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Anticipatory life cycle assessment for environmental innovation

Thomas P. Seager

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[1] Arizona State University, School of Sustainable Engineering, Tempe, AZ 85281, United States, thomas.seager@asu.edu.

Introduction

Environmental life cycle assessment (LCA) has emerged as the preferred perspective from which to evaluate the prospective impacts of innovative technologies. However, conflicting methodological recommendations in the scientific literature may leave technology developers, policy makers, and research funding agencies confused about which approach(es) to adopt. This paper contrasts the features and relevance of *ex-ante* and anticipatory LCA for the purpose of informing EPFL International Risk Governance Center's (IRGC) preliminary recommendations regarding the environmental sustainability of emerging technologies. In particular, it details the advantages, methodological approach and challenges of anticipatory LCA.

The principal feature distinguishing the two methods is the model of innovation with which they are most compatible. Namely, *ex-ante* aligns with technology readiness level (TRL)/stage gate models of innovation, whereas anticipatory aligns with lean/agile. TRL/stage-gate is typical of large, well-funded bureaucratic organizations, such as government agencies, whereas lean/agile is typical of startup companies and teams seeking technology breakthroughs. Thus, anticipatory LCA better recognizes that disruptive innovation rarely follows the linear pathway for which TRL/stage-gate was originally developed (see Box 1).

This paper is divided into six sections. Section 1 reviews the historical development of environmental life cycle assessment and contrasts different approaches to prospective environmental modeling for emerging technologies. Section 2 describes how current ISO guidelines for LCA are consistent with the TRL/stage-gate model of innovation. Section 3 contrasts lean/agile models of innovation with TRL/stage-gate. Section 4 contrasts the *ex-ante* and anticipatory methods. Section 5 describes the different stages and steps of anticipatory LCA. Finally, Section 6 offers recommendations and conclusions.

1.

Historical development of environmental life cycle assessment

The intellectual antecedents of environmental LCA can be traced back to the 1970s when regulations were promulgated in response to an emerging environmental consciousness. In the United States, the Clean Air Act (Daniels et al., 2020) and the Clean Water Act (Murchison, 2005) exemplified the new regulatory approach. For example, when the US Environmental Protection Agency was established by the Nixon administration in 1970 it was organized, and is still organized, around different environmental media. In each regional office, one division regulates air pollution, another solid waste, and another water. Emissions limits and permit reviews are conducted separately by each division, complicating coordination across environmental media.

At the time, the separation of divisions made sense in two ways: (1) it allowed piecemeal, incremental construction of a regulatory structure, without the additional obstacles of having to conceive of a whole systems approach all at once, and (2) it mirrored the typical organizational structures of the large corporations that were the object of regulation.

Nonetheless, critics were quick to recognize shortcomings in a compartmentalized approach (e.g., Lapping, 1975). For example, incineration became a popular solution for the management of solid waste because it reduced waste volumes, conserved landfill space and could be used to generate electricity. However, it also shifted pollution problems from one environmental medium to another. Similarly, storing liquid waste in drums and burying them in the ground offered some protection to surface waters, but came at the expense of land and groundwaters (as the infamous case of Love Canal, New York, made clear to the public in 1977–1978). The separation of regulatory actions by environmental media permitted, if not encouraged, shifting problems from one media to another without considering what might reduce environmental burdens as a whole.

Environmental LCA emerged as an analytic solution to the problem-shifting that characterized early technological approaches. The principal advantage of LCA is that it incorporates broad, explicit boundaries designed to consider all environmental effects along the supply chain, including use and disposal, as a whole system.

The earliest applications of LCA were in the industries that dominated the industrial revolution and were perceived as relevant to its environmental legacy. For example, a famous article in "Scientific American" (Frosch & Gallopoulos, 1989) that popularized the term "industrial ecology" relied on examples from the automobile industry — partly because the authors were scientists at General Motors, and partly because the auto industry dominated manufacturing in the American economy for decades. The article emphasized potential material interconnections between industries, such that "waste" or by-products from one industry might become feedstocks for others. Later, this became known as "industrial symbiosis" (Grant et al., 2010) and, more recently, "circular economy" (Korhonen et al., 2018).

The advantages of the circular economy are exemplified by the industrial ecosystem in Kalundborg, Denmark, where cooperation between different industries has improved material and energy efficiency, reducing exchanges with the environment (Chertow & Park, 2016). Nonetheless, the disadvantage is that interdependent relationships typically exist only between mature, stable industries. They can take decades to develop, and once they are in place, they can become an impediment to innovation.

The historical development of LCA has made it natural to develop standardized methods applicable to mature industries, operating at scale, where data on production processes and emissions is both available and stable. LCA is less developed in steering the development of novel technologies, or guiding innovation. Several theoretical or methodological advances that go by different names have been made, including prospective LCA, *ex-ante* LCA, anticipatory LCA and LCA of emerging technologies. While each term is motivated by the same problem — i.e., the difficulty of gaining environmental insight into problems before they manifest at scale — the terms are not synonymous, and the approaches are different. Table 1 provides a high-level comparative summary focusing on critical differences rather than commonalities.

What often gets lost in the research regarding LCA for innovation is that attempts to force existing models of retrospective LCA, such as those codified by the International Standard Organization (ISO), into prospective applications will suffer from irredeemable shortcomings. Retrospective LCA methods were organized around an understanding of traditional manufacturing, distribution, use and waste collection processes. That is, the ISO standards that dominate thinking about LCA were developed to improve the environmental efficiency of mature supply chains, markets and processes. Consequently, they are structured with models of these industrial processes in mind, to address

Table 1 | LCA methods comparison

Descriptor	Goal	Unique features
Prospective	Improve environmental forecasting	Emphasizes: • absolute rather than relative assessment
Ex-ante	Comparative assessment of pre-market technologies to determine expected or projected environmental gains relative to incumbent	Emphasizes: • uncertainties related to scale-up • seeks compatibility with ISO 14040 series guidelines[2] for retrospective LCA
Anticipatory	Identify uncertainties most critical to the environment, and research priorities	Emphasizes: • sensitivity analysis by stochastic exploration of data uncertainties, including value-based tradeoffs between impact categories • environmental prioritization of critical uncertainties for technology developers

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[2] See ISO 14040:2006 www.iso.org/news/2006/07/Ref1019.html

questions for designers and managers concerned with improving the environmental efficiency of producing, delivering and recycling goods. However, at the early stages of innovation, different concerns dominate.

In research & development, life cycle questions related to manufacturing efficiency are often secondary to questions related to functionality in use. For example, a life cycle examination of single-walled carbon nanotube (SWCNT) production in a laboratory research setting revealed that carbon yield during laser ablation was a critical factor in determining overall environmental efficiency in the fabrication of experimental SWCNT battery electrodes (Ganter et al., 2009). In this case, the environmental analysis was not motivated by comparison to conventional battery electrodes (as *ex-ante* LCA suggests). Rather, analysts were guided by the technology developers' request to identify opportunities for environmental improvement. Subsequent anticipatory analyses revealed that the current research focus on improvements in use-phase functionality would do little to effect environmental life cycle improvements. As a consequence of communicating these findings back to the technology developers, research attention shifted to investigations that improve yield (Wender & Seager, 2014).

An analogous example is the anticipatory life cycle comparison of emerging photovoltaic (PV) technologies. Anticipatory LCA revealed that the most important uncertainty with regard to greenhouse gas emissions was the carbon intensity of the silicon manufacturing processes (Ravikumar et al., 2017). At the time, PV technology developers were preoccupied with making use-phase efficiency gains to increase avoided carbon-dioxide emissions from displaced coal-fired electricity. However, because greenhouse gas emissions were more closely associated with manufacturing than use-phase conversion efficiencies, environmental research priorities would have been better directed to technologies for minimizing or eliminating kerf losses in silicon wafer slicing.

The anticipatory approach can reveal insights into a technology development agenda that might otherwise be hidden by other approaches to LCA. For example, a comparative anticipatory LCA of three PV technologies (amorphous-Si, CdTe, ribbon-Si) indicated that metal depletion in amorphous-Si contributes more to absolute uncertainty than any other life cycle parameter. As such, intuition suggests investigating process improvements in amorphous-Si technology that reduce uncertainty in metal depletion. However, anticipatory testing of hypothetical improvements in metal depletion failed to resolve uncertainties in environmental rank-order preferences relative to other technologies. Instead, relative uncertainties in technology preferences are better addressed by investigating uncertainties in marine eutrophication (Ravikumar et al., 2018).

These examples illustrate difficulties with the assertions that "the ISO standard could and should also be used when LCA is applied in an *ex-ante* manner" (van der Giesen et al., 2020). Because the ISO standards were developed to address questions related to mature manufacturing industries, not the salient questions and uncertainties related to technology development, they place emphasis on goals that are in poor alignment with current trends in research and technology development.

2.

How is innovation modeled in prospective LCA?

Just like LCA was organized with a model of manufacturing in mind, any method of environmental LCA that seeks to inform questions relevant to innovation must be organized with a model of innovation in mind. The most popular model cited in the scholarship of LCA is called Technology Readiness Level (TRL). It has been adopted by NASA, the US Department of Energy and others (Straub, 2015), and is often cited with respect to *ex-ante* LCA (e.g., Moni et al., 2020). In TRL, technologies or products progress from Level 1 — Basic science without a commercial application in mind, to Level 9 — Product tested under real conditions.

The TRL model presumes a linear progression from lower levels of readiness to higher ones, as knowledge from research & development accumulates. It is understood that not all ideas or discoveries will progress all the way to the highest levels, as some will fail to find commercial or practical application. As such, TRL is typically compared to a funnel or pipeline through which many ideas flow in one direction from lower levels to higher. This approach has been elaborated upon for private industry as "stage-gate" innovation, in which ideas are progressed through five stages of the "pipeline" (Cooper & Edgett, 2009, p. 2), including:

1. Scoping,
2. Building a business case,
3. Development,
4. Testing & validation, and
5. Launch.

At the conclusion of each of these stages, prior to making investments that advance to the next stage, the quality of the idea, product, or technology is assessed relative to increasing detailed criteria. Hypothetically, life cycle environmental criteria can be included among any of the gates. For example, breakthrough ideas that require prohibited, tightly regulated, or critical materials might fail environmental criteria before progressing to the development stage. Prospective and *ex-ante* LCA may have been developed with this in mind.

Nonetheless, there are at least two difficulties with TRL: linearity and cost.

Linearity
The single-minded focus at each stage-gate is obtaining an answer to the question "Go or kill?" In its original formulation, the stage-gate process on which TRL was predicated did not encourage feedback loops or iterative cycles (e.g., Cooper, 1990). Although subsequent revisions to stage-gate recognize the importance of iteration (e.g., Cooper, 2014), these have yet to be formalized in TRL. Thus, TRL suggests that innovation success depends on increasing the number of ideas entering the funnel at Level 1 – Basic science. TRL fails to account for real, messy, non-linear product development practices that are often carried out without TRL or stage-gate processes in mind (Wender et al., 2014).

Cost
Progressing from basic science without guidance toward practical application requires long-term capital investment that is typically unaffordable to all but governments, universities with large endowments, and large corporations in dominant market positions. When ideas do emerge from basic science to enter a stage-gate funnel at higher readiness levels, additional research investment is required to assess go/kill at every gate. Because the funnel metaphor suggests increasing the number of new ideas at the beginning of the funnel, increasing the pace of innovation incurs both the increased cost of generating or obtaining these ideas and the cost of assessing them relative to stage-gate criteria. The more criteria added at each gate, the greater the cost. TRL fails to acknowledge the real financial constraints under which innovation occurs, given the enormous costs of gathering complete information.

3.

How does innovation really work?

The suggestion by Cooper & Edgett (2005) that the idea "pipeline was dry" in 2005 proved to be facile. For example, the most valuable American companies in 2005 placed Walmart at the top, followed by Exxon Mobil, two automobile companies, General Electric, two more oil companies, and a bank[3]. While it may be true that each of these corporations was lacking in strong, high-value ideas, revisiting the list in 2022 reveals some significant changes. Apple, Microsoft, and Alphabet (Google) now top the list, followed by Amazon and Tesla.

The linear TRL/stage-gate model that dominated industrial behemoths like General Electric has since been superseded by agile and lean innovation models that emphasize flexibility, recursion, and minimizing capital requirements. Although "lean" originally referred to production management practices that enabled Toyota to deploy quality improvements and retool production systems faster and cheaper than American automobile manufacturers (e.g., Womack et al., 2007), it was subsequently adopted by software and other start-up companies in Silicon Valley to accelerate the launch of imperfect products that could be further developed with the benefit of customer and market feedback (Blank, 2003). Meanwhile, the intellectual antecedents of "agile" innovation trace back to two Japanese business scholars who levied a critique of the linear product development, suggesting that "the traditional sequential or 'relay race' approach to product development exemplified by NASA's phased program planning system may conflict with the goals

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[3] Fortune magazine maintains rankings of the largest companies in the world, measured by market capitalization. Subscribers may browse the historical data at fortune.com/ranking/fortune500/2022/search/

of maximum flexibility" (Takeuchi & Nonaka, 1986). They advocated for a more holistic, team-based approach to innovation that emphasized speed, instability, learning and flexible controls.

Where agile innovation addresses the problem of linearity, lean addresses the problem of expense. As these alternative pathways to product development co-evolved, they have eventually become mingled to the extent that they may be referred to as a single lean/agile model.

Rather than beginning with curiosity-driven basic science, the lean/agile model typically starts with customer problems or market opportunities, iterating through pretotypes, prototypes, and "protoproducts" (Jensen, 2017) to create a continuous improvement loop of new product versions of releases. The lean/agile model emphasizes the launch, revision, and relaunch of inexpensive product innovations that improve ideas rather than discard them. Given the flexibility of the lean/agile innovation and the recognition of resource limitations, one of the central recurring questions lean/agile developers must confront is, "what experiment should we try next?" Lean/agile requires searching among the myriad of those features, improvements, or ideas to identify those that should be prioritized for the next iteration. By contrast, TRL/stage-gate presumes that the development criteria are largely known ahead of time.

While the lean/agile model is particularly well-suited to software companies that can rapidly reconfigure code for new releases, or fix "bugs" that are only discovered after products release, lean/agile has also been adopted at manufacturing companies – especially those like Tesla with close ties to Silicon Valley. Given the success of lean/agile models of innovation, it behooves LCA researchers to develop methods of environmental inquiry that are suitable for them.

The most important distinction between *ex-ante* and anticipatory LCA, as they are currently practiced, is that *ex-ante* seeks to provide answers, while anticipatory seeks to prioritize questions.

To advance an environmental technology development agenda within lean/agile organizations, LCA researchers had to develop new methods of environmental inquiry that are suitable for them. To this end, anticipatory LCA is designed to be effective under conditions of extraordinary uncertainty.

Not all questions or assessments that might be required by TRL/stage-gate will be investigated under lean/agile prior to launch. Rather, lean/agile must prioritize which questions or assessments are essential and which will be reprioritized after product releases. In this respect, only anticipatory LCA is explicit about being designed with a model of innovation that proceeds under high uncertainty, prioritizes uncertainties and responds to recursive feedback (Wender et al., 2014).

LCA methods organized around the TRL/stage-gate model of innovation demand answers before technology development is permitted to proceed. Because the stated goal of *ex-ante* LCA is a comparative assessment of the projected environmental benefits of pre-market technologies or products, relative to the incumbent, it is particularly well-suited for TRL/stage-gate approaches. In *ex-ante* LCA, a product or process that projects as a poor environmental comparison to incumbent technology should either be abandoned, or reprioritized to determine under what conditions the new technology might become superior.

By contrast, the recursive nature of the lean/agile model of innovation demands development of the next question, uncertainty, or experiment to prioritize. In this approach, every iteration is like testing a new hypothesis, and the subsequent product iteration is rarely worked out prior to gathering feedback on the current version from customers or the marketplace. Because the stated goal of anticipatory LCA is to rank-order environmental uncertainties for technology developers, it is particularly well-suited for the lean/agile approaches that currently dominate innovation at the world's most successful companies. For example, in anticipatory LCA, analysis can proceed without data by assigning probability distributions to LCA parameters for which no data exist (such as novel characterization factors). Then, proceeding via internal normalization (rather than external) and stochastic exploration of impact category weights, a global sensitivity analysis determines the uncertainties that are most relevant to undermining confidence in a comparison between novel and incumbent technologies. Thus, anticipatory LCA suggests which research and development questions might be prioritized next.

4.

Ex-ante vs anticipatory LCA

Several aspects of anticipatory LCA are inconsistent, if not in direct conflict with the current ISO guidelines that are the basis of *ex-ante* LCA. While the mathematical models constructed in each are identical in their form, the processes are distinct. Table 2 summarizes the distinctions. For example, in ISO, the interpretation phases that place characterized inventories in context are optional. However, anticipatory LCA cannot proceed without them.

Specific aspects

Uncertainty

One of the most challenging aspects of anticipatory LCA is proceeding in an environment of extraordinary data uncertainty. There are two aspects of the challenge. The first relates to the scientific training of typical LCA analysts, who are habituated to seeking definitive answers to data questions. Most are uncomfortable building LCA models based on hypothetical, probabilistic representations of unknown parameters. Rather than treating uncertainty assignments as scientific hypotheses to be revisited later, many analysts regard such analysis as guesswork that undermines their credibility. Nevertheless, closer coupling of LCA with methods of stochastic exploration already familiar in environmental risk analysis (e.g., Walker et al., 2015) allows anticipatory LCA to proceed even when uncertainties span several orders of magnitude (Eckelman et al., 2012).

The second aspect relates to the commercial software tools available to carry out analysis under conditions of high uncertainty. To date, existing software packages do not automate internal normalization, stochastic exploration of weights, global sensitivity, or rank correlation analyses. Thus, pursuing anticipatory LCA requires custom programming, which may be the single biggest obstacle to its adoption.

Relative vs absolute

When environmental impact assessments became part of regulatory review requirements in the 1970s, they expected absolute assessments of consequences related to stakeholder concerns in measurable units such as excess cancer deaths. By contrast, relative assessments can be reported as a dimensionless preference ordering of alternatives, with such alternatives defined by stakeholders. Thus, relative alternatives assessment has the advantage of being less burdensome for steering developmental pathways towards preferential outcomes. In anticipatory LCA, alternatives must be developed by technology developers in cooperation with analysts and stakeholders.

Normalization

External normalization seeks objective benchmarks beyond the scope of the analysis as context from

Table 2 | Comparison of ISO guidelines to anticipatory LCA

ISO guidelines	Anticipatory LCA
Organized for TRL/stage-gate innovation	Organized for lean/agile innovation
Difficulties proceeding in the absence of data for environmental inventories & characterization factors	Assigns hypothetical probability distributions to essential parameters, allowing analysis to proceed
Emphasizes absolute determination of environmental impacts in characterized inventory	Emphasizes relative comparison of environmental uncertainties in global sensitivity/uncertainty analysis
External normalization typical, albeit not required	Internal normalization typical, albeit not required
Normalization & weighting optional	Normalization & weighting mandatory
No requirement for stakeholder engagement	Stakeholder engagement essential
Reports back a product environmental profile reflecting quality of execution relative to planned performance criteria	Reports back product environmental research priorities reflecting search outcomes

which to interpret characterized inventories. Although external normalization dominates LCA wherever normalization is carried out, research has shown that it can introduce biases that mask significant environmental tradeoffs (Prado et al., 2017). Because elucidation of decision tradeoffs is essential in technology development, internal normalization is preferable to external in anticipatory LCA.

Weighting
Considerable uncertainty exists in application of the proper weights to apply in all types of LCA. For this reason, many analysts avoid applying any weights at all. However, the failure to weigh different impact categories encourages decision-makers to accept equal weights as their default view, which is rarely representative of stakeholder values. In fact, weights (like all LCA data parameters) are uncertain. Thus, they should be subject to the same kind of stochastic exploration and sensitivity analyses as other aspects of LCA (Prado et al., 2020).

Stakeholder engagement
One of the essential distinctions between TRL/stage-gate and lean/agile is the emphasis that the latter places on investigating and engaging with customers, suppliers and other stakeholders in the innovation ecosystem. This aspect is often overlooked in LCA. However, several aspects of any LCA method benefit from direct inputs from stakeholder groups, including determination of functional unit(s), selection of relevant impact categories and preferred weight space constraints (Wender et al., 2014). The mechanism by which these might be elicited in LCA is anything but methodical. Typically, a diverse set of stakeholders are convened in a workshop setting that includes academics, LCA analysts, and technology developers to facilitate conversations that build the capacity for representing multiple perspectives. Regardless of elicitation methods, anticipatory LCA suggests exploring uncertainty in stakeholder-driven parameters. For example, Ganesan & Valderrama (2022) used an online survey to elicit impact category weights in an anticipatory LCA evaluating end-of-life technologies for silicon PV. In exploring the sensitivity of the resulting rank-ordering of preferred technologies, they discovered that preference rankings were sensitive to weightings. While they identified this sensitivity as an “important limitation” of anticipatory LCA, from the perspective of a technology developer or research funding agencies, revealing this sensitivity may also be perceived as a strength.

Product vs priorities
The single most important distinction between anticipatory and other methods of prospective LCA is the insistence of anticipatory approaches on exploring uncertainty in interpretation. For example, *ex-ante* LCA emphasises the environmental characterization of pre-market products, whereas anticipatory LCA focuses on identifying research priorities.

5.

Application of anticipatory LCA

Anticipatory approaches to LCA were designed in concert with technology developers and researchers seeking to incorporate environmental considerations into new technology development. Engagement with technology developers, even before stakeholders, is essential. Table 3 guides LCA analysts in dialog with developers by identifying analogs in LCA that correspond to questions that developers working in a lean/agile model must confront. Developers might be able to guide analysts toward answers for some of these questions, such as competing or incumbent alternatives or thermodynamic process models. However, proposed functional units are more likely to emerge in dialog with developers, while in some categories (e.g., environmental risk modeling), knowledge that is likely outside the technology developers’ expertise will be required.

Specific aspects

(in reference to ISO guidelines, cf. Table 2)

Inventory building
Like other methods of LCA, anticipatory LCA requires constructing a mathematical model representing the thermodynamic (material & energy) process conversions at relevant stages of the life cycle, and the exchanges with the environment at each stage, including resource extractions & emissions. These steps are not novel to anticipatory LCA.

Characterization
Considerable uncertainty exists in the characterization of novel materials released to the environment. Rather than expect to improve risk-analytic models of fate, exposure and effect, anticipatory LCA allows the estimation

Table 3 | Guiding questions

Lean/agile	Anticipatory LCA
What problem is the technology solution attempting to solve?	What functional unit represents the effectiveness of the technology? What boundaries of analysis correlate to that unit?
Who has this problem?	Which stakeholders should be engaged?
What alternatives, competitors or incumbents offer solutions?	What alternatives shall be included in a comparative analysis?
What are they willing to pay for the solution?	What environmental values (e.g., impact categories & weights) represent stakeholder concerns?
What is the lifetime value of customers to the business enterprise?	What environmental liabilities (e.g., end of life) might be hidden from technology developers?
How is the product or technology created & delivered?	What are the thermodynamic (material & energy) requirements of the technology at each life cycle stage? How shall environmental risk assessment models/parameters be modeled for novel materials?
What is the set of minimum viable features to incorporate into the next product release? What is the next set of experiments necessary to develop those features?	To what processes or parameters is environmental assessment most sensitive?

of characterization as probability distributions that could hypothetically span several orders of magnitude. For example, in the case of nanomaterials, the exceptional heterogeneity of available variables makes characterization with confidence an extraordinarily laborious research task. However, allowing the analysis to proceed based on a uniform, log normal, or another probability distribution of risk parameters allows the analyst to explore the sensitivity of results to these risk-based uncertainties. In one case, the environmental impacts of nanomaterials manufacturing so dominated life cycle analysis that uncertainties in the fate and toxicological risk of novel nanomaterials were irrelevant to technology assessment (Eckelman et al., 2012). Thus, proceeding with the LCA analysis on the basis of estimates can reprioritize research resources towards uncertainties with the greatest impact or potential for improvement.

Normalization & weighting

Although optional under ISO guidelines, normalization is essential for anticipatory LCA. In particular, internal normalization techniques developed in multi-criteria decision analysis are applicable. For example, early efforts in anticipatory LCA were predicated on stochastic multi-attribute analysis (Prado-Lopez et al., 2014) that use pair-wise comparison for internal normalization and stochastic exploration of constrained weight spaces. However, other multi-criteria methods are also applicable. The advantages of internal normalization, compared to external, are principally two: (1) normalization relative to alternatives simplifies data requirements by obviating the need for selection of external normalization references, and (2) by avoiding bias and masking effects associated with external normalization, internal normalization is a better approach for elucidating the environmental tradeoffs that pertain to both stakeholder values and development decisions. The advantage of stochastic exploration of weight spaces is that it avoids privileging any default position. The disadvantage is that it requires additional computational effort. Existing commercial software packages in LCA do not automate internal normalization or stochastic weight exploration, which presents a barrier to pursuing anticipatory LCA approaches.

Sensitivity & uncertainty exploration

Where sensitivity analysis is conducted at all in LCA, it typically proceeds by identifying the sensitivity of environmental outcomes to variables that are (in the analyst's judgment) worthy of exploration. In addition to this approach, anticipatory LCA suggests global sensitivity analysis to identify those parameters that contribute the most to the uncertainty of outcomes. For example, Spearman rank ordering coefficients calculated in the anticipatory LCA of emerging PV technologies revealed counter-intuitive results regarding metals depletion and marine eutrophication that analysts may have otherwise overlooked (Ravikumar et al., 2018). Sensitivity results are sometimes presented as a tornado diagram that rank-orders the parameters that contribute most to uncertainties. This allows investigation of hypothetical experimental programs that might improve certainty (i.e., reduce uncertainty) to test comparative confidence. Those parameters that improve confidence in comparative technology assessment can be identified as high priorities for research.

6.

Recommendations and conclusions

Scholars of LCA for emerging technologies typically emphasize both the strength of the ISO guidelines and the necessity of departing from them (e.g., Bergerson et al., 2020). Recognizing that there are at least two models of innovation — TRL/stage-gate and lean/agile — will assist LCA analysts in matching a method of analysis that serves the needs of the development project. In general, TRL/stage-gate is found in large, well-funded organizations operating in mature markets like those for which ISO guidelines were originally developed. In contrast, lean/agile is found in start-up organizations and in large corporations seeking breakthrough innovations for markets that may not yet exist. Additionally, hybrid models of innovation are becoming increasingly common, especially as updated descriptions of stage-gate incorporate more recursive and flexible aspects of agile innovation.

Despite the applicability of anticipatory approaches to lean/agile models of innovation, the lack of automated computational tools in existing LCA software programs is a significant impediment to adopting and improving the methods. Incorporating internal normalization tools, stochastic exploration of constrained weight spaces, and global sensitivity analysis into available software packages would overcome the increased computational obstacles of anticipatory LCA, and likely lead to improved identification of environmental research priorities.

Anticipatory LCA outcomes can be used in a decision-making process where funding agencies, technology investors in industry or grantmaking organizations, or regulators are confronted with the question of having to decide on enabling, funding or authorizing an emerging technology development. This analysis suggests that continuing to explore and develop anticipatory LCA will be valuable to help identify and conduct an early assessment of possible environmental risks and threats to environmental sustainability embedded into emerging technologies.

However, it is too early to recommend that funding agencies and investors suggest or mandate the use of anticipatory LCA by technology developers. Nevertheless, from their perspective, formulating the guiding questions that would be asked during an anticipatory LCA process could help reveal the uncertainties embedded in the vision of the emerging technology design and possible outcomes. Anticipatory LCA offers funding agencies and other investors a basis for identifying those environmentally relevant hypotheses or research questions that are immediate, compared to those questions that are curiosity-based (e.g., at TRL 1) or made necessary by TRL/stage-gate criteria that may have little environmental relevance to the agile/lean innovation process that characterizes today’s technology world.

Box 1: Development of the TRL model of innovation

The TRL model of innovation is consistent with the linear understanding of technological progress that has dominated research & development since the end of World War II. It is based on principles described by Vannevar Bush in his seminal research policy report to the President of the United States (Bush, 1945; Wender et al., 2012). In it, Bush advocated for government sponsorship of basic research, and cited disease and national security as motivating examples of the benefits that will accrue to society.

Bush argued that “Basic research is performed without thought of practical ends. It results in general knowledge and an understanding of nature and its laws.”

He wrote:

> “Today, it is truer than ever that basic research is the pacemaker of technological progress. In the nineteenth century, Yankee mechanical ingenuity, building largely upon the basic discoveries of European scientists, could greatly advance the technical arts. Now the situation is different.
> A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill.”

In other words, Bush argued for federal government investments in scientific curiosity, with the understanding that new knowledge created without concern for its application would provide an intellectual foundation for improvements in the “technical arts” that naturally followed later. As federal government funding for basic research expanded, American Universities underwent a gradual restructuring away from education in either the classics, or the practical arts (agricultural and mechanical) and towards government-sponsored basic science.

Examples of curiosity-driven, or even accidental, discoveries that later found ground-breaking practical applications, such as the laser, reinforced Bush’s view. However, some of the most important technological advances of the 20th century did not develop along this path. For example, the invention of the solid-state transistor at Bell Labs was problem-driven. The creation of the first atomic bomb, and the moon landing, were organized around practical challenges, not scientific curiosity. In these cases, it can be said that basic science followed the need for practical application, rather than preceded it.

References

Bergerson, J. A., Cucurachi, S., & Seager, T. P. (2020). Bringing a life cycle perspective to emerging technology development. *Journal of Industrial Ecology, 24*(1), 6–10. doi.org/10.1111/jiec.12990

Blank, S. (2003). *The four steps to the epiphany: Successful strategies for products that win*. John Wiley & Sons.

Bush, V. (1945). *Science, the endless frontier: A report to the President*. US Government Printing Office.

Chertow, M., & Park, J. (2016). Chapter 5: Scholarship and practice in industrial symbiosis: 1989–2014. In R. Clift & A. Druckman (Eds.), *Taking Stock of Industrial Ecology*.

Cooper, R. G. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons, 33*(3), 44–54.

Cooper, R. G. (2014). What's next? *Research-Technology Management, 57*(1), 20–31.

Cooper, R. G., & Edgett, S. J. (2009). *Generating breakthrough new product ideas: Feeding the innovation funnel*. Product Development Institute.

Daniels, B., Follett, A., & Davis, J. (2020). The making of the Clean Air Act. *Hastings Law Journal, 71*(4), 901. repository.uchastings.edu/hastings_law_journal/vol71/iss4/3

Eckelman, M. J., Mauter, M. S., Isaacs, J. A., & Elimelech, M. (2012). New perspectives on nanomaterial aquatic ecotoxicity: Production impacts exceed direct exposure impacts for carbon nanotubes. *Environmental Science & Technology, 46*(5), 2902–2910.

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American, 261*, 144–152.

Ganesan, K., & Valderrama, C. (2022). Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels. Energy, 245(123207).

Ganter, M. J., Seager, T. P., Schauerman, C. M., BJ, L., & Raffaelle, R. P. (2009). A lifecycle energy analysis of single wall carbon nanotubes produced through laser vaporization. *2009 IEEE International Symposium on Sustainable Systems and Technology*, 1–4.

Grant, G. B., Seager, T. P., Massard, G., & Nies, L. (Eds.). (2010). Information and Communication Technology for Industrial Symbiosis. *Journal of Industrial Ecology*. doi.org/10.1111/j.1530-9290.2010.00273.x

Jensen, C. N. (2017). *Serious play approaches for creating, sharing, and mobilizing tacit knowledge in cross-disciplinary settings* [PhD dissertation,]. Arizona State University.

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics, 143*, 37–46.

Lapping, M. B. (1975). Environmental impact assessment methodologies: A critique. *Boston College Environmental Affairs Law Review, 4*(1), 123–134.

Moni, S. M., Mahmud, R., High, K., & Carbajales-Dale, M. (2020). Life cycle assessment of emerging technologies: A review. *Journal of Industrial Ecology, 24*(1), 52–63. doi.org/10.1111/jiec.12965

Murchison, K. (2005). Learning from More than Five-and-a-Half Decades of Federal Water Pollution Control Legislation: Twenty Lessons for the Future. *Boston College Environmental Affairs Law Review, 32*.

Prado, V., Cinelli, M., Ter Haar, S. F., Ravikumar, D., Heijungs, R., Guinée, J., & Seager, T. P. (2020). Sensitivity to weighting in life cycle impact assessment (LCIA. *The International Journal of Life Cycle Assessment, 25*(12), 2393–2406.

Prado, V., Wender, B. A., & Seager, T. P. (2017). Interpretation of comparative LCAs: External normalization and a method of mutual differences. The International Journal of Life Cycle Assessment, 22(12), 2018–2029.

Prado-Lopez, V., Seager, T. P., Chester, M., Laurin, L., Bernardo, M., & Tylock, S. (2014). Stochastic multi-attribute analysis (SMAA) as an interpretation method for comparative lifecycle assessment (LCA). *The International Journal of Life Cycle Assessment, 19*(2), 405–416.

Ravikumar, D., Seager, T. P., Cucurachi, S., Prado, V., & Mutel, C. (2018). Novel method of sensitivity analysis improves the prioritization of research in anticipatory life cycle assessment of emerging technologies. *Environmental Science & Technology, 52*(11), 6534–6543. doi.org/10.1021/acs.est.7b04517

Ravikumar, D., Wender, B., Seager, T. P., Fraser, M. P., & Tao, M. (2017). A climate rationale for research and development on photovoltaics manufacture. *Applied Energy, 189*, 245–256.

Straub, J. (2015). In search of technology readiness level (TRL) 10. *Aerospace Science and Technology, 46*, 312–320.

Takeuchi, H., & Nonaka, I. (1986). The new new product development game. *Harvard Business Review, 64*(1), 137–146.

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production, 259*, 120904. doi.org/10.1016/j.jclepro.2020.120904

Walker, W. C., Bosso, C. J., Eckelman, M., Isaacs, J. A., & Pourzahedi, L. (2015). Integrating life cycle assessment into managing potential EHS risks of engineered nanomaterials: Reviewing progress to date. *Journal of Nanoparticle Research, 17*(8), 1–6.

Wender, B. A., Foley, R. W., Guston, D. H., & Seager, T. P. (2012). Anticipatory governance and anticipatory life cycle assessment of single wall carbon nanotube anode lithium-ion batteries. *Nanotechnology Law & Business, 9*(201).

Wender, B. A., Foley, R. W., Hottle, T. A., Sadowski, J., Prado-Lopez, V., Eisenberg, D. A., Laurin, L., & Seager, T. P. (2014). Anticipatory lifecycle assessment for responsible research and innovation. *Journal of Responsible Innovation, 1*(2), 200–207.

Wender, B. A., & Seager, T. P. (2014). Anticipatory lifecycle assessment of SWCNT-enabled lithium ion batteries. In D. Rickerby (Ed.), *Nanotechnology for Sustainable Manufacturing*. CRC Press.

Womack, J. P., Jones, D. T., & Roos, D. (2007). *The machine that changed the world: The story of lean production — Toyota's secret weapon in the global car wars that is now revolutionizing world industry*. Simon and Schuster.

Blank S. 2003. *The four steps to the epiphany: Successful strategies for products that win*. John Wiley & Sons.

Bergerson, J. A., Brandt, A., Cresko, J., Carbajales-Dale, M., MacLean HL, Matthews, H. S., McCoy, S., Mc Manus, M., Miller, S. A., Morrow, W. R., Posen, I. D. 2020. Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity. *Journal of Industrial Ecology, 24*(1), 11–25.