.org/10.3390/su152416689 (Dec.).
Jahan, A., Ismail, M.Y., Sapuan, S.M., Mustapha, F., 2010. Material screening and choosing methods - a review. Mater. Des. 31 (2), 696–705. https://doi.org/10.1016/j.matdes.2009.08.013 (Feb.).
Jones, P., Upward, A., 2014. Caring for the future: the systemic design of flourishing enterprises. In: Proceedings of RSD3, Third Symposium of Relating Systems Thinking to Design, Oslo. Available: https://openresearch.ocadu.ca/id/eprint/2091. (Accessed 28 November 2025) (Oct., Online).
Jones, P., Van Ael, K., 2022. Design Journeys Through Complex Systems. BIS Publishers.
Kambanou, M.L., Sakao, T., 2020. Using life cycle costing (LCC) to select circular measures: a discussion and practical approach. Resour. Conserv. Recycl. 155. https://doi.org/10.1016/j.resconrec.2019.104650 (Apr.).
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. Elsevier B.V. https://doi.org/10.1016/j.resconrec.2017.09.005
Lacasa, E., Santolaya, J.L., Biedermann, A., 2016. Obtaining sustainable production from the product design analysis. J. Clean. Prod. 139, 706–716. https://doi.org/10.1016/j.jclepro.2016.08.078 (Dec.).
Leal, J.M., Pompidou, S., Charbuillet, C., Perry, N., 2020. Design for and from recycling: a circular ecodesign approach to improve the circular economy. Sustainability (Switzerland) 12 (23), 1–30. https://doi.org/10.3390/su12239861 (Dec.).
Lin, F., Lin, L., 2003. A discussion of the state-of-art research on environmentally conscious material selection methodologies for the reduction of products' toxic impact. J. Sustain. Prod. Des. 3 (3–4), 119–134. https://doi.org/10.1007/s10970-005-3386-1 (Dec.).
Mesa, J.A., 2023. Developing a Material Selection Index Based on Circularity: A Multiple Lifecycle Approach. https://doi.org/10.1016/j.resconrec.2023.107240.
Meursing, M., Vögtlander, J.. Idemat. Available: https://idematapp.com/about/. (Accessed 28 May 2024) (Online).
Miranda De Souza, V., Borsato, M., 2016. Combining Stage-Gate™ model using Set-Based concurrent engineering and sustainable end-of-life principles in a product development assessment tool. J. Clean. Prod. 112, 3222–3231. https://doi.org/10.1016/j.jclepro.2015.06.013.
Monclús, L., et al., 2025. Mapping the chemical complexity of plastics. Nature 643 (8071), 349–355. https://doi.org/10.1038/s41586-025-09184-8 (Jul.).
OECD, 2019. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. OECD Publishing, Paris. https://doi.org/10.1787/9789264307452-en.

Omodara, L., Saavalainen, P., Pitkäaho, S., Pongrácz, E., Keiski, R.L., 2022. Sustainability Assessment of Products-Case Study of Wind Turbine Generator Types. https://doi.org/10.1016/j.eiar.2022.106943.
Ovam, 2009. Ecolizer 2.0. Danny Wille, Ovam, Mechelen.
Philips Design. Materials Selection in Eco-design.
Prendeville, S., O'Connor, F., Palmer, L., 2014. Material selection for eco-innovation: SPICE model. J. Clean. Prod. 85, 31–40. https://doi.org/10.1016/j.jclepro.2014.05.023 (Dec.).
Rahim, A.A.A., Musa, S.N., Ramesh, S., Lim, M.K., 2020. A Systematic Review on Material Selection Methods. SAGE Publications Ltd. https://doi.org/10.1177/1464420720916765 (Jul. 01).
Reuter, B., 2016. Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles. Int. J. Interact. Des. Manuf. (IJIDeM) 10 (3), 217–227. https://doi.org/10.1007/s12008-016-0329-0.
Richardson, K., et al., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9, eadh2458. https://doi.org/10.1126/sciadv.adh2458.
Rocha, C., Camocho, D., Alexandre, J., n.d..CE Designer. Available: (Online) https://tools.katche.eu/designer/project/new. (Accessed 28 May 2024).
Rossi, M., Germani, M., Zamagni, A., 2016. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J. Clean. Prod. 129, 361–373. https://doi.org/10.1016/J.JCLEPRO.2016.04.051 (Aug.).
Rossi, M., Cappelletti, F., Germani, M., 2022. Design for environmental sustainability: collect and use company information to design green products. In: Procedia CIRP. Elsevier B.V., pp. 823–828. https://doi.org/10.1016/j.procir.2022.02.136
Ryan, A., 2014. A framework for systemic design. FormAkademisk - forskningstidsskrift for design og designdidaktikk 7 (4). https://doi.org/10.7577/formakademisk.787 (Dec.).
Shaharuzaman, M.A., Sapuan, S.M., Mansor, M.R., 2021. Sustainable materials selection: principles and applications. In: Design for Sustainability: Green Materials and Processes. Elsevier, pp. 57–84. https://doi.org/10.1016/B978-0-12-819482-9.00001-0.
Shahbazi, S., Jönbrink, A.K., 2020. Design guidelines to develop circular products: action research on Nordic industry. Sustainability 12 (9), 3679. https://doi.org/10.3390/su12093679 (May).
Sirisalee, P., Parks, G.T., Clarkson, P.J., Ashby, M.F., 2003. A New Approach to Multi-criteria Material Selection In Engineering Design.
Stuart, J.A., Sommerville, R.M., 1998. Materials Selection for Life Cycle Design. In: Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment, pp. 151–158. https://doi.org/10.1109/ISEE.1998.675049. ISEE - 1998 (Cat. No.98CH36145), Oak Brook, IL, USA, 1998.
Sudheshwar, A., et al., 2024. Learning from Safe-by-Design for Safe-and-Sustainable-by-Design: mapping the current landscape of Safe-by-Design reviews, case studies, and frameworks. Environ. Int. 183. https://doi.org/10.1016/j.envint.2023.108305 (Jan.).
Taramsari, H.B., Hoffenson, S., Nilchiani, R., 2025. Holistic sustainable design: incorporating change propagation and triple bottom line sustainability. Sustainability (Switzerland) 17 (5). https://doi.org/10.3390/su17052274 (Mar.).
van de Poel, I., Robaey, Z., 2017. Safe-by-design: from safety to responsibility. Nanoethics 11 (3), 297–306. https://doi.org/10.1007/s11569-017-0301-x (Dec.).
Van Kesteren, I., De Bruijn, S., Stappers, P.J., 2008. Evaluation of materials selection activities in user-centred design projects. J. Eng. Des. 19 (5), 417–429. https://doi.org/10.1080/09544820701716248 (Oct.).
Vogtländer, J.G., Brezet, H.C., Hendriks, C.F., 2001. The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. Int J LCA 6, 157–166. https://doi.org/10.1007/BF02978734.
Wang, W., et al., 2021. Scheme selection of design for disassembly (DFD) based on sustainability: a novel hybrid of interval 2-tuple linguistic intuitionistic fuzzy numbers and regret theory. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.124724 (Jan.).
Wever, R., Vogtländer, J., 2014. Design for the value of sustainability. In: Handbook of Ethics, Values, and Technological Design. Springer Netherlands, pp. 1–31. https://doi.org/10.1007/978-94-007-6994-6_20-1.
Yang, S.S., Ong, S.K., Nee, A.Y.C., 2016. A decision support tool for product design for remanufacturing. In: Procedia CIRP. Elsevier B.V., pp. 144–149. https://doi.org/10.1016/j.procir.2016.01.085
Zarandi, M.H.F., Mansour, S., Hosseinijou, S.A., Avazbeigi, M., 2011. A material selection methodology and expert system for sustainable product design. Int. J. Adv. Manuf. Technol. 57 (9–12), 885–903. https://doi.org/10.1007/S00170-011-3362-Y (Dec.).