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Risk and sustainability: trade-offs and synergies for robust decision making

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Abstract

Decisions about the development of new marketed technologies or products invariably come with consequences for economy, society and the environment. Environmental and health risk assessment on the one hand and sustainability assessment on the other hand are tools that offer different but complementary information about such consequences. Conflicts or synergies between the two tools may arise when there are trade-offs between considerations of specific risks and safety versus long-term sustainability. There is a compelling case for a combined assessment of both sustainability and risks, also in support of a successful safe and sustainable-by-design (SSbD) approach, but this is not straightforward. We offer a roadmap showing when the two assessment tools should be applied together and how to combine them in a consistent way, to support more robust decision-making. Four alternative approaches are evaluated against six performance criteria to recommend an approach that makes use of the broader and more generic sustainability assessment as a baseline and includes iterative applications of risk and sustainability assessment elements to increase specificity, reliability and relevance of the assessment results. The recommended approach provides a basis for better-informed decisions about technology choices for policy and societal stakeholders.

Keywords: Risk assessment, Life cycle assessment, Decision support, Technology development, Optimization

Decisions in context

Risk represents the combined information on the probability and severity of a consequence, and risk assessment is used to guide actions to avoid unacceptable consequences that technological systems may have for human health, the environment, resources, society, and the economy. It is also used proactively in the development of solutions that represent an acceptable level of risk [1], to ensure that the chosen alternative or the developed solution is compliant with existing regulations. The focus of risk assessment is thus typically on activities or events of known or suspected exposure to hazardous agents and associated adverse consequence(s). The causal relationship and the typical focus on selected target populations (e.g., consumers) define the temporal and spatial scope of the risk assessment, ranging from very local (e.g., exposure to consumer products in residential settings) to global scale (e.g., economic risk management). Examples of outcomes range from explicit statements of risk, for instance determining the cancer risk of specific age groups under certain industrial or residential settings [2, 3] to general assessments of confidence about safety based on acceptable risk, such as in the case of drinking water standards [4], air quality standards [5], and food safety [6].

Sustainability, in contrast, concerns the way in which we fulfill human needs and the extent to which technological systems that meet these needs today are compatible with meeting the society's needs and quality standards tomorrow, i.e., whether they represent a practice that can in principle be continued indefinitely without compromising the health, environmental, and/or

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social (or economic) basis for continuing the practice. Sustainability concerns both social/societal and environmental aspects, where the latter are advocated as setting the frame for the overall sustainability due to the importance of our earth's life support systems [7]. Sustainability assessment has a widely encompassing perspective both in terms of spatial and temporal scales. Life Cycle Assessment (LCA) is often used to quantify the environmental sustainability covering the whole life cycle of the technological systems of interest and considering a wide range of environmental impacts. These characteristics enable LCA to reveal any shifts of burden between different environmental problems and between different stages of the life cycle of a considered system. Examples of outcomes range from environmental sustainability performance of individual bulk chemicals [8] or food items [9] at the product level to sustainability implications of e-mobility in individual transport [10] at the level of societal systems.

Assessing risk and sustainability

Assessment of risks and sustainability are important and complementary elements of decision support about system developments involving technology changes that may range from product lines and production systems over food value chains to societal infrastructure. Both are, furthermore, considered core components in the European Green Deal's safe and sustainable-by-design (SSbD) strategy [11].

The current literature includes formalized methods for the assessment of both risks [1, 12, 13] and sustainability [13–16]. Risk assessment and risk management have been internationally standardized in the ISO 31000 series [17], and are formalized for different application fields, e.g., Regulation (EC) 1935/2004 providing a harmonized legal framework setting out the general principles of safety and inertness for food contact materials in the European Union (EU) [18], and Regulation (EC) No 1907/2006 providing the overarching regulatory frame for safety assessment of industrial chemicals not regulated elsewhere [19]. Sustainability comprises three dimensions—environmental, social, and economic sustainability, which have been further detailed by the 17 United Nations' Sustainable Development Goals (SDGs) [20]. Formalized methods are less prevalent but quantitative assessments are often performed for the environmental dimension of sustainability using life cycle assessment (LCA), for which methodology and central applications have been internationally standardized in the ISO 14000 series [21]. Methodologies for assessing, respectively, risk and sustainability have for the most part been developed in separate scientific communities, and the two types of assessments are typically conducted separately and independently. However, many societal decisions and technological developments have consequences both for safety of humans and the environment, and for the long-term sustainability of social and economic systems. Thus, in several contexts there are important trade-offs and synergies between the two that are overlooked due to their separate treatment. Different attempts have been made to combine specific risk and sustainability elements, metrics, results or frameworks [22–28]. However, none of these attempts offers a consistent framework for the combined assessment, and they suffer from inconsistencies with respect to defining system boundaries, aligning input data, considering and aligning uncertainty, or offering a consistent and complementary interpretation of assessment results, (which still leaves important potential trade-offs uncovered).

The case of circular economy

An informative example of problems that can arise when risk and sustainability are evaluated separately is offered by the current European plans for a transformation of the economies of EU Member States towards more Circular Economies [29]. Linear material flows characterize the "use and dispose" strategy that currently dominates consumption and production patterns in Europe and the rest of the industrialized world. In a transition to a Circular Economy, linear flows are turned circular by promoting repair, reuse, refurbishing or recycling of products and materials. Recycling of materials helps to minimize the production of new virgin materials and the waste treatment of the discarded products. This saves use of additional resources and avoids emissions that would accompany these activities. Circularity of the main material flows is thus seen as a prerequisite for a sustainable society as also reflected by specific targets on increased recycling and reuse under the UN SDG concerning consumption and production (SDG 12).

Under the European Action Plan for Circular Economy, polymer materials, for example, have a high priority with a target to recycle 55% of plastic materials in packaging waste by 2025 [30]. A major use of packaging materials is for food packaging, which creates a strong incentive for recycling the largest volume polymers, polyethylene and polypropylene, in food packaging materials. However, when polymer materials are used and reused multiple times in a circular economy, they may accumulate additives from previous uses, such as stabilizers, plasticizers or printing ink components [31]. If a recycled plastic material is used for food packaging, these unintended contaminants may migrate into the packaged food and potentially expose consumers [32]. This type of risks have led the EU to prohibit recycling of plastics into food contact materials apart from a few well-defined closed loop systems for PET bottles [33, 34]. This risk management approach is, not in line with EU's ambitions for circularity and a sustainable use of materials [35]. In a Circular Economy, on the other hand, there is no simple way of tracking which chemicals are present in a polymer material, since it depends on the previous applications and this information is usually lost when the material is recycled. A Circular Economy, which is hence attractive from a resource sustainability perspective, can become unattractive from a human health risk perspective when the sustainability (or LCA) assessment excludes human health as a term of reference. There may thus be a trade-off between improved sustainability from the life cycle of the plastic materials and an increased health risk from their use in food packaging, pointing to the need to combine information from a risk assessment (or health impact assessment) and a resource sustainability assessment to ensure an overall optimization in support of a robust design of Circular Economy systems [36].

Where do conflicts arise between risks and sustainability?

As previously introduced, risk and sustainability differ in both focus and scope. When a decision has elements related to both of them, it is possible that conflicts can arise when decision makers optimize risk or sustainability independently. In some cases, they are aligned with regard to outcomes such that reduction of risk also entails a more sustainable system. In such cases, the recommendation has a much stronger foundation. An example is offered by the case, where managing human health risk of food-borne zoonotic diseases results from efforts to reduce dietary dependence on farm animals through a more vegetable-based diet. This would also entail reduced impacts on the environment through more efficient use of the farmed land for food production [37], hence also improving sustainability. Often, however, risk and sustainability are not aligned as illustrated by the example with increased plastic recycling under a Circular Economy. Another example is genetically modified crops, where the perceived risks of their introduction into the European environment has blocked the potential sustainability gains from, e.g., increased area yields. Yet another example is the treatment of contaminated soils, where the risk for contamination of drinking water or direct human exposure may lead to soil remediation activities entailing excavation and transportation activities with substantial negative sustainability implications [38]. In these cases, conflicts may arise, which can only be addressed by calling for a combined assessment of risk and sustainability to ensure the robustness of decisions and actions by considering both aspects. Combining risk and sustainability can thereby range from the combination of independently obtained results to a full integration of assessment methods. A combined assessment may also qualify the risk assessment by informing about the environmental or social burdens associated with achieving a given level of risk and thus help deciding what is a desirable (i.e., acceptable) level of risk if we take sustainability implications into account. In addition, a sustainability assessment may be useful for identification of potential hot spots in terms of risks along any system's life cycle. This may help focus higher tier risk assessment efforts on those activities that are most relevant to assess in more detail, supporting a more holistic and effective risk management process. Likewise, risk assessments often highlight consequences due to system dynamics that LCA-based sustainability assessment tends to ignore or underestimate, because common LCA practice focuses on typical behaviour of the system rather than the extremes, which could, with some effort, be included.

How can we effectively combine the assessment of risk and sustainability?

It is neither practical nor feasible to combine these complementary assessments through a "brute-force" integration of related data, models and tools applied in the two frameworks [22]. Aims and scopes are quite different and the two approaches should continue to be developed separately by domain experts in their respective communities to ensure the continuous improvement and scientific quality of either approach to answer their specific questions. What we, therefore, propose is a combination, where both assessments are run in parallel but each with an adapted scoping to ensure their consistency in terms of the question that is asked, the assumptions that are made, and the data that is used in the modeling of the relevant systems. In our proposed concept, the systems evaluated by risk and sustainability assessment approaches are fundamentally the same, and risks and sustainability metrics provide two perspectives on the consequences of the decision that is to be made. The assessment focus varies from the whole life cycle of the system (the life cycle perspective applied in sustainability assessment) to specific processes or activities (where the assessment of different risks is concentrated), and from specific impact types such as toxic impacts on human health or ecosystems in health-related risk assessment to a coverage of all relevant impact types in sustainability assessment. Nevertheless, the development of decision alternatives to be assessed, the scoping of the assessments, and the assumptions that are made regarding the consequences of the decision alternatives all need to be aligned in the risk assessment and the sustainability assessment to ensure that their results become compatible. This is essential to allow for the identification

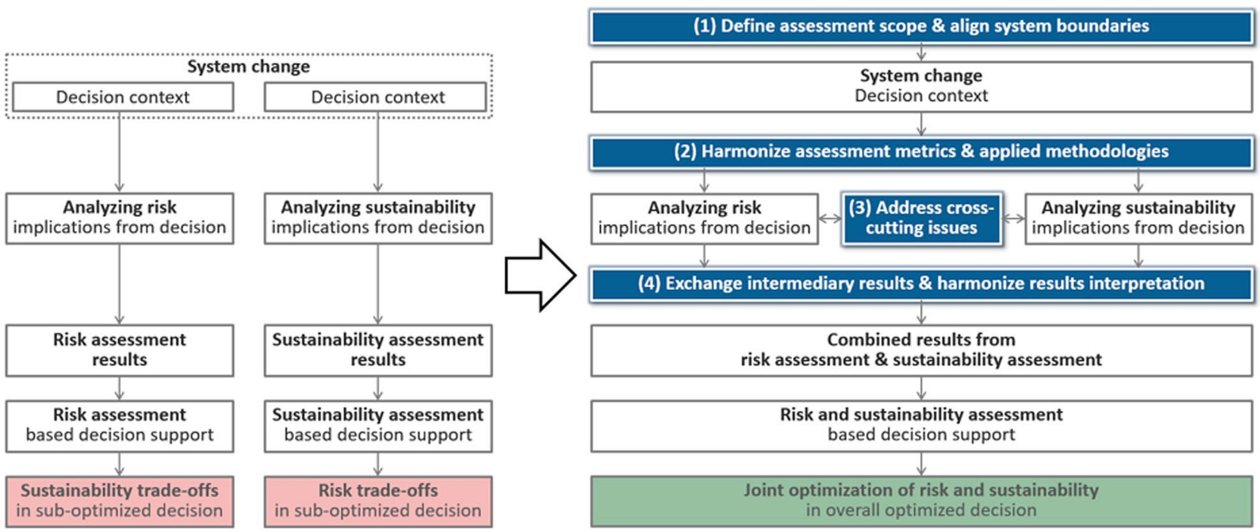

Fig. 1 A shift from decoupled assessments of risks and sustainability for a decision is required to successfully identify and minimize risk-sustainability trade-offs and maximize related synergies for an optimal decision. Four steps of alignment and harmonization are proposed

of trade-offs and synergies between risk minimization and sustainability improvements. Consistent use of data about the assessed systems additionally supports a synergy in sharing of data between the two assessment approaches. Based on these considerations, we propose the following roadmap (see Fig. 1) for an *effective combined assessment of risks and sustainability*, which we have applied to the example of polymer recycling in Box 1.

1. First, *potential risk-sustainability trade-offs and synergies should be identified* (qualitative assessment). If there are no trade-offs, there is no need for combining risk and sustainability assessment. If potential trade-offs are identified, we proceed to a combined and quantitative assessment of risk and sustainability. In the combined approach, the decision context should first be scoped. What is the question asked to the risk assessment, and what is the question asked to the sustainability assessment? Do they concern the same system change? Does the combination of the two perspectives inspire to modify one or both of them – do we ask the right question? Are system boundaries defined consistently for the two assessments so the alternative solutions are relevant to compare?
2. In a second step, the *assessment metrics and the applied methodologies are harmonized* to eliminate unnecessary differences, i.e., differences that are not caused by the fundamental difference in the perspectives and practices of RA and LCA. Risks and sustainability impacts are then quantified using existing methodologies.
3. When performing the analysis, *crosscutting issues are addressed* in a third step to ensure that the two assessments are aligned in terms of building on consistent assumptions.
4. In a fourth step, uncertainties in the results are presented in a way that allows them to be treated consistently in the interpretation of the risk assessment and sustainability assessment results to further support informed decisions. *Intermediate results are interchanged* in this step and iterations may be performed based on this information. Risk assessment and sustainability assessment results are expressed in metrics that make them comparable to allow a combined interpretation of the two. Overall improvement potentials are analysed and recommendations are developed considering both risk and sustainability performance.

Figure 1 illustrates the shift from a decoupled to a combined approach to assess risk and sustainability for a given system.

Box 1: Steps for an effective combined assessment of risks and sustainability applied to an illustrative example of polymer recycling

First step: There is a conflict between the wish to avoid a human health risk from exposure to contaminants in recycled plastics through migration into food and on the other side the sustainability-based ambition to recycle plastic materials to avoid production and wasting of large plastic streams. *Questions for risk assessment*: What is the risk associated with the use of recycled plastics in food contact materials, where do the contaminants come from, and are there ways of avoiding their presence in the recycled plastics? *Questions for sustainability assessment*: What are the sustainability implications associated with the use of recycled plastics in food contact materials, what drives the benefits, and are there ways to retain them that do not entail the risks of exposure to contaminants? Based on these questions, aligned system boundaries are defined to represent the same recycling case—e.g., the annual generation of food packaging plastics in the considered region.

Second step: Risk assessment metrics could be DALYs as a consequence of the potential human exposure to contaminants migrating from the recycled plastics into food. Metrics of the LCA used to assess the sustainability implications could be DALYs gained as a consequence of avoiding the production of virgin plastics in accordance with the analyzed scenario. In addition, there will be metrics for saved environmental damage (e.g., species loss) and loss of resource availability (e.g., a monetary metrics, such as Euro).

Third step: Consistent assumptions need to be made in the scoping of the analyzed system for the two assessments, e.g., in terms of the quantities and types of plastics that are considered for recycling, and the contaminants present in the plastics.

Fourth step: Considering the uncertainties inherent in the two assessments, their results are compared and the human health gains by not recycling (DALYs saved by not exposing consumers to contaminants in the recycled plastics) are compared to the human health savings by recycling (DALYs saved by avoiding the production of virgin plastics and wasting of the used plastics) and the additional savings in environmental damage and resource loss (potentially brought brought together through a weighting scheme, such as monetarization). Improvement options that can combine the wish to mitigate risks and strengthen sustainability are sought and analyzed as alternative scenarios starting again from the First step.

Evaluation of alternative combined approaches

By applying the suggested roadmap of alignment and harmonization steps in Fig. 1, we propose four alternative options for combining risk and sustainability assessment with a specific emphasis on life cycle assessment (LCA) as an illustrative method for assessing environmental sustainability. The four options include: (1) carry out both an independent RA and LCA, and evaluate outcomes separately in the context of each study. (2) Apply utility theory to compare fully quantified outcomes obtained from separate LCA and RA studies. (3) Embed details of RA in LCA for all product-service system components. (4) Embed RA in LCA iteratively to judge the level of RA detail needed to maximize the value of LCA results. For each of these four options we discuss the details and the relative merits of each approach and judge them against the following evaluation criteria: feasibility, reliability, completeness, transparency, compatibility with principles of decision-making, and compatibility with value of information principles.

Option 1: Carry out independent RA and LCA and evaluate outcomes separately in the context of each study

For this option, we assume that one has sufficient information to carry out for a selected product-service system both a comprehensive LCA covering the life cycle and risk assessments for the most impactful substances added, created, or emitted during the life cycle. In the example of chemicals in recycled plastics, this translates into, e.g., assessing consumer risk from a given material as such, while considering recycling loops and related trade-offs over the entire life cycle in a separate LCA [39]. In organizing the two assessments, the decision maker must recognize that the two separate assessments may not address the same space of outcomes. To gain insight from the two separate assessments, the decision maker needs to separately define "acceptable" outcomes in the context of risk assessment and in the context of sustainability. This means defining a metric of risk—the measure of harm—and a metric of sustainability—such as environmental footprint. Although it is common practice in risk analysis to have “acceptable risk” guidelines, LCA commonly provides input to comparisons that are not intended as absolute measures of footprints. One challenge for this option is to assess sustainability performance on an absolute scale [40] by developing some measure of acceptable footprints expressed in, e.g., disability-adjusted life years, DALYs, for expressing damages on human health, toxic impact or species loss units for ecological damages, CO_2 equivalents for climate change impact, or adapting the life cycle impact assessment method to existing measures of absolute sustainability, such as the Planetary Boundary framework [41, 42]. Once there is agreement on acceptability for sustainability metrics, there can be an opportunity to make iterative calculations and comparisons of the boundaries of the acceptable risk region and the acceptable sustainability region on the response surface of risk and sustainability outcomes attributable to the life cycle of the product-service system.

Option 2: Apply utility theory to compare fully quantified outcomes obtained from separate LCA and RA studies

This option again makes use of both a detailed LCA and RA applied to a product-service system, but applies utility theory to monetize and compare monetized outcomes from the two approaches. Ideally, outcomes of both the LCA and RA can be quantified so they have similar measures of utility, such as translating DALYs into monetary cost terms [43]. In the example of chemicals in recycled plastics, both RA and LCA results are monetized for utility-based comparison of results. The concept of utility is used in economics to represent an agent's preferences related to a set of alternatives. Preference is typically modeled with a utility function derived from information collected on consumers, companies or decision makers. In risk management, utility theory has been used as a tool for ranking preference among alternative risks, typically representing negative impacts as dollars of damage to guide societal preference for decision makers. Although cost–benefit analyses are commonly applied to RA results, examples of cost–benefit analysis in life-cycle management are rare. The most likely analog is the use of LCA to make cost allocations. Option 2 differs from Option 1 in that rather than seeking some measurement of acceptability from two alternative impact-assessment approaches, the two methods are used to seek a common measure of utility to quantify the tradeoffs in a joint optimization of both assessments. As a result, Option 2, while still maintaining the separation of the RA and LCA approaches, strives for a common metric that makes comparison more transparent.

Option 3: Embed details of RA in LCA

The third option follows the approach of an LCA but adds detailed elements of RA to increase the spatial and temporal resolution of the impact assessment phase of LCA. In this approach, one embeds the fundamental aspects of a risk assessment into every step of an LCA. That is, for modelling an impact in the LCA, such as human-health or ecosystem impacts, one carries out all the steps of the risk assessment approach (hazard identification, exposure assessment, dose–response assessment, and risk characterization) for each substance of concern in the life-cycle inventory and at each specific site (or a set of representative sites), where those substances are released. The outcomes of this approach are LCA impact characterization factors, providing endpoints based on risk but converted to a metric relevant to LCA, such as DALY, ecosystem degradation potential, global warming potential etc. This approach is very comprehensive and has a significant information demand that gives rise to the potential for delay and for introducing unintended error and uncertainty. Because the supply chain for many products and services involves large numbers of components, perhaps 30 or more, the process for aggregating and allocating impacts can be challenging. However, there are examples of where this has been done. For example, the US National Academies considered mortality impacts individually and then in aggregate from every one of the hundreds of US power plants in its consideration of the life-cycle health impacts of electrical energy services [44].

Option 4: Embed RA in LCA iteratively to judge the level of RA detail needed to maximize the value of LCA results

In contrast to Option 3, Option 4 embeds RA in LCA selectively and iteratively. The approach begins with a standard LCA and uses some form of sensitivity analysis applied to the LCA results to identify elements of the product-service system, where RA can increase the resolution and reliability of the LCA outcomes. The common practice in LCA, particularly for human health and ecological impacts is to assess fate, transport, exposure, and damage using generic scenarios that capture typical patterns of global or regional economic/environmental systems. The concept here is to iteratively explore the addition of site specificity to an LCA by adapting site-specific elements of RA. The process is iterative in its effort to find components of the product-service system (in terms of inventories, emissions, life stages, and locations) that have the largest contribution to impacts and/or significant uncertainties. This approach follows guidance from the US National Academies of Science, Engineering and Medicine regarding solutions-based risk assessment and tiered approaches to managing uncertainty [1], which is also adopted in guidance documents for European chemicals management [45, 46]. This approach has been employed in adapted form in the recent UNEP-SETAC guidance on conducting LCA for fine particulate matter ($PM_{2.5}$) [47]. Because the location of $PM_{2.5}$ emissions in relation to exposed populations is a key factor influencing associated exposure and health risks, the guidance provided both regional, city-specific, and indoor characterization factors for $PM_{2.5}$ sources. This guidance provides a modified LCA with options for (1) global default factors and their associated variability, (2) region and city-specific factors along with ranges of variation, and (3) factors for indoor emissions in a range of building types.

Criteria to evaluate the effectiveness of alternative combined approaches

Feasibility

To assess feasibility we must determine whether there is sufficient understanding of the product-service system and sufficient data to carry out the study. That is, there needs to be information on use patterns, quantities of chemicals used, chemical properties, and toxic (or other impacts) to make quantitative estimates of risk or some life-cycle impact metric, such as DALYs for human health impact.

Reliability

Reliability relates to accuracy and precision of an RA or LCA. Lack of reliability arises from uncertainty (about structure and behavior of industrial and environmental systems) and variability of systems and system parameters. Uncertainty comes about from lack of knowledge and lack of data, and it can be reduced (at a cost of time and money) by compiling more and better knowledge and data. Variability arises from the variation in (1) how product-service systems are structured and used, (2) factors governing the environmental transport and transformation of contaminant emissions from these systems, and (3) human variability with regard to exposure factors. Even with very detailed information on product-service systems, environmental systems, and human exposure factors, variability places a burden on both the risk assessor and the life-cycle assessor to capture the large range of quantitative outcomes. Therefore, even with very detailed knowledge, data variability can affect reliability with regard to system selection choices.

Completeness

In a decision making context completeness refers to whether an assessment, such as an RA, provides a full range of decision options [1]. The concept of completeness is linked to the context in which an LCA or RA will be used and whether the assessment provides adequate information to support an outcome classification—such as unacceptable risk in the case of RA or sufficient clarity for comparing alternatives in LCA. Completeness is enhanced by the selection of scenarios that best inform the assessment. Completeness is constrained when there is not sufficient understanding of product-service systems to construct realistic scenarios and alternatives for assessment.

Transparency

For any assessment process used in support of decisions to reduce impacts, it is a scientific and a policy-making objective that there is transparency in both the process of conducting the assessments (LCA and RA) and in the interpretation of their outcomes. "Transparency is a requirement that is always present, but it is rarely defined in operational terms" [1]. Guidelines for seeking transparency focus on reproducibility and traceability—that sufficient information is provided for a skilled analyst to be able to follow all the reasoning and independently reproduce the results [48]. Because RA and LCA typically inform decision-making, transparency is often related to parsimony with the aim to find the lowest level of computational detail needed to provide and outcome that is unlikely to change with the addition of more computational detail.

Compatibility with principles of decision-making under uncertainty

LCA and RA inform decisions involving matters of public health, environmental risk and environmental sustainability. The US National Research Council notes that these types of decisions have five common elements: "(1) the desire to use the best scientific methods and evidence in informing decisions, (2) uncertainty that limits the ability to characterize both the magnitude of the problem and the corresponding benefits of proposed interventions, (3) a need for timeliness in decision-making that precludes resolving important uncertainties before decisions are required, (4) the presence of some sort of tradeoff among disparate adverse outcomes (which may be health, ecologic, or economic outcomes, each affecting a different set of stakeholders, and (5) the reality that, because of the inherent complexity of the systems being managed and the long-term implications of many decisions (such as cancer latency, changes in the structure of ecosystems, or multiple simultaneous sources of exposure), there will be little or no short-term feedback as to whether the desired outcome has been achieved by the decisions" [1]. The literature on decision analysis makes clear how policies are possible under conditions of uncertainty, but such policies must explicitly take account of such uncertainty. A well-developed theory of decision-making under uncertainty has been described in a number of major textbooks [48–51]. These authors emphasize the need for flexibility to address margins of error; to consider reducible versus irreducible uncertainty; to separate variability from uncertainty; and to consider benefits, costs, and comparable risks in the decision-making process. This literature characterizes a "good decision under uncertainty as one that uses the most appropriate processes and methods to assemble and interpret evidence, to apply the decision-maker's values properly, and to make timely choices with available resources rather than defining a good decision only according to its (apparent) outcomes" [1]. It is this goal that we consider a measure of whether a combined LCA/RA process is compatible with principles for decision making under uncertainty.

Compatibility with value of information (VOI) principles

A key challenge of decision-making under uncertainty involves the inevitable choice between making an immediate decision with information at hand or delaying the

Table 1 Summary of the Results of evaluating the Four Options for Combining RA and LCA against the Six Evaluation Criteria. "+" option meets a specific criterion, "-" option does not meet the criterion, "±" option might meet the criterion but with limitations or significant challenges. Colors indicate ranking within each criterion from red (worst) over orange to yellow (best)

Options / Criteria	Option 1: Use both RA and LCA separately; compare outcome acceptability based on both	Option 2: Apply utility theory to fully quantified outcomes of separate LCA and RA studies	Option 3: Embed details of RA in LCA	Option 4: Embed RA in LCA iteratively to judge the level of RA detail needed to maximize the value of LCA results
Feasibility	+/- Likely feasible for some product-service systems. Limited by the need to work with two outcome metrics	+/- Feasibility challenge to develop a utility metric for LCA with a lack of literature on utility theory applications in LCA	+/- Questionable feasibility because of the significant information demands	+ Scores high with respect to feasibility because it is anchored in a standard LCA as a starting point
Reliability	- Likely degraded significantly by the need to work with two approaches	- Reliability will be degraded by the need to work with two approaches	- Demand for many inputs and models can limit reliability	+/- May not be as reliable as a comprehensive RA, but it offers strategic insight
Completeness	- The two approaches may not ever be constructed to cover the same space of outcomes	- The two approaches may not ever be constructed to cover the same space of outcomes	- Because of the large information demands, completeness is unlikely in a timely manner	+ Meets our criterion for completeness in LCA but may not fully meet the criterion for RA
Transparency	+/- Possible but tracking two separate calculations can significantly diminish transparency	+/- Single outcome metric for RA and LCA can increase transparency, need to monetize outcomes can diminish transparency	+/- Formal use of RA may increase credibility but large numbers of embedded assumptions can obscure calculation pathways	+ Limits on the computational detail on RA can increase transparency
Compatibility with decision-making principles	+ Key advantages with regard to this criterion because of the use of two acceptability criteria	+ Likely compatibility with principles of decision making under uncertainty	+/- May lack compatibility/ credibility due to significant delay in providing results to decision makers	+ The iterative nature of the assessment provides a level of detail needed by a decision makers
Compatibility with VOI principles	+/- Partial but not full compatibility with VOI principles if there is explicit characterization of uncertainty for alternative acceptability criteria.	+/- Partial but not full compatibility with VOI principles if there is explicit characterization of uncertainty for utility	+/- If applied without some control over the level of detail needed for the RA embedded within an LCA it will not be useful for VOI assessments	+ Iterative nature of LCA/RA analyses works best with VOI to decide where and when in life cycle stages RA calculations will increase the reliability

decision until additional data collection and modeling can be applied to the issue. In this choice, the delay of action is a concern as well as the direct and indirect costs of acquiring new information. A common approach for valuing information in the context of decisions is value-of-information (VOI) analysis, which provides "a set of methods for optimizing efforts and resources to gather, to process, and to apply information to help decision-makers achieve their objectives" [1]. To be compatible with VOI analysis, an assessment such as LCA or RA must be in a format that is open to sensitivity analyses that can provide insight on where additional information is likely to alter outcome values so as to have impact on decision making with regard to that outcome. For example, a VOI analysis should offer insight on whether greater spatial resolution or information from site-specific risk assessments could alter the value of a characterization factor to the point, where it supports a different product-service system choice.

Recommendations

To develop recommendations, we evaluate each of the four options for combining risk and sustainability assessment with regard to the six evaluation criteria. Table 1 provides a summary of the comparison and supports a ranking of the four options with regard to their utility for supporting a combined assessment of risk and sustainability.

Option 1: Carry out independent RA and LCA and evaluate outcomes separately in the context of each study

The biggest challenges confronting this approach are the needs to determine the appropriate metrics of risk and sustainability, then to establish acceptability criteria for each outcome (risk, sustainability) and the system definition for modeling—in particular for the RA modeling. Additional challenges are that LCA and RA cover different outcome spaces entailing differences in uncertainty and variability, and in how they are characterized and compared across the two assessment options.

Scoring with respect to our Evaluation Criteria:

Feasibility: It is likely feasible to carry out LCA and RA in parallel for at least some product-service systems.

However, feasibility is limited by the need to compare outcomes that are usually not easily compatible or comparable based on different assessment protocols. *Reliability*: The reliability will likely be degraded significantly because of the need to work with two different approaches. However, there is some advantage in making use of two approaches to gain more insight than either could provide on its own. There remains significant input demands—giving rise to many potential sources of uncertainty. *Completeness*: The two approaches may not ever be constructed to cover the same space of outcomes so a complete comparison may not be feasible. *Transparency*: If done correctly this approach can communicate how acceptability in two domains apply. However, tracking the two separate full assessments of risk and sustainability can significantly diminish transparency. *Compatibility with principles of decision-making*: There are key advantages with regard to this criterion, because the use of two or more acceptability criteria allows decision makers to both see, where there are regions of overlapping acceptability and to make trade-offs among meeting risk and sustainability acceptability. *Compatibility with value of information principles*: The approach offers partial but not full compatibility with VOI principles so long as there is an explicit characterization of uncertainty with regard to meeting the alternative acceptability criteria. Without an explicit treatment of uncertainty, the alternative approach for assessing VOI is to identify regions, where the risk and sustainability acceptance metrics diverge significantly.

Option 2: Apply utility theory to compare fully quantified outcomes obtained from separate LCA and RA studies

This option makes of use risk assessment and sustainability assessment to calculate a common monetary metric based on the utility theory as applied in cost–benefit analysis. This approach requires that for both the LCA and the RA, all impacts are monetized using the methods of economic policy analysis. In comparison to option 1, this option sets a common metric for both the RA and the LCA. However, issues of feasibility, reliability, and transparency arise as significant challenges.

Scoring with respect to our Evaluation Criteria:

Feasibility: In contrast to Option 1, the approach does not have the feasibility challenge of working with two outcome metrics and the need to establish acceptability criteria. However, the feasibility challenge in this case is the need to develop a utility metric for LCA. The lack of literature on utility theory applications in LCA limits the initial feasibility of this approach. *Reliability*: Similar to Option 1, the reliability of the merged assessment will be degraded because of the need to work with two different approaches but there is some advantage to making use of two approaches to gain more insight than either alone could provide. There remain significant input demands—giving rise to many potential sources of uncertainty. The need to monetize outcomes and the valuation assumptions that this entails will likely reduce reliability. *Completeness*: As was the case in Option 1, the two approaches may not necessarily cover the same space of outcomes so a complete comparison may not be feasible. *Transparency*: The use of a single outcome metric for both RA and LCA outcomes can increase transparency, but the need to monetize outcomes can diminish transparency. *Compatibility with principles of decision-making*: Because there is a significant literature and body of practice linking decision making to utility calculations, there is likely compatibility with principles of decision making under uncertainty. *Compatibility with value of information principles*: The approach offers partial but not full compatibility with VOI principles so long as there is an explicit characterization of uncertainty with regard to the calculation of monetized utility of RA and LCA outcomes.

Option 3: Embed details of RA in LCA

This approach develops impact characterization factors based on LCA and then enhances the detail of outcome calculations by applying an RA into the life cycle stages. Although this approach can increase the credibility of a sustainability assessment by bringing in RA insights and tools, it can also give rise to a significant computation burden and a great deal of information management.

Scoring with respect to our Evaluation Criteria:

Feasibility: The feasibility of this approach is questionable because of the significant information demands. The information needs and information management of this approach could paralyze rather than facilitate effective life-cycle decision making. This constraint though could be addressed using some process to reduce RA applications to only those life stages and/or harmful emissions for which the added reliability is useful. However, we note that the process of reducing the level of RA detail drives Option 3 to be similar to Option 4 in terms of the level of detail. *Reliability*: The need to perform RA at most or many stages of the life cycle require multiple inputs and models, among which many could be of questionable reliability thus introducing significant uncertainty. Assessing and managing reliability is always challenging when calculation detail increases. *Completeness*: Because of the large information demands, completeness is unlikely in a timely manner. Such a merged LCA/RA assessment could take much longer to carry out than a standard LCA or RA. *Transparency*: Because of the more formal use of risk assessment, the approach could have the appearance of greater credibility, but a significant number of embedded assumptions will likely obscure a number of important intermediate results. *Compatibility with principles of decision-making*: This approach may lack compatibility with effective decision making, because it can lead to significant delay in providing input to decision makers and the level of uncertainty can result in significant degradation of confidence in selecting among alternatives. If the approach includes a process of deciding when and where in the life cycle to apply RA to LCA, then it could provide some options that are currently unavailable to improve the reliability of impact characterization factors. Again, such efforts would drive Option 3 towards Option 4 in terms of level of detail applied. *Compatibility with value of information principles*: If the approach is applied without some control over the level of detail needed for the RA embedded within an LCA, it will not be useful for VOI assessments. If there is a process for deciding when and where in the life cycle to embed RA approaches, this option could be guided by and compatible with VOI principles.

Option 4: Embed RA in LCA iteratively to judge the level of RA detail needed to maximize the value of LCA results

This approach uses LCA as a baseline to find hotspots, where risk assessment can offer insight and greater resolution. It follows from the recommendations of the US National Academies on "solutions-based" risk assessment. This approach is inherently iterative and requires a more formal treatment of uncertainty/variability in LCA.

Scoring with respect to our Evaluation Criteria:

Feasibility: This option scores high with respect to feasibility, because it is anchored in a standard LCA as a starting point. *Reliability*: Because this approach begins with LCA and adds RA, where it is most relevant, it may not be as reliable as a more comprehensive RA approach, but it offers the opportunity to consider, where it is useful in the life cycle to reduce uncertainty by adding more RA detail. This is a very positive feature and limits the need to add RA at every stage, which could ultimately reduce reliability rather than increase it, as discussed under Option 3. *Completeness*: As an LCA, this approach meets our criterion for completeness. There can be concerns that this option will not meet the completeness criterion for RA, since RA will only be added, where it has value for decision-making. *Transparency*: Because this approach limits the computational detail on RA compared to other approaches, it scores well with respect to transparency. *Compatibility with principles of decision-making*: The iterative nature of the assessment providing LCA and RA information at a level of detail needed by a decision maker makes it very compatible with principles of decision making under uncertainty. *Compatibility with value of information principles*: The iterative nature of the combined LCA/RA analysis will work best when it makes use of VOI principles to decide, where and when in the life cycle stages RA calculations will increase the reliability and usefulness of the assessment. Indeed, this approach is very compatible with VOI principles.

Recommended option

All of the presented options considered offer some potential for combining LCA and RA, and have been discussed in the literature [21–28]. However, Option 4, which begins with LCA and adds RA elements based on VOI principles, scores best with respect to all six evaluation criteria. The other three approaches, which favor developing more RA details independent of the LCA results, tend, for different reasons, to be computationally burdensome—something that can increase the time needed to carry out an assessment, reduce transparency, and likely reduce reliability.

Overall, the combination of RA and LCA perspectives and results finds application in different fields, such as substituting hazardous substances along product life cycles, where the assessment scope is broadened in different tiers from assessing use-stage risks to assessing full life cycle impact profiles [52], based on metrics that allow adopting both a risk and a life cycle perspective [53].

Outlook

With the pressure from a changing climate, growing populations, and accompanying pressures on the environment and biodiversity, sustainability and risk management are moving higher on the agenda of many nations and enterprises, supported by an increasing trend to adopt digitalization techniques for assessing and managing risks and sustainability impacts [54]. A roadmap for the combined assessment of risks and sustainability is proposed, based on a consistent scoping of the two. This offers more robust support for optimizing decisions and avoiding shifting burdens from one problem to another, ultimately catering for technological solutions that are not only safe or sustainable, but both. In addition, new data and methods will be needed and are progressively becoming available to advance both RA and LCA, for example using new-approach methods to overcome existing data gaps, or including additional impact categories and pathways [39, 55]. This may in some cases lead to changes of (earlier) recommendations based on a continuously improved understanding of the systems under study, avoiding the introduction of regrettable solutions that are often based on limited assessment scopes [52, 56].

The development of a framework for combined assessment of risk and sustainability has identified some challenges that need to be overcome to allow uncovering trade-offs and concluding on the optimal decision from an integrated risk and sustainability perspective. We have not explicitly addressed socio-economic impacts/benefits, because, although they are now LCA terms of reference, they are rarely the subject of risk assessments. Thus, it is difficult to propose how to integrate socio-economic results from risk and sustainability assessments due to lack of examples. In general, it is the areas of human health and ecosystem risk that are both the subject of many sustainability and risk assessment studies. To make our proposed integrated framework more compatible with risk management policies, there is a need for risk managers to move beyond simply defining safety based on absolute risk. Historically, risk assessments were used to set regulatory goals in the absence of other assessments. However, this approach has often failed to prevent the appearance of more risky technologies or chemicals to provide societal demands for products and services. To achieve the need to better address alternatives, risk managers are and will continue to consider safety at an aggregate level rather than focusing on single chemicals or specific locations.

There is a need to build on metrics that support comparison of the risk assessment and sustainability assessment results. A candidate could be to map the adverse outcomes of the risk assessment and the damages modelled in the sustainability assessment on a common (monetary) scale, which is an area that requires additional research. However, first attempts already exist, such as the consistent integration of monetized results from risk-based technoeconomic assessment and LCA for optimizing biochemicals manufacturing [57]. Furthermore, both assessments involve modelling that is accompanied by uncertainties and there is a need to address these in a consistent manner for both perspectives, and to interpret and communicate results in a way that respects these uncertainties to ensure robust conclusions on the combined assessment. This will ultimately provide a basis for better-informed decisions about technology choices for policy and societal stakeholders.

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Authors' contributions
MH and PF have been responsible for the concept of the manuscript, drafted the manuscript and were involved in its finalization. TM has been responsible for further elaborating the manuscript and its finalization. KA, TH, BN and SM have assisted in drafting the manuscript and contributed specific aspects. All authors read and approved the final manuscript.

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