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The Evolution of Life Cycle Assessment in Pharmaceutical and Chemical Applications – a Perspective

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This paper provides a broad strokes perspective on the evolution for the application of Life Cycle Assessment (LCA) within the pharmaceutical and chemical industries. This focus is mainly on the challenges faced to produce the needed inventory data and using the resulting LCA output in decision making, which are the backbone of any LCA estimation and practical application in industry. It also provides some of the insights the authors have derived over the last two decades of work in this area, and proposes a series of development needs within life cycle assessment as it becomes more integrated into decision-making in industry.

Introduction

Life cycle assessment (LCA) is a methodology used to estimate the environmental impacts beyond the traditional boundaries of the chemical or manufacturing plant. An LCA quantifies the resource consumption (materials and energy), emissions, and the resulting environmental impacts throughout the supply chain, including raw material extraction and conversion, manufacturing, transportation, sales, distribution, use, and final fate. Depending on the objectives, the life cycle evaluation impacts can have different boundaries.[1,2] For instance, it could cover the entire supply chain (cradle-to-grave, or CtG), a single chemical plant (gate-to-gate, or GtG), or impacts downstream from production. Life cycle metrics can either be

- direct life cycle inventory (LCI) data, for example life cycle energy, life cycle mass, life cycle emissions;
- or they could come from a life cycle impact assessment (LCIA), which measures either individual impacts such as global warming potential, or aggregates the impacts into a score or index, such as the EcoIndicator 99 method.[3]

Life cycle thus provides a framework of more holistic 'green metrics' to estimate the environmental footprint of a route, process, or reaction. The use of LCA to measure the 'greenness' of chemistries has been championed previously elsewhere as a strategic need in the development and use of green metrics.[4, 5, 6, 7, 8, 9]

There has been an increased interest in the utilization of LCA techniques to evaluate 'greenness' of chemical and pharmaceutical routes in the last few years, perhaps primarily driven by the increased global interest in climate change and the drive to estimate the global warming potential impacts of a chemical route. Even with this increased uptake, the routine use of LCA is not fully embedded as a business process, and continues undergoing an evolution, with different companies being at diverse stages in the journey.[10, 11] This paper provides a broad strokes perspective on the evolution of the application of LCA within the pharmaceutical and chemical industries, focusing mainly on the challenges faced to produce the needed inventory data and using the resulting LCA output in decision making, which are the backbone of any life cycle assessment estimation and practical application in industry. It also provides some of the insights the authors have derived over the last two decades of work in this area, and proposes a series of development needs within life cycle assessment as it becomes more integrated into decision-making in industry.

Life Cycle Assessment in the Pharmaceutical and Chemical Industries – an evolution

In a broad view, life cycle capabilities have continued to increase as an evolutionary process in the pharmaceutical and chemical industries. This evolution started from the initial exploration of the concept with a few case studies. Then it slowly transformed to the industrial recognition of the need to account for impacts external to the synthesis or process at hand. Moves then occurred towards an accelerated phase with more widespread understanding and application of the concept and finally becoming part of an overall strategic direction in some instances (Figure 1). In terms of the methodology, LCA has also moved from initial academic ad-hoc approaches to currently having existing ISO standards that guide the LCA practitioners on the elements needed to conduct an assessment, which includes uncertainty and sensitivity analysis as well as critical review.[1, 2] In addition, Product Category Rules (PCR) and Environmental Product Declarations (EPD) are being explored more frequently by different industries.[12]

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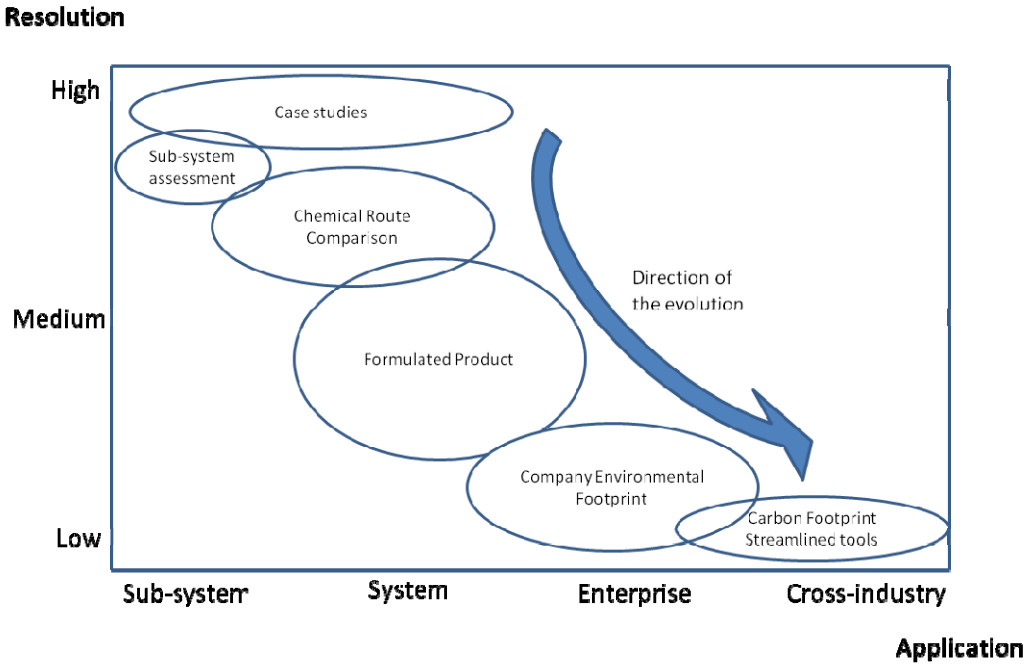

Figure 1. Evolution of life cycle assessment application in the pharmaceutical and chemical industries

Table 1 shows some selected examples that illustrate in high level the overall evolution of life cycle assessment practice. Some examples in the table deserve some additional discussion

- Boustead (1979). The use of an industrial group, making a similar chemical or material, to share manufacturing data with a third party. These data are then averaged to reflect the GtG LCI of a chemical. This approach requires considerable time per chemical (6 months – 2 year) and is a challenge to assure each contributor is making the same assumptions and allocations. The Plastics Europe (2005) data are an example of this LCI evolution step for the pharmaceutical and chemical industries.[13, 14]
- SETAC-Europe. The designation that a life cycle consist of three stages in series (LCI, LCIA, and life cycle decision-making) led to the understanding that life cycle inventory is the fundamental information or building block that drives the results.[15]
- Specific case studies. In this approach, data of an entire plant or subsection that makes a specific product are used to estimate energy and material use. These studies are typically from one company sponsoring the study, and as such are rarely published or made available to the public. In addition, looking at a variety of these LCI/As, it is unclear the same assumptions and boundaries are used thus posing a challenge when integrating different studies.
- Economic input-output (EIO). EIO uses comprehensive national economic data (developed for critical national policy needs) as a top-down methodology to estimate environmental impacts.[16] The theory is that the economic linkages among industrial sectors gave the indirect or overhead plus the direct use of energy and chemicals for the manufacture of a given products. Again, the availability of user-friendly software has attracted users. While useful in high-level assessments, EIO has such low granularity and so many embedded assumptions that make variability sufficiently large and so the LCI comparisons of alternatives (A versus B) are challenging within acceptable uncertainty (even though quantitative LCI values are derived). The development of EIO-hybrid approaches (combined EIO and direct manufacturing data) has reduced the variability, but these still remain a generalized profile of alternatives.

- Process or Design-based LCI. The use of industrial, engineering, and scientific data to mimic the methods used to actually design or analyze the process for manufacturing a chemical or material links the process-based (or design-based) results to common industrial practice. Since the engineering principles used are widely accepted, the LCI results are generally non-proprietary and can thus be used by others. The variability is generally in the 10% - 30% range.
- ISO Standards. The practice of LCA has been codified with the aim to consolidate procedures and methods to perform LCA. The ISO Standards provide both a framework of the methodology and the guidance to be used while conducting LCAs. The standardization also extends to conducting Environmental Product Declarations and setting the Product Category Rules.

Table 1. Illustrative examples of the historical evolution of life cycle practice

Year	Illustrative example
1969	Coca Cola (Type of packaging)
1972	REPA (Resource & environmental profile analysis (Mobil/polystyrene tray)
1979	Boustead (Glass milk bottle)
1973	Germany (Degradable plastics)
1974	Initiation of public life cycle thinking (e.g., REPA, Plastics, Solid waste, Primitive impact assessment).
1975	U.S. Federal Energy Agency – Solid waste to energy
1977	Switzerland – First accessible database – BUWAL
1987	Germany – Creation of economic equivalent of life cycle
1990s-present	Specific case studies – targeting a given plant, process, or product
1990	Paper versus plastic- public awareness
1990 – 1993	SETAC-Europe (Development of life cycle method)
1993	European Plastics Study – Aggregate Industrial Methodology
1995	Process or Design-based LCI
1998	Economic Input Output Life Cycle Inventory
1997 – 2006	ISO Standardization of life cycle assessment
2000s-present	Streamlined LCA tools

However, as the life cycle practice develops and gets more codified as a discipline, the devil is still in the details and the challenges remain primarily focused on:

- the practical approach to obtain the information needed that is representative of the system at the appropriate level for the objectives of the assessment
- how to effectively use the results to improve decisions on the development of new chemicals, active ingredients, formulated products, processes, or materials.

Challenge 1 – Obtaining appropriate data

With this evolution in mind, as one starts the task of performing an LCA, one of the initial questions would be the data strategy to be followed, including the level of detail needed and the approaches used to obtain the data. Obtaining data for an LCA in the pharmaceutical industry is not a simple endeavour given the large amount of data required from a variety of sources. For a typical active pharmaceutical ingredient (API), the bill of materials may involve anywhere from 20, 50 or more chemicals (depending on the complexity), each of which will require their own inventory data to complete the assessment. For instance, typical pharmaceutical active ingredient cradle-to-gates can involve 200-250 LCI GtGs - that is, individual chemical plants. The other main challenge is the absence of data for many of the raw materials needed in the production of most typical APIs. Overall one can classify the approaches to data strategy currently used for LCA into three general categories, each with advantages and limitations.

i. **Life cycle thinking –** the examination (even at a preliminary level) of how the entire system of a drug, chemical, or product is connected and hence how change can propagate. This underlines how various parts of the system affecting the environment are all connected. This category is rapidly growing as people inquire about the broader environmental effects of a product. The data required at this stage are less detailed and often either qualitative or relying on high level streamlined LCA tools to get a general first approximation of the impacts. Since life cycle thinking is generally qualitative, it is relatively easy to undertake this form of life cycle analysis (have we thought about the whole cradle-to end-of-life of a product?).

ii. **Current commercial software and databases and streamlined tools –** a large number of companies, universities, and organizations utilize these systems to conduct LCAs. These alternatives (such as Boustead, SimaPro, Ecoinvent, Gabi, FLASC™, ABPI, etc.) are relatively user friendly, providing both an LCI and and LCIA. Streamlined tools are very useful. Some examples are the tools developed by GlaxoSmithKline (GSK) and later adapted by the American Chemical Society Green Chemistry Institute Pharmaceutical Roundtable[17, 18] or such as the UNEP's LCA Initiative, Life Cycle Regional Networks, ACLCA, Calcas, CCaLC, ETH, amongst others.[19, 20, 21, 22] The limitations are that the individual blocks (the gate-to-gate data) are often nontransparent, use a variety of allocation systems, have very different original data, and include proprietary data that cannot be reviewed.

These limitations may not be substantial if the objective is to perform a screening assessment. However, if the goal is to deepen understanding of the system, use of these systems may introduce additional uncertainty. In addition, decision-makers are limited to using the life cycle information for the qualitative value, despite the quantitative results displayed by the software.

Engineering-based life cycle assessments– Engineering-based (also known as design-based or process-based) LCI utilize the fundamentals of the manufacturing unit processes to provide an integrated gate-to-gate analysis; thus, using an analogous approach to the engineering designs. The high level of transparency (chemical reactions, separations, engineering calculations, assumptions) increases the ease of technical review and adds to credibility. The unit process analysis has the limitation of the time consumed to generate the data (about one week per GtG per person). However, it provides two new benefits: first it provides an understanding of the variables or parts of the LCI that most impact the results, and secondly this understanding allows for the development of streamlined tools that speed results for timely decision-making, thus circumventing the timing challenge. In addition, as all too often companies would consider externalization and outsourcing, engineering-based LCIs help to better assess the environmental impacts of the outsourced processes, thus providing a more complete footprint estimation. Engineering-based assessment has also allowed the development of the corporate LCI databases given in Table 2. The work of Environmental Clarity[23, 24] and recent work by Franklin Associates (2011)[25] and Rowan University are some examples of this LCI data strategy approach.[26]

Table 2. Development history of life cycle programs at selected pharmaceutical and chemical companies

Corporation	Year
Dow Chemical	1990
DuPont	Late 1990s
BASF, Corp.	1996
GlaxoSmithKline, Plc	1997
Pfizer, Inc.	1997
Albemarle Corp.	2010
Israel Chemicals Ltd	2010
EMD Millipore Corp.	2008

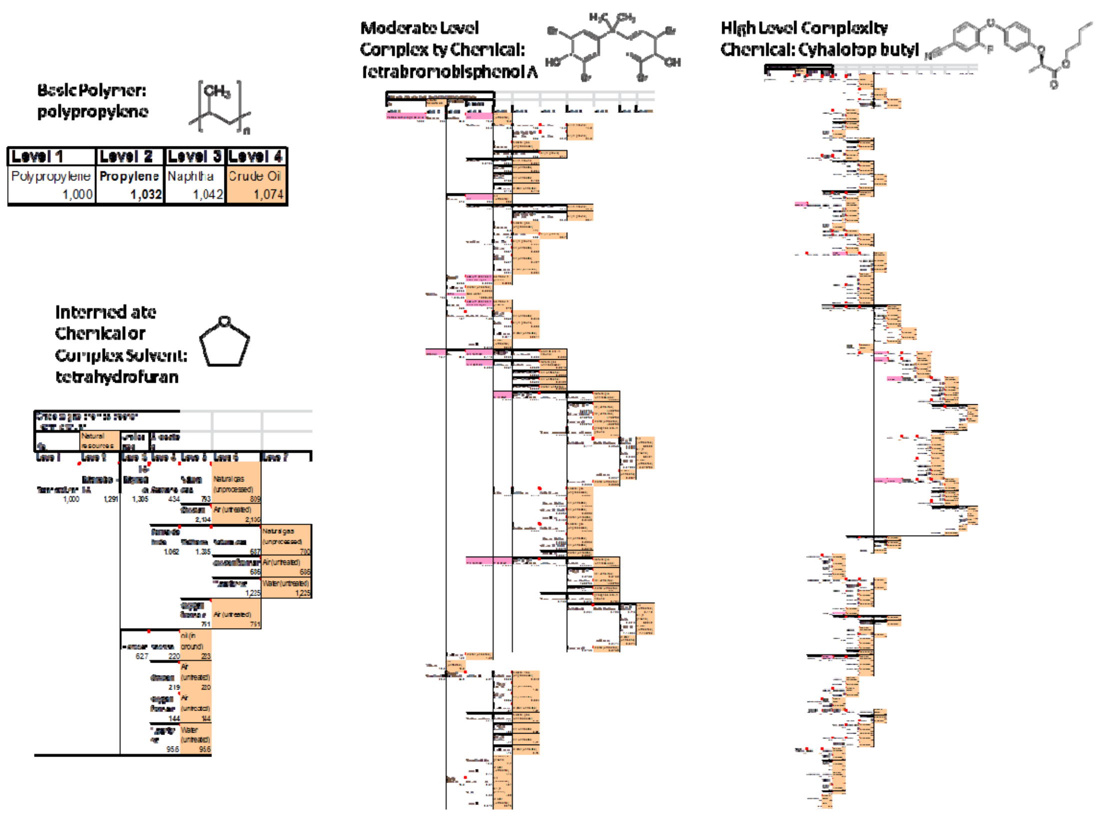

Figure 2. Life Cycle Inventories of Chemicals at Different levels of Complexity. Note that the resolution will be lower the more complex the supply chain is, going from polypropylene and tetrahydrofuran, with 4 and 11 gate-to-gate blocks respectively, to molecules such as Tetrabromobisphenol A (45 GtGs) and Cyhalofop butyl (63 GtGs).

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The early LCIs were basic polymers for packaging, such as the chemical tree of polypropylene shown in Figure 2, which are found in these three approaches. The engineering-based approach has allowed more complex chemical life cycles, such as the other examples shown in Figure 2. Figure 2 also illustrates how the resolution of an LCA changes with the complexity of the supply chain; the two more complex supply chains make it impossible to even read the names of the components in the chemical tree! Of course, while conducting an LCA, a hybrid approach of these strategies could be used. This would depend on the goal and scope of the assessment, the time available for the level of granularity required, and the acceptable uncertainty and sensitivity desired. For instance, one can conceive of having streamlined tools providing some initial estimate when the initial goal is to identify hot spots or to obtain insights to pose research questions; then, after the areas of focus are identified, a full LCIA can be conducted with a higher degree of resolution.

Challenge 2 – Effectively applying LCIA insights

To put this into context, one can review two typical applications of an LCA. First, in basic terms, life cycle could be seen as a means to compare alternatives from the environmental footprint standpoint to make development or improvement decisions. For instance, when comparing reaction A with reaction B, in which either

- A is better than B (A>B)
- B is better than A (B>A), or
- A and B are essentially similar (A≈B).

Examples of this is the comparison of several routes to Pfizer's Sertraline[27] the footprint of two active pharmaceutical ingredients, one from Roche and another from GSK,[28] or the comparison of a chemical or enzymatic route.[29] Using LCA to compare alternatives is made challenging by the uncertainty introduced by poor granularity, variability in parameters of estimates, proprietary data, and allocation methods (unless one neglects the variability, as it is still often done in practice). Some of life cycle evolution has made this variability worse, but some changes have improved the ability to compare alternatives.

Second, life cycle is also used as a comprehensive methodology for understanding the major contributors to the environmental footprint of a product, therefore allowing to make environmental and energy improvements across larger systems (like supply chain or end-of-life), instead of a single manufacturing plant. Examples include the assessment of an active pharmaceutical ingredient at Pfizer[27] or GSK[30] or routes to a solvent.[31] Thus, life cycle increases the opportunities to have a net improvement on the environment. It is in this area of expanded opportunities that life cycle has improved substantially.

In pharmaceuticals, the application of LCA metrics is still not a widespread practice. However, the use is definitely more widespread now than a decade ago. Nowadays, practitioners in the pharmaceutical industry use LCA in an array of different applications: through case studies to better understand the wider environmental implications of processes, to compare different chemical routes, or to compare the use of different unit operations, to name few. In the same fashion as LCA has evolved in general, one can see that within the pharmaceutical industry the application of LCA has also proceeded through several stages, namely:

- Probing case studies through LCA of specific molecules. The initial foray into LCA by several companies was focused on particular case studies intended to expand the understanding of the life cycle impacts of an activity and to identify opportunities to reduce the environmental impacts. Ostensibly, the initial publicly available pharmaceutical LCAs \were focused on chemical routes used to synthesize important active ingredients (e.g., Sertraline).
- Sub-system assessment. To answer some specific questions the pharmaceutical industry has sometimes used LCA to answer specific questions pertaining to parts of the system, such as solvents, catalysts, equipment, particular waste streams, and processing options.
- Chemical route comparison. The logical evolution of the initial LCAs moved to comparing chemical route or processing alternatives. This was the typical A versus B example described above. Some examples include comparing chemical and biological routes, or comparing the impacts of producing different molecules. The initial emphasis was to perform assessments to compare chemical routes for the production of the API, given that most of the cost and intellectual property value resides in the API
- Formulated Product LCAs. From the initial emphasis placed in APIs, some intelligence was gained on typical hot spots, and on whether the environmental profile mirrored the cost structure, and on what was the environmental profile of different dosage forms, such as devices, tablets, liquids, creams, etc. Several pharmaceutical companies have undertaken LCAs of key products and product classes to answer specific questions. These assessments have

been both in full LCAs or more streamlined carbon footprint.

- Enterprise environmental footprint. Companies have undertaken environmental and carbon footprints covering their global operations, with different sets of boundaries. Very frequently this is an extension of their corporate responsibility reporting activities, and in some cases as part of the identification of 'hot spots' and opportunities for improvement.
- Streamlined tools. The two challenges we have discussed above have driven the use of streamlined life cycle analysis techniques in order to gain insight into the environmental impacts of pharmaceutical activities within reasonable timelines. The continuous development of reliable, common, easy-to-use, streamlined LCA tools continues to be an important need for industry

Table 3 presents some illustrative examples of the application of LCA within the context of the pharmaceutical industry. Although these stages are evolutionary in nature when thinking of the practice of LCA, any company could make efficient use of the different type of applications.

Table 3. Selected Illustrative Examples of Application of LCA in Pharmaceuticals

Type of application	Examples	References
Probing case studies through LCA of specific molecules	• Pfizer– evaluation of chemical routes for the production of Sertraline, which identified hot spots for improvement assessment • Novartis – Limited LCA of two products • GSK - cradle-to-gate LCIA case study in the synthesis of an API to help define the practical methodology used in GSK • Pfizer – evaluation of the route for Pregablin	• 27 • 32 • 30 • 33
Chemical route comparison	• Comparison of a chemical vs. an enzymatic route for an intermediate • LCA assessment to compare APIs from Hoffmann La-Roche and GSK	• 29 • 28, 34
Materials assessment	• GSK and AstraZeneca – incorporation of LCA into solvent selection • EHS and LCA solvent assessment • Enzymes LCA assessment • In-process solvent assessment • GSK Reagent Selection guides, including LCA	• 35, 36 • 37 • 38, 39 • 26 • 40
Sub-system assessment	• Waste treatment, Pfizer, Novartis, BMS, GSK • Disposable vs. reusable processing equipment • Exergetic LCA for technology options	• 41, 42 • 43, 44, 45, 46, 47 • 48, 49
Formulated Product LCA	• Carbon footprint of respiratory products • GSK's Cradle-to-gate LCA for pharmaceutical product in device	• 50 • 9
Enterprise-wide footprint	• GSK enterprise wide carbon and water footprint	• 51, 52
Streamlined tools	• GSK's Fast Life Cycle Assessment of Synthetic Chemistry • UK's National Health System Green House Gas Accounting for Pharmaceutical Products and Medical Devices • Pharmaceutical Roundtable Process Mass Intensity-LCA Tool • Systematic way of filling data gaps on provided by the ACS GCI Pharmaceutical Roundtable to the Swedish Voluntary Incentive Scheme • ABPI and Carbon Trust tool blister pack carbon footprint tool	• 17 • 53 • 8 • 54 • 55

One of the general observations from this evolution, is that given the challenges both in terms of application of LCA insights and data collection and quality, the evolution has been driven in terms of both reducing the level of detail or complexity of evaluations and extending the boundaries. One consequence is that more limited approaches to LCA need to be used in an attempt to improve the decision-making process. For example, to circumvent the challenges of applying LCA learnings that can be complex with many metrics and trade-offs, many companies are currently focussing more in one metric, global warming potential (also referred to as carbon footprint) in isolation to highlight process improvements that may address climate change challenges. This was the case of GlaxoSmithKline, which used carbon footprint analysis across its entire global supply chain to determine the main areas of concern directly under the control of the company.[51] On the other hand, to circumvent the lack of data challenge, companies have developed streamlined tools that would provide approximations or systematic methods to fill in the data gaps in a consistent manner, thus reducing the time to perform an assessment within reasonable timelines and agreed levels of uncertainty.

These limited approaches are trading resolution and holistic view against the ability to incorporate LCA insights into industrial decision-making, which is a calculated and practical trade-off. The key to having these limited approaches not be too constraining, is the recognition that having to work at a lower resolution and higher uncertainty space may not be applicable to all scenarios, and that it is necessary to maintain an appropriate level of transparency regarding assumptions and limitations.

Lessons learned and current needs – a practitioner's perspective

The following concepts are the authors' observations of the life cycle analysis field in the chemical and pharmaceutical industry over the last two decades:

1. Corporations with advanced life cycle capabilities have a significant advantage when integrating broad environmental benefits and consequences of products into decision-making for R&D and for process improvement. These capabilities allow them to also diagnose other similar products to gain a competitive advantage.
2. The conversion of LCI data to LCIA data increases the variability (for example human toxicity variability increases from ±10% - 30% at the LCI stage to ± 10,000% at the LCIA stage) thus making comparisons of alternatives more challenging. In fact, the LCIA results that reflect energy use are often 90%-95% of the footprint, while impacts from process chemical emissions are typically 5%-10%. Thus LCI energy comparisons are both more effective in signalling differences and actually drive the LCIA results without high variability.
3. LCIA data, even for just the major categories (5-7 impacts) are not available for most of the chemicals in the LCI databases (~ 1,200 chemicals), and this is a pronounced limitation to capturing actual impact information. These missing data are rarely identified in the LCIA results.
4. Life cycle publications are increasingly not building the LCI databases needed by the community since, for a variety of reasons, LCIA data and data expressed as percentages are published, but the underlying LCI are not. The lack of transparency reduces the credibility of life cycle studies.
5. Economic Input-Output LCI remains at such low granularity that results are restricted for most practical comparison of alternatives.
6. Uncertainty Analysis is still not routinely used in the LCA assessments. Frequently, life cycle variability means that the conclusion is A and B have about the same environmental impact (within ± 20% - 30%).
7. Similar to the uncertainty analysis, sensitivity analyses are in practice often not performed as part of an LCA assessment, thus potentially masking or overestimating the importance of certain elements or variables.

Given the observations described above, and the challenges on data availability and application of insights discussed previously, we submit that the following research needs on LCIA can be highlighted:

Data Availability.
It is necessary to continuously improve the consistency and transparency of the information and the assumptions used in such tools to ensure the quality and the validity of the decisions made with the aid of LCA metrics. The challenge is to have access to LCI information for all chemicals in commerce (~ 100,000 manufactured at greater than one metric tonnes/yr) as a framework to allow LCI analysis by researchers and users on a global basis.[56] Some particular examples include

- Databases with higher geographic resolution, especially for water and eventually for land
- Better understanding of LCIA of bioprocesses, biopharma and bio-derived materials.
- Improved consistency and transparency of LCIA methodologies
- Enhanced understanding of LCIA impacts of processes and chemistries using emerging technologies (e.g., reusable bio-processing equipment, process intensification equipment, novel catalysts, novel reagents, novel solvents).
- Continuous development of reliable, common, streamlined LCIA tools that are easy to use with an appropriate degree of transparency for a given application.
- Updates to industry-average data sets available , such as the data from Plastics Europe
- The ability to compare LCI results against quantitative and absolute scenarios or data.
- Methodologies to guide practitioners on how to best measure and describe the life cycle impacts related to land use and changes
- Enhanced understanding of the overall environmental impacts of formulated products, especially as consumers become more aware of these
- The inclusion of quality indicators while communicating LCA results in a routine basis (such as sensitivity and uncertainty analysis).
- Incorporating routine peer-reviews in performed LCAs, as the current LCA expertise in pharmaceuticals and chemicals continues to be very limited

Application of LCA insights into decision-making.
The communication of LCI information for effective use by wider audiences (even within the technical community) could be a challenge, as it may be easy to either overcomplicate or oversimplify the results. As companies become more focused on a single issue they run the risk of neglecting important trade-offs or losing sight of other emerging issues. For instance, as the focus has rightly increased on climate change in the last few years, it is easier to focus only on carbon whilst data on other impacts can be obtained in the same calculations. This is particularly the case with emerging issues such as water (it has been said that 'water is the next carbon'), nutrients, land use, and other ecosystem impacts. All of this can be overwhelming, and could drive a company to play catch up with the external environment. A few thoughts here to improve the incorporation of LCA into decision making, sometimes without people even needing to know what an LCA is:

- Start with the end in mind – LCA is a tool for a given goal, not a goal per se. Practitioners need to be rigorous about the goal and scope of any LCA performed and have that drive the data strategy, boundaries, accuracy and resolution of the outcome. What may be completely appropriate when comparing two chemical routes may not be appropriate when setting strategy.

- Small steps count. Routine use of LCA metrics into ongoing practice remains a gap. Some companies would have the resources to start a comprehensive program, some will not. Depending on the degree of sophistication of the LCA understanding in the company, one option to embed these metrics is to start communicating relatively simple LCA metrics (e.g., carbon footprint, cumulative energy demand), and use these as a bridge for collection and communication of more complex LCA metrics.
- Find data-driven insights. Estimating an LCA or a carbon or water footprint is just the beginning, the real gold mine of LCA is to be able to use the data to identify the most effective development changes and improvements that can be targeted and actionable at the lab or shop level. For instance, in early research GSK found that consistently solvents contributed the most to the footprint of synthetic routes, so there was a targeted focus on solvent selection, and on decreasing the solvent use
- Make it easy at the lab or shop level. There is a continuous need to develop application tools that embed the insights from LCA into everyday decision-making use. Data visualization techniques will need to be used to effectively drive the right behaviour changes and find that right balance between simple, but not simplistic.

Conclusions and Final Remarks

The demand for life cycle information, particularly quality LCI, is increasing issues such as from carbon footprint questions, Product Category Rules and Environmental Product Declarations, government aspirations to have life cycle understanding of all purchases, EU funding agency requirements for life cycle in all projects, product consortia life cycle initiatives, and corporate groups. This demand can easily exceed the body of LCI and LCIA data leading to frustration. The data infrastructure to meet this demand will need to be constructed and continuously enhanced in the future.

In addition to the need to enhance the LCI data quantity and quality, there should be an increased emphasis on how to present and use both the LCI and LCIA information at the right level. As important as having better LCA data is, the need remains to continuously focus on first ensuring that we are asking the right questions. Only after the goal and scope are well defined, can we then perform LCAs that will give useful insights to drive the right specific behaviour.

When these requirements are fulfilled, LCA metrics can be used as powerful tools to aid the decision-making towards greener products and processes.

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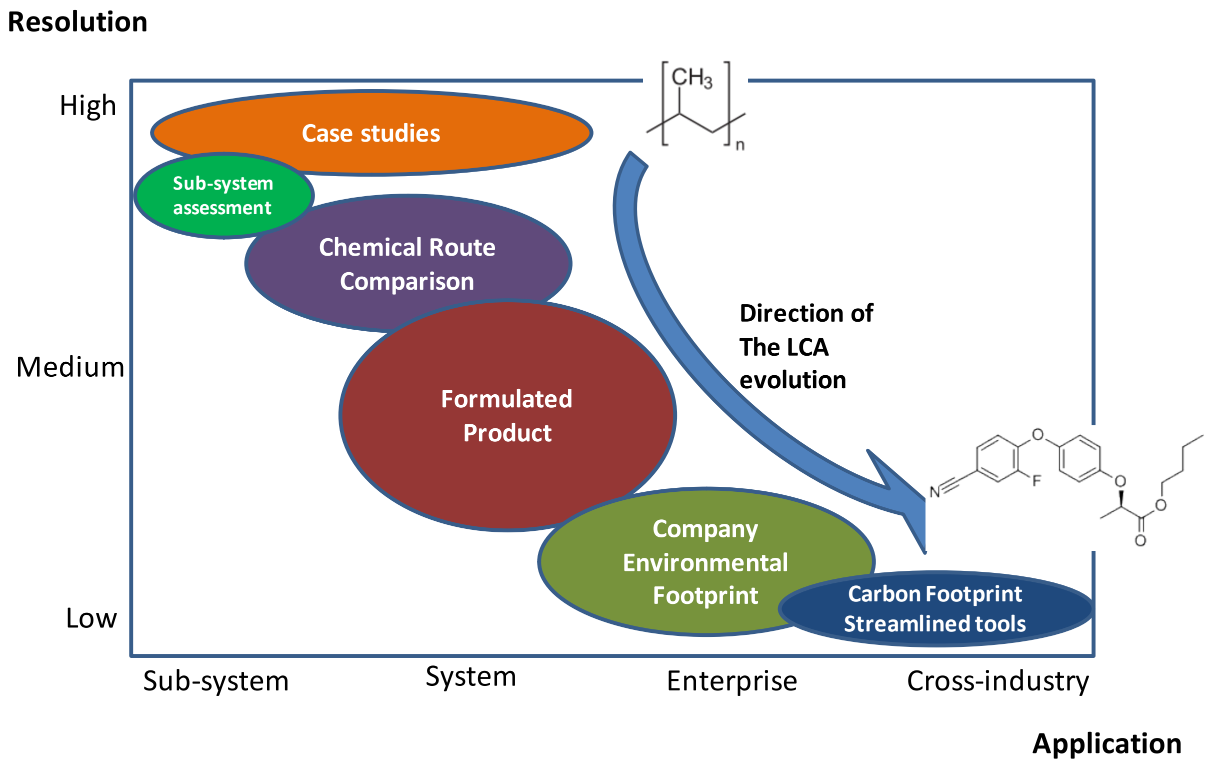

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