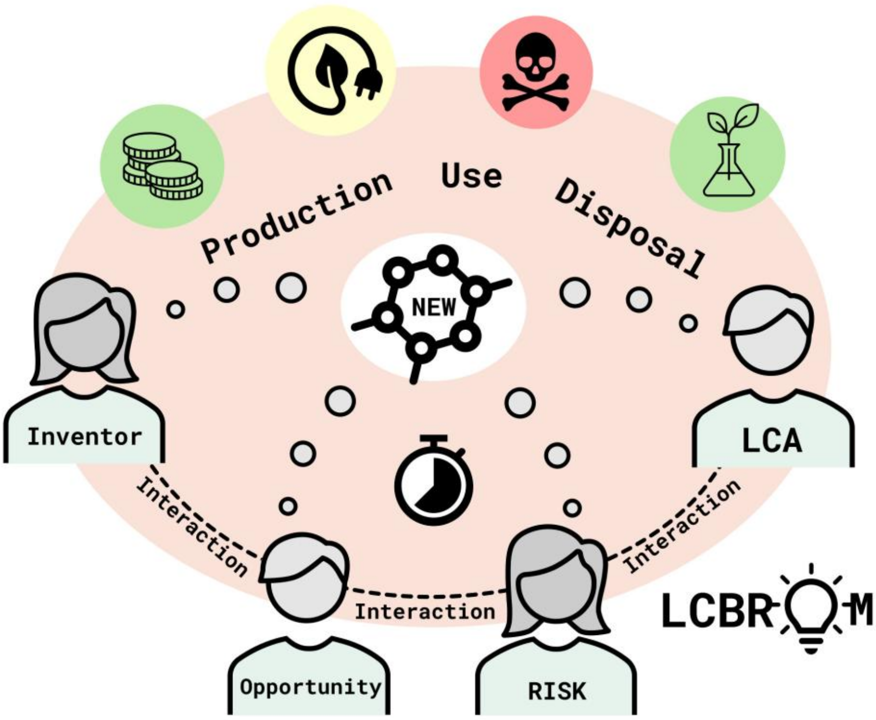
Life Cycle Based Risk and Opportunity Mapping: A systematic collaborative procedure to integrate environmental and health aspects in early innovation as possible pre-screening to the safe and sustainable by design assessments[1]

Authors: Kärnman T.[a], Schellenberger, S.[b], Gottfridsson, M.[a], Halling, M.[a], Johansson, K.[a], Rydberg, T.[a] and Hildenbrand, J.[b]

a: IVL Swedish environmental research institute; b: RISE Research Institutes of Sweden

GRAPHICAL ABSTRACT



Key words: Safe and sustainable early innovations, Safe and Sustainable by Design (SSbD) pre-assessment, Hotspot analysis, LCA dialogue.; Sustainable innovation; Life cycle-based opportunity mapping; Life cycle thinking;

Abstract

In this article we introduce a method to be used for life cycle-based assessment in early innovation to fill the gap of tools for assessing emerging technologies. The approach is intended to support innovation processes for clean technology. Thus, it needs to facilitate a dialogue and encourage innovators to share uncertain information. Such information could

[1] Title based on a presentation to be held at the SETAC Europe 35th Annual Meeting.

potentially hamper the development process if conclusions are drawn based on concepts before scale-up. For the required flexibility and transparency, we propose a series of direct exchanges and preliminary evaluations. The Chemicals Strategy for Sustainability, outlined to implement the European Green Deal, calls for the transition towards use of safe and sustainable chemicals, hence the Joint Research Center (JRC) published a framework for Safe and Sustainable by Design (SSbD) chemicals and materials. Among the key features of the framework is the application for early-stage developments of innovations, during which the outcome can be influenced, and parameters are not fully decided. The method proposed in this publication, life cycle-based risk and opportunity mapping (LCBROM), may be used both prior an SSbD assessment to facilitate its scoping process, as well as during an SSbD procedure. An LCBROM intends to bring together knowledge and requirements from different stakeholders in an innovation process and has been applied in four case studies within the area of clean technology. By applying the method we have realized that i) opportunity mapping is key for good involvement of the innovation owner but can only be performed if there is a suitable benchmark technology as reference or the consequences of inaction can be defined, ii) Several methods exist that in theory could be applied for assessing emerging technologies, although none seems to be commonly used, and iii) LCBROM has the potential to fulfill four criteria that we see as crucial for tools intended for assessing innovations at low TRL. A major benefit of the mapping approach is the increased transparency and communication between technology developer, problem owner and assessment experts. Such communication guides the process and allows for understanding of each other's questions and feedback. LCBROM will be further improved and tested in the EU funded research programme BioSusTex.

Introduction

In 2020, the European Commission (EC) presented the Chemicals Strategy for Sustainability as a response to the European Green Deal (European Commission, 2020). The strategy calls for the transition towards use of safe and sustainable chemicals, hence the Joint Research Center (JRC) published a framework for Safe and Sustainable by Design (SSbD) chemicals and materials (Caldeira et al., 2022). It defines criteria and evaluation procedures for chemicals and materials.

The first part of the EC SSbD framework, hereafter referred to as the SSbD framework, considers the (re)design of chemicals and materials. The framework presents a (non-exhaustive) list of design principles to consider during the (re)design (Caldeira et al., 2022). In early innovation, there may be challenges in addressing all those design principles due to lack of data and other causes. Having a life cycle-based tool for assessing the innovation against these principles would make the transition towards SSbD materials smoother for the industry. As a response for that need, we suggest the use of Life Cycle-based Risk and Opportunity Mapping (LCBROM), conceptually illustrated in Figure 1.

LCBROM is a mostly qualitative screening approach to investigate potential risks as "red flags" and "critical hot spots" in early innovation by considering all life cycle stages (material sourcing, production, use, and disposal). When a benchmark technology with known risks and shortcomings is available, advantages of the innovation can be highlighted as opportunities. The goal of LCBROM is to analyze concerns and opportunities for innovations at low technology readiness levels (TRL) to guide it towards a more sustainable solution. Where quantitative results from other studies are available in a suitable format (e.g., from previous life cycle assessment of related materials or processes) they should be considered. For some substances complementary hazard and risk assessments may be performed to better understand results related to toxicity impacts. Transferable results from completed LCBROM studies should be stored as modules in a repository for further use in other application contexts.

The second part of the SSbD framework covers safety and sustainability assessment of the chemical/material and consists of five assessment steps (the fifth being voluntary). Before initiating an extensive SSbD assessment it is beneficial to clarify its scope. To facilitate this, LCBROM can serve as a starting point for exploring the entire life cycle of the innovation (the innovation being a chemical, process, material or article). Throughout this process, the innovation is assessed qualitatively and where possible, quantitatively against human- and environmental risks and opportunities in different life cycle steps. During the LCBROM assessment, the technology developer gains insight into how their innovation affect humans and the environment across different life cycle phases by identifying key hotspots. For this to be effective, the safety and sustainability expert leading the assessment must develop an understanding of the function of the innovation, how it is integrated into a product system or process application, as well as its production, use, and disposal scenarios. The purpose of the LCBROM is not to replace any quantitative assessment, but rather to pinpoint potential hotspot for upcoming assessments by identifying knowledge and information gaps. Consequently, parts of the life cycle for which available information is sufficient to indicate low or negligible negative impacts on human and/or environmental health and safety can be put on hold.

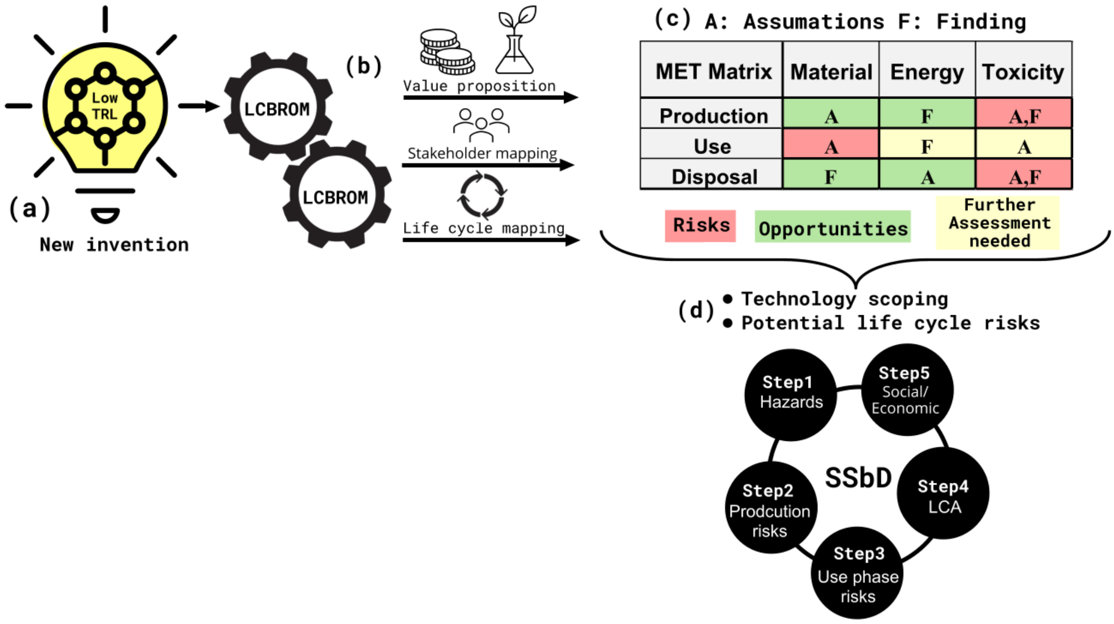


Figure 1. The LCBROM methodology to assess (a) early innovations in chemicals, materials, or processes. The (b) collaborative LCBROM assessment includes a value proposition for the new invention, a mapping of relevant stakeholders for further assessment, and a life cycle mapping of the process or product system. Risks and opportunities at all life cycle stages are systematically analyzed and summarized in a (c) Material, Energy, and Toxicity (MET) matrix. This methodology serves as a (d) pre-assessment for SSbD, supporting technology scoping and identifying potential hotspots for life cycle risks in early innovations.

Long before the EC launched the SSbD framework, Lang-Koetz et al. (2008) (among others) recognized the need for environmental assessments of product ideas and concepts in early innovation, and how this could be done by applying life-cycle thinking and integrating environmental assessment into the innovation process. In our work, we have built upon the research questions explored by Lang-Koetz et al. (2008) while also incorporating opportunity mapping, which we recognize as a powerful driver for decision-makers. Moreover, the discussion of opportunities in terms of value proposition of the innovation can strengthen the engagement of technology developers. This approach fosters greater involvement in the assessment, which may be lower if the focus is solely on risks and environmental concerns. Hence, our research explored the question: ***How can risks and opportunities of innovations be assessed at low TRL?***

In this article we introduce a method to be used for life cycle-based assessment in early innovation to fill the gap of tools for assessing emerging technologies. To test out the method, it has been applied in four case studies in the research programme Mistra TerraClean: i) Development of a technology to concentrate rare earth elements (REEs) from water from a discontinued mine; ii) Application of iron sulphide doped activated carbon to remove mercury from a side stream in an enrichment plant; iii) Chemical modification of PEX material to prevent unwanted bacterial growth in the distribution of drinking water; iv) Removal of CO_2 from indoor air with filters based on cellulose nano fibrils and activated carbon. All the technologies from the case studies were at low TRL when the technology concept and application was formulated. The first of the described case studies will be used as an example in this article. All applications in the case studies are related to material and device development to smartly treat emissions to water and air from current processes and to treat contaminated areas while recovering resources.

Methodology

<u>The structured development of LCBROM</u>

This article highlights the absence of tools that can assess human- and environmental impact of emerging technologies in an easy, comprehensive, and cost-efficient way. We address this issue by presenting a method that can serve as a tool fulfilling these requirements. While doing so, we also present the structural procedure for our method development, which has been inspired by the development of the Circular Strategies Scanner (Blomsma et al., 2019) which in turn was developed using the Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009).

We initiated the method development during fall 2022. To describe its development journey, we have chosen to divide it into three phases, all containing of a descriptive study and a prescriptive study. Table 1 describes the aim, main activities, and outcome of each study.

Table 1. The structured development of LCBROM divided into three phases, all of which containing a descriptive study and a prescriptive study.

Phase I	
Descriptive study I	
Aim:	Apply a methodological procedure for the evaluation of the

	most important environmental and human health aspects of material production, application, post-consumer fate and management in early innovation using a MET matrix or similar eco-design tool to obtain a life cycle-based risk mapping.
Main activities:	Unstructured dialogues were initiated with technology- and problem owners to identify the function of the innovation and the best approach for identifying potential human- and environmental impact of the innovation.
Outcome:	Realization that a structured framework and well thought questions is needed to facilitate communication.
Prescriptive study I	
Aim:	Develop a structured method for mapping human- and/or environmental risks of emerging technologies using a life cycle thinking.
Main activities:	Internal discussions on what aspects to include, how to facilitate communication with non-experts, how to ensure that no aspect is overlooked, and how to formalize the procedure.
Outcome:	The concept of life cycle-based risk mapping (LCBRM) was developed in which the MET matrix was in focus. Questionnaires (Q1 and Q2) to be used as basis for discussion topics on stakeholder meetings was developed.
Phase II	
Descriptive study II	
Aim:	Test out the first version of the method.
Main activities:	Introduced the MET matrix and questionnaires to the technology- and problem owners.
Outcome:	Realization that technology owners may not be willing to discuss risks of their innovation unless also opportunities is presented as a counterpart.
Prescriptive study II	
Aim:	To refine the framework based on the outcome of the feedback received from technology- and problem owners.
Main activities:	Internal discussions on how to improve to method.
Outcome:	By adding focus on opportunities LCBRM method was transformed into LCBROM.
Phase III	
Descriptive study III	
Aim:	Test out the improved method in four case studies and concretize its applicability domain.
Main activities:	Continued meetings with stakeholders in various case studies.
	Structuralized documentation of the method development itself as well as a description of its approach and possible uses.
	Poster presentation of LCBROM at SETAC LCA symposium 2024.
Outcome:	The developed LCBROMs in the case studies was presented to the steering group of the research programme at which feedback was obtained. Hence, the iterative nature of the method could be tested.
	The method was formally described in case study reports.

	Dissemination of the method via the SETAC LCA symposium 2024.
	Realization that the method has great potential to be used in the SSbD framework outlined by the EC.
Planned prescriptive study III	
Aim	Identify further improvement of the method as well as dissemination of the method.
Main activities:	Application of LCBROM in at least three case studies in BioSusTex, an EU funded research programme that will implement the SSbD as outlined by the EC. To be initiated during spring 2025.
	Platform presentation of the method at the 35th SETAC Europe Annual Meeting in May 2025.
	Publishing a scientific article describing LCBROM.
Outcome:	Learnings from the application of LCBROM in BioSusTex.
	Further dissemination of the method via this article and SETAC conference 2025.

The procedure for carrying out an LCBROM assessment

The LCBROM method is an iterative process, illustrated in Figure 2, with continuous interaction between stakeholders to derive at potential risks and opportunities of the innovation. It is recommended to have the MET matrix in mind throughout the whole assessment. To guide the LCBROM practitioner, a non-exhaustive list of questions to keep in mind during the assessment is presented in Table S1 in the Supplementary Information.

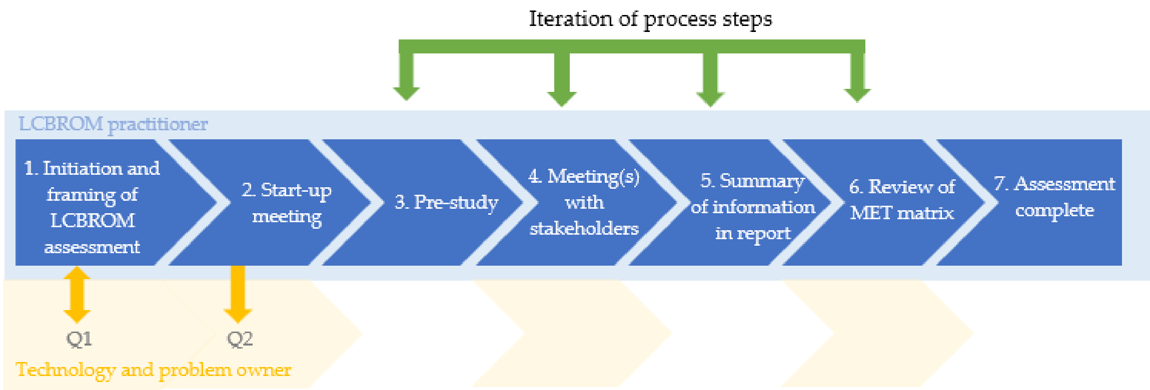


Figure 2. Flowchart describing the steps of the LCBROM method. The arrows represent the iterative nature of the process. Q1 and Q2 indicate questionnaires that may be used in step 1 and 2 for early information gathering, both being presented in Table S2 in the Supplementary Information.

Initiation and framing of LCBROM assessment

An LCBROM is ideally initiated once there is a distinct application for the innovation and laboratory experiments show positive results. The first step for the LCBROM practitioner (often someone with an LCA background, not necessarily involved in material development) is to perform an initial stakeholder mapping. As there are several stakeholders involved with different expertise and goals, stakeholder mapping is an essential part of the LCBROM method to ensure that the LCBROM practitioner has the possibility to access the right information and data needed to perform a useful assessment. The core team in the LCBROM assessment could be rather small in the beginning, for example a three-person team with competences in LCA, risk assessment, and technology systems, and successively expanded during the course of the assessment. The stakeholder mapping facilitates this expansion of the LCBROM team.

Specifically, a three-person team is recommended in which competences of LCA, risk assessment, and technology systems are required.

Once the stakeholder mapping is completed, an information meeting is recommended at which the LCBROM method can be presented. During such a meeting, we suggest that the strengths and limitations of LCBROM is discussed to ensure reasonable expectations of the upcoming assessment, both in terms of actual result but also what will be required from each stakeholder.

After the information meeting, a questionnaire (Q1) may be sent to the identified stakeholders. The purpose of Q1 is to document the problem definition including a background describing a specific case, benchmark technologies (if any) and stakeholders involved in the case. Note that the purpose of the questionnaire is to support the LCBROM practitioner in what information is needed at the start of the LCBROM assessment. Depending on the dynamics of a working group (e.g., technology owner, problem owner and LCBROM practitioner), an approach without questionnaires may be applied to populate the MET matrix, for example using documentation from dialogues or workshops.

<u>Start-up meeting</u>

The purpose of the start-up meeting is to get started with the LCBROM assessment. The following topics may be discussed.

- Introduction of the LCBROM purpose and method
- Problem definition
- Introduction of the technology/material and the intended application
- Discussion on benchmark technologies
- Discuss any uncertainties regarding Q1 (if relevant)
- The need for a non-disclosure agreement

The purpose of the meeting(s) with stakeholders in the assessment is to populate the MET matrix. Moreover, the meetings provide an opportunity to initiate a dialogue among stakeholders about technological developments and the associated cycle-based risks and opportunities. The workshop allows participants to learn from one another and to establish a common ground and a trusting atmosphere where ideas and information can be freely shared. To simplify that process, a second questionnaire (Q2) may be sent after the start-up meeting to allow the technology owner and problem owner to reflect upon the technology from a material, energy, and toxicity perspective. For that reason, the questions in Q2 may be briefly discussed at the end of the start-up meeting. The questions in Q2 lie the foundation for the agenda of the upcoming meeting(s), hence no answers to Q2 are expected beforehand.

Pre-study

At this step, the LCBROM practitioner is supposed to initiate a literature review scanning the availability of existing studies of the benchmark technology. Such studies could for example be LCAs and/or risk assessments. The answers added to Q1 may serve as key words for this literature review. Depending on whether (impact assessment) methods are up to date and described transparently, this can either be used immediately or replicated to fill in data in the matrix.

The pre-study also includes documentation of the problem definition into the report template. Potential usage(s) of the material should be described to facilitate a life cycle perspective of the assessment. If there are no specific use cases for which the material is being developed, it is recommended to define an assumed case to assess the full life cycle and identify opportunities. Benchmarks should be at least state of the art, meaning that the technology to which the innovation is being compared with should be the most advanced and sophisticated alternative currently available.

Meeting(s) with stakeholders

As the LCBROM procedure is iterative, several meetings are likely needed during the process. The stakeholders and LCBROM practitioner should discuss the questions in Q2 and fill in an MET matrix. When answering the questions both risks and opportunities should be considered. If any risk mitigation measures are planned this should also be described. Knowledge gaps identified during the discussion should end up as action points for further work by either the LCBROM practitioner, material developer, or problem owner to reduce uncertainties of the assessment.

Summary of information in a report

The report template for the LCBROM is continuously updated throughout the entire process. Towards the end of the assessment, the LCBROM practitioner is supposed to refine the information already added to the template and wrap up the assessment using the MET matrix, introduced in Figure 3, and final conclusions and recommendations.

Every cell in the MET matrix combines either material, energy or toxicity related to the life cycle stage, such as material use in production or energy use during disposal. Input added to the matrix should be self-explanatory in that sense that the reader should understand the underlying message without consulting the bulk text.

Depending on whether different aspects are identified as opportunities, risks or areas requiring further investigation, a color coding is suggested (e.g., green, red or yellow, similar to a traffic light) to provide a better overview. Although most information in the MET matrix comes with uncertainties due to low TRL, some may be particularly uncertain and highlighting those with italic font is recommended.

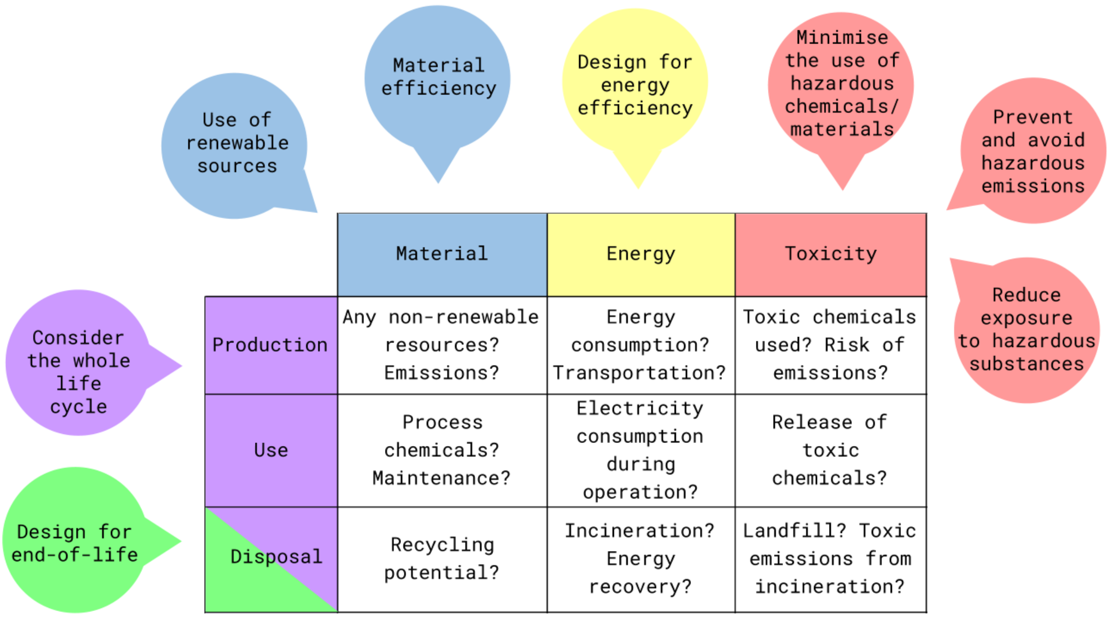
The results from an LCBROM can be used for several purposes, depending on the scope of the assessment. If the objective of the assessment is to guide the innovation towards a more sustainable alternative compared to a benchmark technology, the results may be used for decision-making. If the method is used as a pre-step or part of an SSbD assessment, it is not just the MET matrix itself that represents the main result. Equally important are the lessons learned during the assessment regarding life cycle mapping and system understanding, which may lead to optimization of the new invention (redesign) if negative impacts are identified.

How does the LCBROM method support SSbD assessment for technologies in early innovation?

LCBROM is a tool for early review of the life cycle stages and potential risks and opportunities of an innovation. The integration of human and environmental health evaluations in early innovation of chemicals/materials has been climbing on the agenda for the last couple of years. Not least because of the publication of the SSbD framework by (Caldeira et al., 2022). Even though LCBROM was not originally developed for the sole purpose of SSbD assessments, its usefulness in such assessments is high. Hence, this section exemplifies how the method can support SSbD assessments.

<u>The (re)design phase</u>

As illustrated by Moniruzzaman Moni et al. (2019), improvements made during the design phase potentially have a larger impact on the environmental performance than improvements implemented at higher TRL when many decisions are already established. LCBROM allows the innovation to be successively improved using a systematic MET matrix[2] as a tool to evaluate completeness and balance of information. Applying the SSbD design principles into the MET matrix facilitates the evaluation of the (re)designed material against Material, Energy and Toxicity using a life cycle perspective at an early stage. The connection between the MET matrix and the eight (non-exhaustive) SSbD design principles are illustrated in Figure 3.



[2] References indicates a report by can Hemel and Brezet ("A Promising Approach to Sustainable Production and Consumption") as origin to the MET matrix, although it is now out of print.

Figure 3. SSbD design principles (colored bubbles) connection to the MET matrix used in LCBROM.

<u>The safety and sustainability assessment</u>

Step 1 – Hazard assessment of chemicals/materials

The starting point for an SSbD assessment according to the SSbD framework is to investigate the intrinsic hazard of the chemical/material being developed. Even though the LCBROM method does not serve as a tool itself to assess the intrinsic hazard of the chemical/material, it allows the technology developer to start thinking of the innovation in terms of toxicity early on as the toxicity aspect is a cornerstone of the LCBROM method. Depending on the working group and resources available, one can apply toxicity assessments as a support for exploring the toxicity aspects of the MET matrix. This has been tested in a couple of case studies, one of which being introduced for illustration in this paper.

Step 2 – Human health and safety aspects in the chemical/material production and processing phase

The life cycle perspective, more specifically cradle-to-gate (gate being the production and processing phase), is introduced in step 2 of the SSbD framework. Having performed an LCBROM prior to the SSbD assessment would result in a smoother transition toward expanding the scope as one moves from step 1 to 2 since the life cycle would already have been mapped and the supply chain is identified. Occupational hazards in a preliminary supply chain can thus be identified. As the purpose of LCBROM is not to deliver a quantitative assessment, it is not intended to replace any assessments in step 2. However, it may pinpoint hotspots to separate those areas of the life cycle that may require further attention from those that may require less attention in the qualitative assessment. Requirements for protective equipment and prevention through layout (encasing processes and logistic) can be identified and discussed with the technology developer.

Step 3 – Human health and environmental aspects in the final application phase

The third step of the SSbD framework is focusing on human health and environmental aspects in the final application phase of the innovation**.** Mapping potential risks and opportunities of the use phase is included in the LCBROM method and could potentially serve as a starting point for the quantitative assessments in this step.

The innovations considered in the four case studies (introduced earlier in this article) were mostly applied by professional users. From a toxicity perspective, it is important to establish whether the innovation is intended for consumers and/or professionals. Consumers are likely not trained to use personal protection equipment (PPE) while professionals do, meaning that the risk of exposure may be higher for consumers than professionals.

Assessing the innovation against energy consumption during different life cycle stages is an important part of the LCBROM assessment. In the use phase, energy consumption can be related to climate change and pollution if fossil energy carriers are used.

Step 4 – Environmental sustainability assessment

The core of the fourth step is life cycle assessment (LCA) following the procedure suggested for product environmental footprints, which poses a challenge for materials in early innovation (i.e., those at low TRL). Challenges associated with LCA in early innovation was pointed out by Hetherington et al. (2014). For example, the challenge of future unknown features and data gaps was discussed. There may be data gaps considering different life cycle stages, upscaling parameters and emissions. In addition to those challenges pointed out by Hetherington et al. (2014), it is very costly to perform a full LCA, both in terms of effort and money. Hence, there is a need for life cycle-based tools for assessing innovations at low TRL, which was also pointed out by Moniruzzaman Moni et al. (2019). Data that are available for benchmark processes may be aggregated and thus representative for average industry processes, but not suitable to guide development of innovations and identify relevant parameters.

Challenges of performing an LCA at low TRL (<5) was also pointed out in the SSbD framework. To overcome such challenges, the framework suggests the use of Prospective LCA. Although there are challenges in performing prospective LCAs as well, there are several frameworks, e.g., Picchino et al. (2016), Buyle et al. (2019) and Thonemann et al. (2020), that can guide the LCA practitioner in performing such assessments. However, we would argue that the use of prospective LCA would benefit from the application of an LCBROM in advance. For example, applying LCBROM at TRL 1-2 would allow the LCA practitioner to map the life cycle and understand what type of challenges he or she may face during the upcoming assessment once the technology reaches TRL 3-5. Additionally, the SSbD framework calls for the application of LCA for all uses and production routes of the innovation. Performing an (prospective) LCA for all those scenarios will be costly and time consuming. Having applied LCBROM in advance would enable the LCA practitioners to gain an understanding on which are the most likely areas of concerns and hence require extra effort in estimating its input parameters.

Applying the SSbD concept in early innovations requires tools and methods that are adapted to low data availability and high uncertainty. Except for prospective LCA, there are no such methods communicated in the SSbD framework or its guidance for the life cycle-based assessment. Some tools exist (or are under development), for example the screening level approach developed by Pizzol et al. (2023) that specifically addresses multi-component nanomaterials. It uses extensive questionnaires that may be difficult for technology developers to answer, hence expert input may be required. Another example of an existing tool is the Environmentally responsible product assessment matrix developed by Graedel et al. (1995). Although there are existing tools, none seem to capture all necessary ingredients for being *the commonly applied* tool for emerging technologies: i) easy-to-use, ii) inclusion of all relevant impacts, iii) wide applicability domain, and iv) low cost in terms of time and money. We would argue that LCBROM could potentially fill that gap of tools because of its iterative nature and use of general questions that can be applied to most technology fields.

As already pointed out, there are not enough data to perform full LCAs at low TRL. Instead, LCBROM can be used to map out relevant life cycle stages and identify potential risks that the material may face during upscaling. Additionally, if there is a benchmark technology available on the market, it can also identify potential opportunities for the innovation based on known shortcomings of the benchmark technology. Identifying such risks and opportunities will help to avoid lock-in to unsustainable decisions and to continuously improve the material. As the material reaches higher TRL and more data becomes available, the LCBROM can be further refined. Eventually, there will be enough information on the innovation to perform a first, rough, LCA and finally a full LCA. Hence, LCBROM could serve as a starting tool for the life cycle-based assessment required in step 4 of the SSbD framework for materials in early innovation.

Step 5 – Scientific basis for the socio-economic sustainability assessment

A fifth step is available in the SSbD framework, focusing on socio-economic assessments. Even though methods exist, such as life cycle costing (LCC) and social life cycle assessment (S-LCA), for the purpose of this type of assessment, the framework is pointing out that it requires further work to ensure its applicability. Hence, this step is voluntary. Despite that, we foresee this step to be mandatory in the future, which is why we have initiated discussions on how to incorporate social and economic factors into the LCBROM assessment. This is, however, out of scope of this article.

Case study results

LCBROM has been applied in four case studies, one of which is focusing on the development of a technology used to concentrate REEs from water from a discontinued mine using a hollow fibre liquid supported membrane (HFSLM). Its life cycle is being described in Figure 4 consisting of material production via impregnation, use via selective sorption of REE and disposal via incineration and/or recycling. The hypothesis of the work was that a REE solution can be concentrated by selective separation of REE. To further improve the technology, an LCBROM was performed to identify potential risks and opportunities.

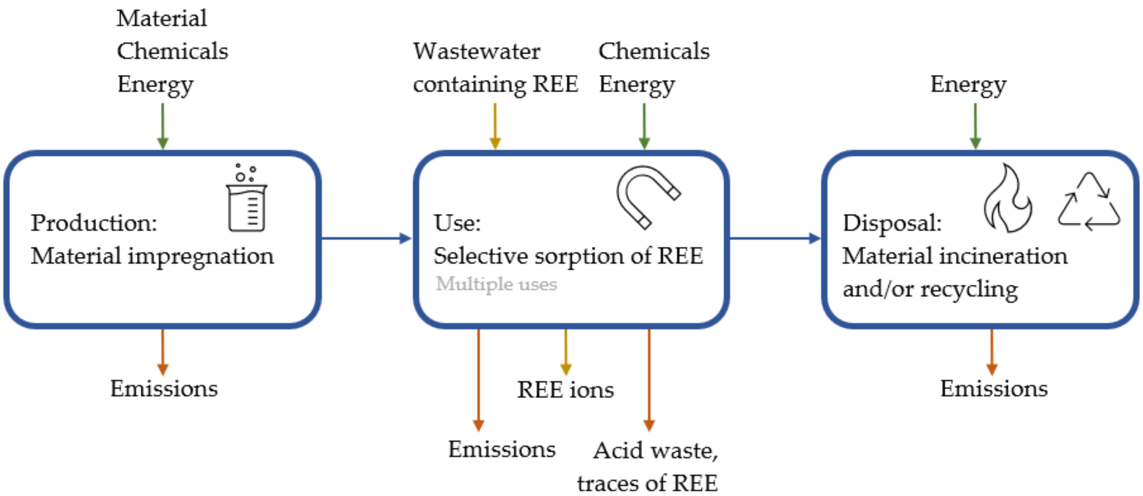


Figure 4. Life cycle description of the technology used for retrieving REE from wastewater from discontinued mines.

During the pre-study it became clear that solvent extraction (SX) in mixer settlers was the benchmark technology to be used for identifying opportunities (Turgeon et al., 2023). For that purpose, a literature review was performed to identify the major challenges that SX faces from an environmental point of view.

The first significant finding, also identified by Navarro & Zhao (2014), was that there are very few LCAs (or other articles focusing on the environmental impacts) of REE production and specifically the solvent extraction step. In fact, we only found two articles focusing on the solvent extraction phase (Vahidi & Zhao, 2016, 2017).

This was somewhat surprising as the second finding was that the main contributor to the overall environmental impact in REE production seems to be the solvent extraction step (approximately 30% according to Vahidi & Zhao (2017)). It should, however, be noted that most articles highlight that there are, in general, very few LCAs on REE production in combination with poor data quality and information (Schreiber et al., 2021).

The use of hydrochloric acid (HCl) in SX was identified as a challenge since it is being used in high quantities which generates a significant environmental impact (Vahidi & Zhao, 2016, 2017). For that reason, using lower amounts of HCl, or no such use at all, was highlighted as an opportunity for the novel technology. On the other hand, both alternatives, the benchmark technology and the proposed new extraction method, are using kerosene which is a petroleum-extracted mixture of aliphatic and aromatic hydrocarbons, cycloalkanes and alkylbenzenes with varying structures and toxicities. As such, there is high uncertainty in establishing safety risks with this mixture since various compounds in the mixture are more toxic than others. Many of the potential components of kerosene are known to be mutagenic and reproductive toxic as well as highly toxic to various organs. Due to its toxicity, the use of kerosene was marked as a risk in the MET matrix. Table 2 provides a simplified MET matrix from the case study, anonymized to avoid disclosure of confidential information.

Table 2. Overview of a simplified MET matrix from a case study in Mistra TerraClean. Colour-code: green = opportunities, red = risks, yellow = further research is needed. Findings and assumptions are denoted F and A respectively.

	Materials	**Energy**	**Toxicity**
Production	F: Possibly use of recycled and/or renewable polypropylene and polyethylene in the HFSLM.	F: Perhaps not a significantly energy intense production process of the membrane.	A: Production of solvents and extractants may release toxic emissions.
Use	F: Upscaling is difficult because of gel formation which occurs at sub-optimal operating conditions.	F: Possibly less energy intense than the current? state-of-the-art technology.	F: Less hazardous extractants needed. F: Use of kerosene.
Disposal	F: Hazardous waste containing acids must be handled.	F: The HFSLM is likely to be incinerated.	A: Waste may contain traces of metals.

Once the first draft of the MET matrix was delivered to the technology owner, it was presented for the steering group of the research programme, which brought in an early-stage peer evaluation. Based on feedback from that presentation and the content of the MET matrix, the iterative nature of LCBROM was tested. The findings of the LCBROM were refined and the technology owners decided to investigate the possibility to substitute kerosene. That was firstly done via a toxicity assessment in which the hazards of kerosene were mapped. Secondly, a literature review was performed in which it was found that alternatives for kerosene are available. Since the research programme is coming to an end, there was not enough time or budget to follow the innovation towards higher TRL and refining the LCBROM further. Despite that, the LCBROM did show its potential in identifying risks and opportunities to steer the innovation towards a more sustainable alternative.

Discussion

Using a matrix to summarize learnings from a life cycle-based assessment has been done since 1995 when Graedel et al. (1995) introduced a 5x5 matrix called the Environmentally Responsible Product Assessment Matrix. In that matrix, an innovation is assessed against material choice, energy use, solid residues, liquid residues, and gaseous residues using a life cycle perspective. The assessment is qualitative in its nature in which expert input, surveys and checklists are used to derive a figure of merit for the innovation. LCBROM is a modernized version of this tool with some commonalities and some differences. An important difference is that the tool by Graedel et al. (1995) used a grading system for a deriving single score to be used for tracking improvements. As LCBROM is intended to be used for hotspot identification for a various number of technology types, a scoring system has not been deemed necessary at this point.

Another distinctive difference between LCBROM and the Environmentally Responsible Product Assessment Matrix is the possibility to identify opportunities. To ensure that the innovation ends up with lower human and environmental impact than the state-of-the-art technology, the opportunity mapping is as important as the risk mapping. As the LCBROM is intended to be used in early innovation, the developer has the chance to fine tune the innovation regarding its production process, usage and/or future waste treatment in terms of material, energy and/or chemical choices. For that reason, LCBROM requires a reference technology to be able to identify opportunities. If no reference can be established, the comparison should be made against a scenario at which no action at all is made.

Several other tools have been suggested throughout the years in addition to the 5x5 matrix by Graedel et al (1995). An example of such a tool is the concept of Material Input Per Service (MIPS) unit developed at the Wuppertal Institute (Ritthof et al., 2023). MIPS consider predominantly resource use and assume that this correlates to potential emissions. Detailed evaluation of different types of contaminants and the severity of their effects are beyond the scope. Other examples are the Life-Cycle e-Valuation by Lang-Koetz et al (2008) and the Environmental Effect Analysis (EEA) by Lindahl & Tingström (2001). We see several similarities among these approaches and LCBROM, for example, the qualitative life cycle-based questions that identify pathways for a more sustainable innovation. Additionally, the EEA framework explicitly states that the assessment is designed to be carried out in a multifunctional team, which aligns with LCBROM in that sense that a small team of experts is recommended to be involved. Specifically, a three-person team is recommended in which competences of LCA, risk assessment, and technology systems are required.

The main characteristic that distinguishes LCBROM from other qualitative and/or semi-qualitative life cycle-based assessment tools is the O in LCBROM, i.e., the mapping of opportunities. We have found that the inclusion of opportunities in the assessments open up the interest of the problem- and technology owners to put resources on performing human health- and environmental assessments in early innovation. With an opportunity mapping, one can not only reduce the obvious hot spots of the innovation but also identify no-goes that the benchmark technology has been locked into. Additionally, it allows for identification of multiple uses of the innovation and/or prolonged life cycle of material within the technology. Another characteristic that distinguishes LCBROM from other approaches is that its result is presented in an easy-to-understand format using a MET matrix. That facilitates a quick and transparent result communication to decision-makers and other experts, which also allows for further improvements via iterations through quick feedback routes. The latter has been tested in a couple of case studies with a positive response.

During the development of the method and its application in case studies, it became clear that the formalized stepwise approach and defined input information facilitated the execution of the method. The MET matrix is intuitive and easy to understand, which is important as there is a strong need for tools that can be used by small and medium-sized enterprises (SMEs). Although SMEs may not have the resources and/or competence to carry out an LCBROM themselves, SMEs possess a technological expertise that is essential in the execution of an LCBROM.

A well-thought-out and defined working group is crucial to obtain a successful LCBROM as there must be a common understanding and driving force for performing the assessment as well as the possibility to get access to the right information. A common understanding of the strengths and limitations of LCBROM is important to establish early on. Additionally, to derive at a successful LCBROM, non-disclosure agreements may have to be signed. If no such agreement is signed, it can be difficult to identify risks and opportunities if there is resistance in sharing sensitive information. However, if non-disclosure agreements are signed, it may be difficult to publish the results from the assessment, which ultimately may hinder further development of the method itself. To solve such an issue, the LCBROM practitioners are recommended to carry out the assessment as far as possible using the shared information and present the result to the technology- and problem owner. While doing so, it is important that the result is communicated in a way that clearly points at the relation between uncertainty and data gaps. It should also be explained that more reliable results will come with more transparent information sharing.

Further work

Although the concept of MET matrix is old, the use of it in combination with a life cycle-thinking for the purpose of assessing innovations at low TRL is new. For that reason, the LCBROM method has several areas for improvements, and some are planned to be tested shortly. An example of such an improvement is the expansion of the MET matrix into a METES matrix: Material, Energy, Toxicity, Economy and Social aspects. Even though the socio-economic assessment is marked as optional in the SSbD framework (step 5), it is of interest to test out LCBROM for that purpose as well since the tools does not necessarily have to be used in an SSbD context.

As many other environmental assessments, it is tricky to summarize the result in a way that is easy to communicate. As of now, the documented result of an LCBROM is the MET matrix. To facilitate communication, the information written in the matrix must be self-explanatory in that sense that the reader should not have to consult the bulk text of the report to understand the results. Alternative ways of presenting the results from an LCBROM assessment must be investigated to further improve its accessibility and understandability for non-experts.

Beyond Mistra TerraClean, the LCBROM method will be revised and tested in the EU funded research programme BioSusTex with a focus on new chemical raw material and process developments for the textile sector (https://www.biosustex.eu/).

Conclusions

In this article we propose a qualitative screening approach that can be used to support SSbD assessments. It may be used both prior an SSbD assessment to facilitate its scoping process, as well as serving valuable input to the two phases (the (re)design phase and the safety and sustainability assessment) of the SSbD framework. Additionally, the tool can be used in the environmental sustainability assessment (step 4) in early innovation when there are not enough data to perform a quantitative LCA.

The method offers a structure that facilitates the identification of the foreseen most relevant issues in a comprehensive manner without having to dig into details. It requires a joint collaboration between a number of different experts and can be applied to most technology fields with relatively low cost in terms of time and money.

LCBROM has been successfully applied in four case studies to materials and technologies that are in the early innovation stage. The main learning from its development and application is the importance of having a state-of-art benchmark and/or a specific case to relate the innovation to for opportunity identification. If no such reference is established, opportunities can only be identified by considering a scenario where no action is made at all.

Acknowledgement

We thank Mistra for financial support in the research programme Mistra TerraClean II (project number 2015/31) and in the programme Mistra SafeChem (project number 18/21). We also thank the European Commission for financial support of the project BioSusTex (No 101135372). We also thank Nilay Elginoz Kanat at IVL Swedish Environmental Research Institute for performing a first external review.

References

Blessing, L. T. M., & Chakrabarti, A. (Eds.). (2009). DRM: A Design Reseach Methodology. In *DRM, a Design Research Methodology* (pp. 13–42). Springer. https://doi.org/10.1007/978-1-84882-587-1_2

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C. A., Hildenbrand, J., Kristinsdottir, A. R., Kristoffersen, E., Shahbazi, S., Nielsen, K. D., Jönbrink, A.-K., Li, J., Wiik, C., & McAloone, T. C. (2019). Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of Cleaner Production*, *241*, 118271. https://doi.org/10.1016/j.jclepro.2019.118271

Buyle, M., Audenaert, A., Billen, P., Boonen, K., & Passel, S. (2019). The Future of Ex-Ante LCA? Lessons Learned and Practical Recommendations. *Sustainability*, *11*, 5456. https://doi.org/10.3390/su11195456

Caldeira, C., Farcal, L., Garmendia, I., Mancini, L., Tosches, D., antonio, amelio, Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). *Safe and Sustainable by Design chemicals and materials Framework for the definition of criteria and evaluation procedure for chemicals and materials* (No. JRC128591). Publications Office of the European Union. https://doi.org/10.2760/487955

European Commission. (2020). *Chemicals Strategy for Sustainability Towards a Toxic-Free Environment*.

Graedel, T. E., Allenby, B. R., & ComrieE, P. R. (1995). Matrix Approaches to Abridged Life Cycle Assessment. *Environmental Science & Technology*, *29*(3), 134A-139A. https://doi.org/10.1021/es00003a751

Hetherington, A. C., Borrion, A. L., Griffiths, O. G., & McManus, M. C. (2014). Use of LCA as a development tool within early research: Challenges and issues across different sectors. *The International Journal of Life Cycle Assessment*, *19*(1), 130–143. https://doi.org/10.1007/s11367-013-0627-8

Lang-Koetz, C., Beucker, S., & Heubach, D. (2008). Estimating Environmental Impact in the Early Stages of the Product Innovation Process. In S. Schaltegger, M. Bennett, R. L. Burritt, & C. Jasch (Eds.), *Environmental Management Accounting for Cleaner Production* (pp. 49–64). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8913-8_3

Lindahl, M., & Tingström, J. (2001). *A small textbook on: Environmental Effect Analysis*. Department of Technology, University of Kalmar, Sweden. https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-87257

Moniruzzaman Moni, S., Mahmud, R., High, K., & Carbajales-Dale, M. (2019). Life cycle assessment of emerging technologies: A review. *Journal of Industrial Ecology*, *2019*. https://doi.org/10.1111/jiec.12965

Navarro, J., & Zhao, F. (2014). Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review. *Frontiers in Energy Research*, *2*. https://doi.org/10.3389/fenrg.2014.00045

Piccinno, F., Hischier, R., Seeger, S., & Som, C. (2016). From laboratory to industrial scale: A scale-up framework for chemical processes in life cycle assessment studies. *Journal of Cleaner Production*, *135*, 1085–1097. https://doi.org/10.1016/j.jclepro.2016.06.164

Pizzol, L., Livieri, A., Salieri, B., Farcal, L., Soeteman-Hernández, L. G., Rauscher, H., Zabeo, A., Blosi, M., Costa, A. L., Peijnenburg, W., Stoycheva, S., Hunt, N., López-Tendero, M. J., Salgado, C., Reinosa, J. J., Fernández, J. F., & Hristozov, D. (2023). Screening level approach to support companies in making safe and sustainable by design decisions at the early stages of innovation. *Cleaner Environmental Systems*, *10*, 100132. https://doi.org/10.1016/j.cesys.2023.100132

Ritthof, M., Rohn, H., Liedtke, C., & Merten, T. (2023, May 30). *Calculating MIPS - Resource productivity of products and services*. Wuppertal Institute for Climate, Environment, Energy. https://wupperinst.org/en/a/wi/a/s/ad/584

Schreiber, A., Marx, J., & Zapp, P. (2021). Life Cycle Assessment studies of rare earths production—Findings from a systematic review. *Science of The Total Environment*, *791*, 148257. https://doi.org/10.1016/j.scitotenv.2021.148257

Thonemann, N., Kerps, A., & Maga, D. (2020). How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. *Sustainability*, *12*, 1192. https://doi.org/10.3390/su12031192

Turgeon, K., Boulanger, J.-F., & Bazin, C. (2023). Simulation of Solvent Extraction Circuits for the Separation of Rare Earth Elements. *Minerals*, *13*(6), Article 6. https://doi.org/10.3390/min13060714

Vahidi, E., & Zhao, F. (2016). Life Cycle Analysis for Solvent Extraction of Rare Earth Elements from Aqueous Solutions. In *Rewas 2016: Towards Materials Resource Sustainability* (pp. 113–120). https://doi.org/10.1002/9781119275039.ch17

Vahidi, E., & Zhao, F. (2017). Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction. *Journal of Environmental Management*, *203*, 255–263. https://doi.org/10.1016/j.jenvman.2017.07.076