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Published in:
Science of the Total Environment

Link to article, DOI:
10.1016/j.scitotenv.2020.140700

Publication date:
2020

Document Version
Peer reviewed version

Citation (APA):
Beloin-Saint-Pierre, D., Albers, A., Hélias, A., Tiruta-Barna, L., Fantke, P., Levasseur, A., Benetto, E., Benoist, A., & Collet, P. (2020). Addressing temporal considerations in life cycle assessment. *Science of the Total Environment*, *743*, Article 140700. https://doi.org/10.1016/j.scitotenv.2020.140700

Addressing temporal considerations in life cycle assessment

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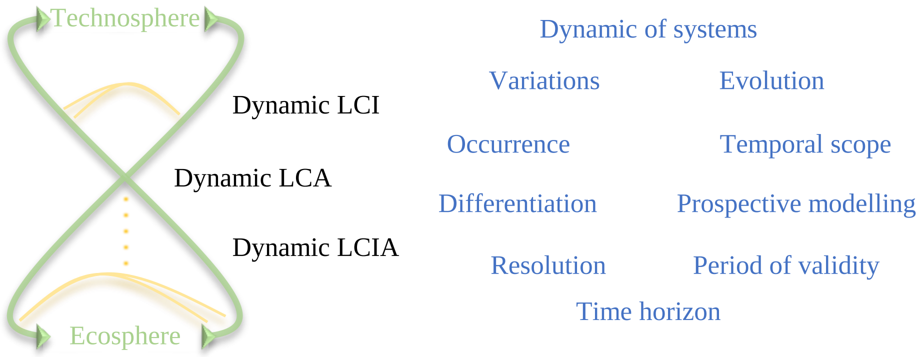
HIGHLIGHTS:

- Review of temporal considerations in the life cycle assessment methodology
- Glossary of important terms for time considerations in life cycle assessment
- Key aspects of dynamic life cycle assessments
- Current implementation challenges for dynamic life cycle assessment
- Development pathways for future dynamic life cycle assessment



ABSTRACT

In life cycle assessment (LCA), temporal considerations are usually lost during the life cycle inventory calculation, resulting in an aggregated "snapshot" of potential impacts. Disregarding such temporal considerations has previously been underlined as an important source of uncertainty, but a growing number of approaches have been developed to tackle this issue. Nevertheless, their adoption by LCA practitioners is still uncommon, which raises concerns about the representativeness of current LCA results. Furthermore, a lack of consistency can be observed in the used terms for discussions on temporal considerations. The purpose of this review is thus to search for common ground and to identify the current implementation challenges while also proposing development pathways.

This paper introduces a glossary of the most frequently used terms related to temporal considerations in LCA to build a common understanding of key concepts and to facilitate discussions. A review is also performed on current solutions for temporal considerations in different LCA phases (goal and scope definition, life cycle inventory analysis and life cycle impact assessment), analysing each temporal consideration for its relevant conceptual developments in LCA and its level of operationalisation.

We then present a potential stepwise approach and development pathways to address the current challenges of implementation for dynamic LCA (DLCA). Three key focal areas for integrating temporal considerations within the LCA framework are discussed: i) define the temporal scope over which temporal distributions of emissions are occurring, ii) use calendar-specific information to model systems and associated impacts, and iii) select the appropriate level of temporal resolution to describe the variations of flows and characterisation factors.

Addressing more temporal considerations within a DLCA framework is expected to reduce uncertainties and increase the representativeness of results, but possible trade-offs between additional data collection efforts and the increased value of results from DLCAs should be kept in mind.

KEYWORDS:

Dynamic LCA, temporal considerations, review, recommendations, implementation challenges

1. INTRODUCTION

Disregarding temporal considerations[1] has been identified as an inherent limitations of life cycle assessment (LCA) (ISO14040, 2006; ISO14044, 2006). Indeed, the importance of properly considering the dynamics of environmental sustainability for the comparison of products, services or systems has been explored, debated and confirmed during the last 20 years by many researchers like Owens (1997a), Herrchen (1998), Reap et al. (2008a; 2008b), Finnveden et al. (2009), Levasseur et al. (2010) and McManus & Taylor (2015), to name a few. In this discussion, Rebitzer et al. (2004), Reap et al. (2008a) and Yuan et al. (2015) have mainly explored the subject of dynamics in human activities. During the same period, Reap et al. (2008b), Shah & Ries (2009), Fantke et al. (2012), Kendall (2012), Levasseur et al. (2012b) and Manneh et al. (2012) have proposed different ideas on the dynamics of environmental responses to human pressures. Additionally, Hellweg et al. (2003b; 2005; 2014), Levasseur et al. (2013), Saez de Bikuña et al. (2018) and Yu et al. (2018) have underlined different potential effects from the choice of temporal boundaries in LCA studies. These three general subjects have covered the bulk of the conversation on temporal considerations in the LCA framework and a growing awareness of the LCA community on this topic is shown in figure 1[2] with a growth in the number of publications where some aspects are addressed.

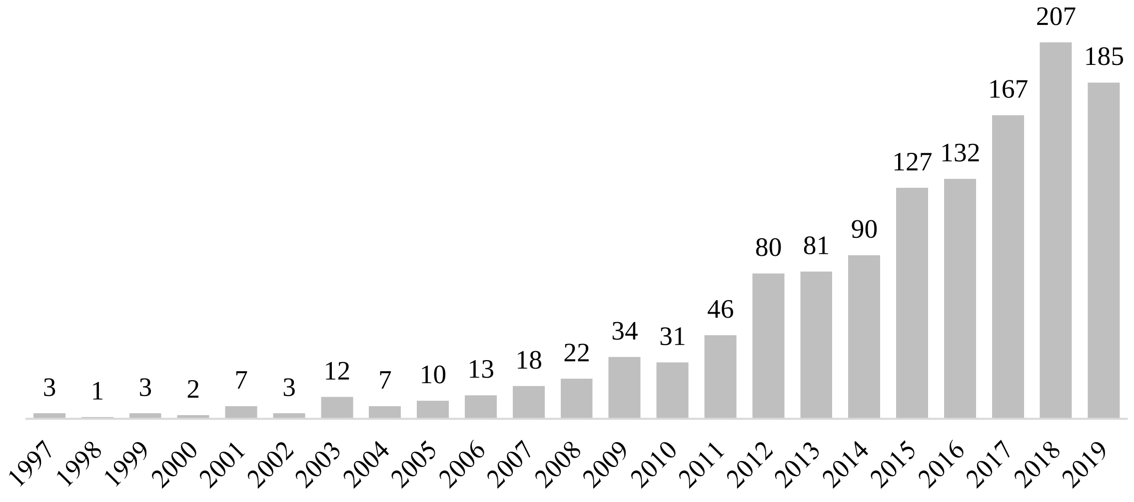


Figure 1: Numbers of LCA publications per year where temporal considerations are discussed

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[1] Consideration encompass all aspects relating to the description of time and dynamics of systems (see glossary in Table 1).

[2] The annual number of publications were found with the advance search function on web of science. The following words and conditions were searched for in the topic section: (“life cycle assessment” AND temporal) + (“life cycle assessment” AND “time horizon”) + (“life cycle assessment” AND dynamic). The word “time” was not part of the search to avoid mentions of the time required for data gathering activity and because it can be part of words like “sometimes”. The search was made on the 17 of December, 2019.

Within the identified 1281 publications, 53 review papers present several discussions about temporal considerations in different sectors (*e.g.* agriculture, building and energy) or in the general LCA framework. Very recently, Sohn et al. (2020) and Lueddeckens et al. (2020) have proposed reviews on aspects or issues that are connected to the approach of dynamic LCA (DLCA). In Sohn et al. (2020), three types of dynamism have been defined: dynamic process inventory, dynamic system inventory and dynamic characterisation, thus focusing on the concern of changes in human activities and environmental responses with many implementation examples. Lueddeckens et al. (2020) have offered a clearly structured analysis of 60 documents that have been published until the end of 2018 where interdependencies are underlined and solutions from the literature are identified for six types of temporal issues (i.e. time horizon, temporal weighting/discounting, temporal resolution of the inventory, time-dependent characterisation, dynamic weighting and time-dependent normalisation). While comprehensive for these six issues, the work of Lueddeckens et al. (2020) does not offer a detailed discussion on questions like computation, uncertainty and variability for the DLCA approach.

When looking at the abundant literature on the subject of temporal considerations in LCA, it rapidly becomes clear that the vocabulary in recent and older reviews varies considerably for common aspects such as the temporal scope or time horizon. We believe that this lack of consistency in terminology is hindering a clear discussion on the subject and therefore the development of new propositions that can be accepted by a majority of researchers. Furthermore, while many ideas, concepts, approaches and tools have been suggested by researchers and are now used in publications under the term DLCA, their widespread implementation by practitioners is still far from reached. This lack of temporal considerations in most LCA studies is worrisome since it was shown that such aspects may have significant effects on LCA results mainly in the sectors of buildings (Collinge et al., 2018; Negishi et al., 2019; Roux et al., 2016b) and energy (Amor et al., 2014; Beloin-Saint-Pierre et al., 2017; Menten et al., 2015; Pehnt, 2006). It thus seems important to identify and address the current implementation challenges that prevent LCA practitioners from more frequent accounting of temporal considerations.

These challenges are tackled in the following sections. First, a glossary in section 2 proposes definitions for terms related to temporal considerations in LCA, which should clarify shared aspects of past discussions and help in building consensus. These terms are then used consistently in the text. Section 3 follows with a review of the LCA literature that highlights current implementation challenges for a broad application of the DLCA approach. Recommendations for current implementation options and further developments are then provided in section 4.

Finding a clear structure to organise and analyse the numerous options for temporal consideration that have been discussed in the last 20 years of LCA development can be a daunting task. Previous reviews have chosen different strategies mainly based on specific sectors, themes or issues. These scheme have often limited the scope of the analysis or the identification of connections between ideas. We therefore chose another perspective that classifies temporal considerations based on why they are used (i.e. purposes). Indeed, from our understanding, temporal considerations are employed in LCA studies to define the temporal scope, to describe the dynamic of systems and to increase the representativeness of models. We also differentiate the temporal considerations within the standard phases of the LCA framework to provide a frame of reference that is well-known to practitioners. We thus hope to cover most options for temporal consideration in LCA with this strategy and to comprehensively address the topic for a broader implementation of DLCA studies in the future.

2. PROPOSED GLOSSARY

Table 1 proposes key terms and definitions to discuss temporal considerations within the LCA framework. These terms are used throughout this review to ensure a consistent and non-ambiguous discussion for future developments. It is also the authors' hope that this glossary might bring some uniformity in future discussions. Concepts behind the most recently proposed definitions for types of dynamism and four subtypes of DLCA (Sohn et al., 2020) can be found in this table with a somewhat different perspective.

Table 1: List of proposed terms defining key temporal considerations in the LCA framework. The list is in alphabetical order so all terms from this glossary are underlined to highlight the links. Words in brackets are synonyms from the literature

Term	Definition
Dynamic LCA (DLCA)	LCA studies where relevant <u>dynamic of systems</u> and/or <u>temporal differentiation</u> of flows are explicitly defined and considered.
Dynamic LCI (DLCI)	Life cycle inventory (LCI) that is calculated from supply and value chains where <u>dynamic of systems</u> or <u>temporal differentiation</u> is considered, resulting in temporal distributions to describe elementary flows.
Dynamic LCIA (DLCIA)	Characterisation models of environmental mechanisms that account for the dynamic of ecosphere systems and can therefore use temporal information of *DLCIs*. The chosen <u>temporal differentiation</u> (e.g. day, season, and year) can depend on the impact categories. Both case specific and calendar-based characterisation models can be used, depending on the chosen indicators.
Dynamic of systems	System modelling that considers inherent variations, periods of occurrence or evolution within the temporal scope of models' components. Such a dynamic modelling can be applied to both technosphere systems (for LCI) and ecosphere systems (for LCIA).
Evolution	Changes of process, structure or state <u>models' components</u> (e.g. technology replacement, pollutant concentration in a compartment of the environment).
Inherent variations	Variations of flows in the <u>models' components</u> (e.g. cycles of solar energy production, growth rates of vegetation, seasonal functional traits, biogeochemical and biophysical dynamics). The discontinuities of flow rates are also part of such changes.

Models' components	Information structuring all models. At the technosphere level, components are elementary flows, product flows and processes. At the ecosphere level, components of LCIA models differ between impact categories. For example, components for freshwater ecotoxicity can be environmental fate, ecosystem exposure and ecotoxicological effects (Fantke et al., 2018).
Period of occurrence	The moment when a model's component is starting, modified or finishing over time. (e.g. lifespan of a building, beginning of waste management, start of a life cycle)
Period-specific characterisation factor (CF)	CF for a given temporal scope or period of occurrence. It results from the dynamic of systems in the ecosphere and can be calendar-specific, relative to the length of the temporal scope, or defined by a TH. Period-specific CFs are modelled as constant over the chosen period.
Period of validity	The period over which datasets, LCIs or LCIA methods are considered valid representations. This information should be calendar-based. [Time context (ILCD), time frame, range of time, period of time, time period, timespan, temporal boundary, time scale and time horizon]
Prospective modelling	A prospective LCA addresses future life cycle impacts using different modelling strategies (e.g. scenario-based, technology development curves and agent- or activity-based models). The evolution of systems is thus defined and/or simulated using a list of explicit assumptions regarding the future. Prospective modelling can be applied to both the technosphere and ecosphere and is a subset of the dynamic of systems, which only concerns future forecasts.
Temporal considerations	Any aspects (i.e. information) described in relation to the time dimension or dynamic of systems in the LCA framework. This is the overarching term relating to all other terms of the glossary. [Time-aspect in ILCD documents]
Temporal differentiation	The action of distributing the information on a time scale related to the models' components. For example, elementary flows could be described per day or year. Different processes representing yearly average are another example. [Temporal segmentation in ILCD]
Temporal resolution	Describes the time granulometry when temporal differentiation is carried out. For instance, a monthly or daily resolution can be used to describe the flows in technosphere models. The same term can be used to describe a time step for period-specific CFs. [Time step]
Temporal representativeness	Qualitative or quantitative assessment of data, processes or LCIA methods in relation to how appropriate their information fits with their temporal scope. [Time-related representativeness (ILCD), Time-related coverage (ISO14044)]
Temporal scope	Defines any type of period that is considered in a LCA study (e.g. temporal considerations along a life cycle, service life of a product, data collection period).
Temporalisation	Attribution of temporal properties to the models' components. (e.g. definition of temporal scopes)
Time horizon (TH)	Relative temporal scope over which environmental impacts are summed up to provide LCA results.

3. TEMPORAL CONSIDERATIONS FOR DIFFERENT PURPOSES

Many temporal considerations have been described in previous publications, reports and standards to develop the general LCA framework (ISO14040, 2006; ISO14044, 2006; Joint Research Center, 2010) and its dynamic counterpart. For instance, Sohn et al. (2020) classified 56 DLCA studies by their technological domains and types of assessed dynamism. In this section, the considerations are first regrouped by their purposes. A Venn diagram in figure 2 presents this organisation of temporal considerations where gold, purple and red rounded rectangles respectively highlight the purposes of defining the temporal scope, considering the dynamic of systems and increasing the temporal representativeness. 10 classes of temporal considerations are also presented with rectangles of different colours and linked to the phases of the LCA framework where they most commonly appear. In figure 2, the interpretation phase is excluded because the identified temporal considerations are first accounted for in the three mentioned phases and can then be used to analyse the results.

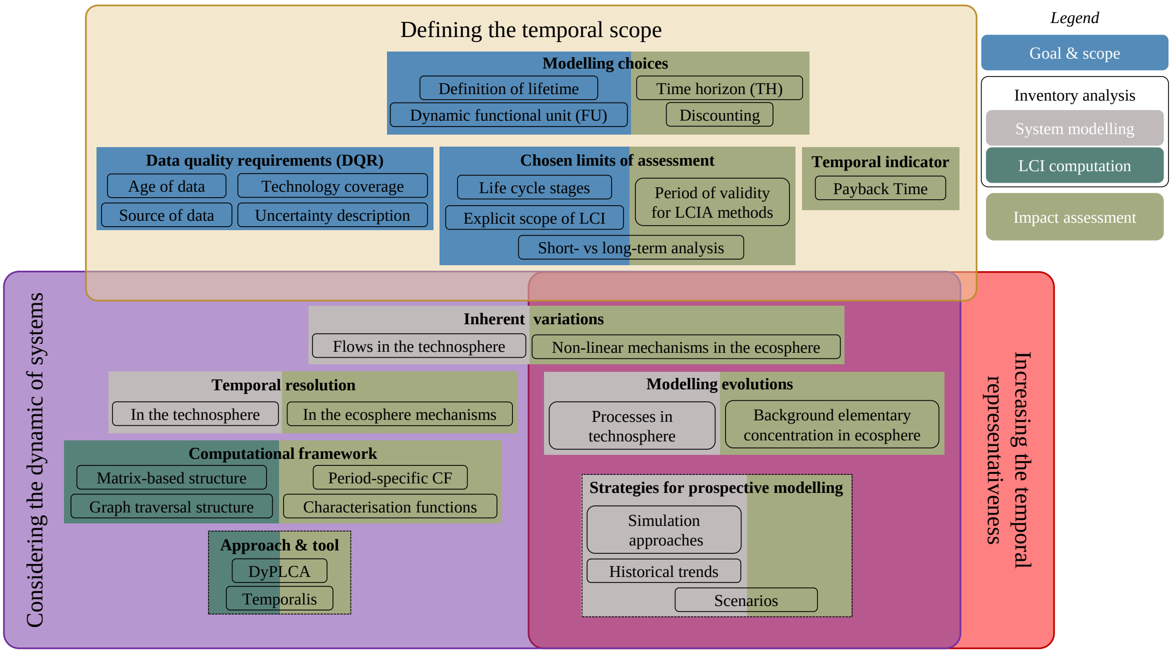

Figure 2: Venn diagram of temporal considerations in relation to their purposes (grey rectangles), the phases of the LCA methodology (coloured rectangles) and 10 classes (Bold titles). Existing connections are presented by arrows.

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126 The level of relevance, conceptual development and operationalisation for the temporal considerations of figure 2 127 are qualitatively assessed with scores ranging from A (highest) to C (lowest) (detailed in table 2) to evaluate the 128 state-of-the-art shown in table 3. A more detailed analysis, including examples, is provided in the following 129 subsections to clarify the qualitative appraisal of table 3. Possible temporal feedback between the LCI and LCIA 130 are not assessed, although they may influence LCA results (Weidema et al., 2018).

131 Table 2. Meaning of different scores for the qualitative assessment of temporal considerations in LCA

Ranking categories	A	B	C
Relevance	Demonstrated at least in some LCA studies	Expected by authors of this article	Unknown
Conceptual development	A standard method is accepted by the LCA community	At least one method for consideration has been proposed	Theory or concepts have been explained
Operationalisation	Available in the data of most LCA studies when relevant	Some examples have been published	Not found in the literature

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3.1. Phase of goal and scope definition

In the goal and scope definition, temporal considerations can be introduced by the modelling assumptions, data quality requirements (DQRs) and model limitations. They mostly offer insights on the temporal scope in which LCA studies are representative and useful. This temporal scope also provides an indication of when the dynamic of systems should be considered.

3.1.1. Modelling choices

Definition of lifetime

The lifetime of systems or products, which frames the use phase of the life cycle, is probably the most common temporal consideration in LCA studies (Anand and Amor, 2017; AzariJafari et al., 2016; Fitzpatrick, 2016; Helin et al., 2013; Mehmeti et al., 2016). This temporal scope, which is relative to the overall life cycle, has often been used to ensure a fairer comparison (Joint Research Center, 2010; Jolliet et al., 2010). However, more comprehensive temporal information on the full life cycle, which is not mandatory in international LCA standards (ISO14040, 2006; ISO14044, 2006), would be necessary to explicitly frame the full temporal scope over which elementary flows and impacts might occur. For example, a house can be used for a lifetime of 50 years (Hoxha et al., 2016; Standardisation, 2009), but this temporal scope does not include the phase of forest growth, which supplies wood for the fabrication of the building's components (Breton et al., 2018; Fouquet et al., 2015) or for advanced biofuels (Albers et al., 2019a).

Dynamic functional units

Some practitioners have suggested that the temporal scope should always be provided with the definition of questions (Finnveden et al., 2009; Huang et al., 2012; Ling-Chin et al., 2016) and functional units (FUs) (Inyim et al., 2016; Santero et al., 2011). The concept of dynamic FUs has been proposed (Kim et al., 2017), which could consider the evolution and comparability of products and would explicitly define the period of validity for a LCA study when the behaviour of consumers and markets have changed significantly. For example, the rapid evolution of technologies for mobile phones has changed their functionalities and demand thus modifying their global production volumes.

Table 3: List of temporal considerations in the LCA framework. Rankings for relevance, conceptual development and operationalisation are provided for each consideration on a scale from A to C with their colour code (see table 2). The colour for the three columns of purpose is based on the code of figure 2. The numbers for the rows are the text's subsections.

Sections	**Subsection**	**Temporal considerations**	**Defining temporal scope**	**Considering dynamics of systems**	**Increasing temporal representativeness**	**Relevance**	**Conceptual development**	**Operationalisation**
3.1 Phase of goal and scope definition	3.1.1 Modelling choices	Definition of lifetime	X			A	A	A
		Dynamic FU	X			A	B	B
	3.1.2 Data quality requirements (DQRs)	Age of data	X			A	A	B
		Technology coverage	X			A	B	B
		Source of data	X			A	C	A
		Uncertainty description	X			A	B	B
	3.1.3 Limits of assessment	Considered life cycle stages	X			A	A	A
		Temporal scope of LCI	X			A	B	B
		Short- vs Long-term	X			A	C	B
3.2 Phase of inventory analysis: System modelling	3.2.1 Inherent variations	Flows in technosphere		X		A	B	B
	3.2.2 Temporal resolution	In technosphere		X		B	B	B
	3.2.3 Modelling evolution	Processes in technosphere		X		A	B	B
	3.2.4 Prospective modelling	Simulation approaches		X	X	B	B	B
		Historical trends		X	X	A	B	B
		Use of scenarios		X	X	A	B	B
3.3 Phase of inventory analysis: LCI computation	3.3.1 Framework	Matrix-based		X		A	B	B
		Graph traversal		X		A	B	B
	3.3.2 Approach and tool	DyPLCA		X		A	B	B
		Temporalis		X		A	B	B
3.4 Phase of impact assessment	3.4.1Modelling choices	Time Horizons	X			A	A	A
		Discounting	X			C	B	C
	3.4.2 Limits of assessment	Period of validity	X			B	B	B
		Short- vs Long-term	X			A	C	B
	3.4.3 Temporal indicator	Payback time	X			B	B	B
	3.4.4 Inherent variations	Non-linear mechanisms		X	X	B	B	C
	3.4.5 Temporal resolution	Ecosphere mechanisms		X		B	C	C
	3.4.6 Modelling evolution	Background concentration		X	X	B	B	C
	3.4.7 Prospective modelling	Scenarios		X	X	B	B	B
	3.4.8 Computational framework	Period-specific CFs		X	X	B	B	B
		Characterisation functions		X	X	C	C	C
	3.4.9 Approach and tool	DyPLCA		X		A	B	B
		Temporalis		X		A	B	B

3.1.2. Data quality requirements (DQR)

Age of data

Some metadata of datasets, which should be defined in the DQR (ISO14044, 2006; Joint Research Center, 2010), informs on their age and minimum length of time for data collection. Potential temporal discrepancies between used datasets and the targeted temporal scope of a modelled system can thus be partially evaluated. Such information also provides some insights on the temporal scope of a system model when it represents human activities (Bessou et al., 2013; Yuan et al., 2015). For example, the description of solar energy installations from the 1990s would probably be relevant for LCA of solar energy before 2000. Nevertheless, using such periods of validity require expert opinion, thus limiting the usefulness for this kind of metadata.

Technology coverage

In some cases, the definition of technology coverage in the DQR of datasets can inform on the actual temporal scope of the study (ISO14040, 2006; ISO14044, 2006; Joint Research Center, 2010) with the ensuing qualitative assessment of temporal representativeness. For example, ecoinvent (Wernet et al., 2016) uses five levels of technology (i.e. new, modern, current, old and outdated) to describe transforming activities. Using datasets with new or modern technology levels should therefore be relevant for LCA studies on future products. However, this information is relative to each sector, as the modern level could be representative for 10 years of technology evolution in an established sector, whereas fast-paced sectors like electronics may use modern technologies for only 1 year before switching to new options.

Source of data

The choice of data sources and the qualitative assessment of their overall representativeness provide an indirect assessment of the temporal scope for modelled systems and LCA studies (Rebitzer et al., 2004). For example, when data are sourced from scientific journals, date of publication is the primary indication for its period of validity. More precise temporal information is also often provided in case studies for systems with longer lifetimes or in DLCA studies like (Heeren et al., 2013; Pahri et al., 2015; Sohn et al., 2017a; Vuarnoz et al., 2018). The use of up-to-date LCA databases can bring a false sense of security on the temporal scope and representativeness of the data for recent products or systems. Indeed, database updates do not always follow the changes in market shares or evolution of technology because of the lack of new data.

Nevertheless, different temporal metadata is given for most datasets. For instance, ecoinvent guidelines (Wernet et al., 2016) require the definition of the date of generation, the date of review and the period of validity with a start date and end date for any dataset. These temporal considerations fulfil most of the requirements from ISO 14044 (2006) except for the definition of the averaging period of dataset inputs. The ILCD handbook (2010) has set further requirements defining temporal properties: the expiring year of datasets and the duration of the life cycle, which respectively relates to the period of validity for LCI datasets and the temporal scope of elementary flows for a dataset. This metadata is available in most datasets of the ELCD (Recchioni et al., 2013). Many of these temporal metadata are more relevant to assess the temporal scopes of studies than the choice of a database and its version, but the place (e.g. in dataset descriptions) and the different definition under which they can be found hinder their use in most LCA studies.

Uncertainty description

The description of the uncertainty associated with flows (e.g. in ecoinvent (Wernet et al., 2016)) is another indirect source of information to clarify the temporal scope and period of validity. Indeed, the temporal correlation indicator provides a quantitative assessment of the discrepancy between the time when the data was acquired and the intended temporal scope for the dataset (Weidema et al., 2012). For example, a product flow with a temporal correlation indicator of 3 means that its value has been gathered between 6 and 9 years before or after the targeted temporal scope of the dataset. With the current definition of the temporal correlation indicator, the precision of this temporal information is rather low (i.e. >3-year period) and is widely missing in LCA databases and studies, limiting its applicability.

3.1.3. Chosen limits of assessment

The definition of limitations in the stage of goal and scope definition is probably the step where temporal scopes are defined with higher precision and clarity in LCA studies, even more in recent DLCA studies. While this is useful, typical LCA reports mainly offer qualitative definitions, which are not sufficiently transparent to describe the considered period in assessed life cycles.

Considered stages of the life cycle

LCA studies can limit the temporal scope of their analysed systems and LCIs by considering only a part of the life cycle. Setting the end-of-life outside the boundaries is an example of such a limited temporal scope. The ISO 14044 (2006) allows this limitation, but only if they do not significantly change the overall conclusions of a study because such phases are not linked to significant impacts. Most of the LCA reports clearly state the excluded life cycle stages, but they often provide an imprecise description for the limitation of the temporal scope. Moreover, the specification of the considered stages of a life cycle will not explicitly state the temporal scope in which elementary flows are considered (e.g. 2 years) nor offer a calendar-based period of occurrence (e.g. from January 2019 to December 2020).

Temporal scope of life cycle inventories

More specific and precise descriptions of temporal scopes for LCI have been provided in recent scientific publications that focus on some temporal considerations (i.e. DLCA). For example, relative temporal scopes have been used to define the periods of LCIs for many studies on different products, for example considering the lifetime of wood-based products and buildings between 50 and 100 years (Fouquet et al., 2015; Levasseur et al., 2010) including tree growth period over 70 and 150 years (Levasseur et al., 2013; Pinsonnault et al., 2014) , lifetime of marine photovoltaic of 20-30 years (Ling-Chin et al., 2016) and zinc fertiliser over 20 years crop rotation (Lebailly et al., 2014). In these cases, the LCIs are enclosed within a quantified period of time that can be relevant for some impact categories, but they lack any reference to a calendar year or period. Several DLCAs studies defined calendar-based temporal scopes, but discussions on the potential usefulness of this contextual information could be further enriched. Some were based on reference calendar years of building materials (Collinge et al., 2013b), hourly energy demand in buildings (Vuarnoz et al., 2018), as well as seasonal and annual variations in crop rotations (Caffrey and Veal, 2013). Other studies were based on calendar-specific periods detailing domestic hot water production (Beloin-Saint-Pierre et al., 2017), future biomass production (Menten et al., 2015), the lifetime of buildings (Roux et al., 2016a; Roux et al., 2016b), the energy use in hourly, daily and monthly temporal resolutions (Collinge et al., 2018; Karl et al., 2019), or for introducing back-time horizon (Tiruta-Barna et al., 2016).

Short- vs long-term analysis

Several publications describe the temporal scopes of technosphere models (Dandres et al., 2012; Menten et al., 2015) or LCI (Finnveden et al., 2009; Morais and Delerue-Matos, 2010; Pettersen and Hertwich, 2008; Roder and Thornley, 2016) with adjectives such as short-, medium- or long-term. These qualitative and relative attributes thus inform the considered periods, but are vague. This lack of a precise temporal definition can be partly explained by the lack of consensus on how temporal scopes should be defined.

3.2. Phase of inventory analysis: system modelling

In the system-modelling step of the LCI phase, temporal considerations are found in the descriptions of the system inherent variations and evolution. They define the dynamics of systems and can improve the temporal representativeness of models for technosphere activities (i.e. network of processes). Although considering system evolution and inherent variations in both the foreground and the background data is still not a common practice, its importance has long been acknowledged in ISO 14040 (2006), stating that "*all significant system variations in time should be considered to get representative results*".

Strategies to consider inherent variations and evolution have been proposed by different authors, mainly for energy (Amor et al., 2014; Zaimes et al., 2015), transport (Tessum et al., 2012), agriculture (Fernandez-Mena et al., 2016; Yang and Suh, 2015) and waste management (Bakas et al., 2015). For example, the energy share of electricity production in a country varies throughout days, weeks, months and seasons (Beloin-Saint-Pierre et al., 2019; Vuarnoz and Jusselme, 2018). LCA case studies have shown that inherent temporal variations of production can have significant effects on results, mainly when consumption of these products is not constant over time.

3.2.1. Inherent variations with flow differentiation

Inherent variations can be modelled with temporal differentiation of flows or dynamic modelling. For instance, electricity production (Messagie et al., 2014; Vuarnoz and Jusselme, 2018; Walker et al., 2015) and its use in buildings (Collinge et al., 2013b; Collinge et al., 2018; Karl et al., 2019; Roux et al., 2016b; Roux et al., 2017; Vuarnoz et al., 2018; Walzberg et al., 2019a), cloud computing (Maurice et al. 2014) and wastewater treatment (de Faria et al. 2015) have all been modelled with such approaches. In different ways, all these approaches convert flows into temporal distributions, thus supplementing temporal properties to the core data of the model components in the LCA framework. The applicability of such data in other LCA studies is often limited because the temporal information is valid only for the temporal scope of a given case study. A way to address this limitation is to use a reference "time 0" in the temporal distribution as a period of occurrence relating to a starting period of a process (Beloin-Saint-Pierre et al., 2014; Tiruta-Barna et al., 2016). This "time mark" creates process-relative descriptions, which can be reused in any period of a life cycle or even for different life cycles. Tiruta-Barna et al. (2016) and Pigné et al. (2019) provided process-relative temporal distribution archetypes for ecoinvent v3.2, applicable to foreground and background datasets. As underlined by Beloin-Saint-Pierre et al. (2014), the additional efforts needed to provide temporal information for all the flows of LCA databases are still significant and the prioritisation of data-gathering remains important.

3.2.2. Temporal resolution

The level of temporal resolution to models the dynamics of systems depends on the sector and the modelling approach. For instance, hourly resolutions have been chosen for electricity production and consumption (Amor et al., 2014) or the transportation sector (Tessum et al., 2012). For assessing long-term emissions, for instance from waste treatment, a temporal resolution of centuries is more appropriate (Bakas et al., 2015). Some authors have proposed a temporal differentiation based on archetypes. For example, archetypal weather days (Risch et al., 2018) have been developed to contrast the relative importance of episodic wet weather versus continuous dry-weather loads. So far, studies about the consequences for choosing different temporal resolutions to describe the flows are limited. Indeed, only two examples are found in the building sector where a monthly resolution is deemed sufficient to consider most of the temporal variability (Beloin-Saint-Pierre et al., 2019; Karl et al., 2019).

3.2.3. Modelling evolutions with process differentiation

The basic strategy to describe evolution is to differentiate processes when a system is considered to change substantially over time. The key challenge here is to identifying when changes are significant enough without expert opinion on the modelled product. A simple application can be performed, if calendar-based periods of validity are consistently provided for all datasets in LCA databases; they could then be changed automatically when they are no longer valid representations over the full life cycle of any system. Such metadata is, however, required only in the (discontinued) ELCD database (see subsection 0) and, currently cannot be easily integrated in LCA software.

Collet et al. (2011) proposed an approach to tackle this problem and identify where temporal differentiation of processes during system modelling is needed. Their general idea is to recognise when the combined emission and impact dynamics justify the additional effort for temporal differentiation. Moreover, the selective introduction of the time dimension in background processes has been studied by Pinsonnault et al. (2014) and more recently by Pigné et al. (2019). The authors have shown that the temporal variations of a selection of background processes and the entire ecoinvent database can significantly affect climate change impacts for processes in some sectors (e.g. transport and building).

3.2.4. Prospective modelling

Modelling future evolution of systems is another common example of temporal considerations that is often performed under the umbrella of DLCA studies. Indeed, many DLCA studies have explored different prospective models for a range of products like: photovoltaic panels (Pehnt, 2006; Zhai and Williams, 2010), buildings (Collinge et al., 2013a; Frijia et al., 2012; Scheuer et al., 2003; Sohn et al., 2017a; Sohn et al., 2017b; Su et al., 2017), bioethanol (Pawelzik et al., 2013), passenger vehicles (Bauer et al., 2015; Miotti et al., 2017; Simons and Bauer, 2015), metals (Stasinopoulos et al., 2012) or ammonia (Mendivil et al., 2006). Any temporal assumptions made to define future evolution are thus considered for system modelling and LCI calculations. While major advances have been reached to offer explicit descriptions of assumptions made for temporal considerations in DLCA, *e.g.* (Collinge et al., 2013b; Herfray and Peuportier, 2012; Menten et al., 2015; Pehnt, 2006; Roux et al., 2016b), they are currently not the standard. Prospective modelling assumptions can be grouped within three categories that have fundamental differences on how they justify their forecasting.

Simulation approaches

Economic models, such as partial equilibrium models (PEM) or general equilibrium models (GEM), are frequently used in, but not limited to, consequential LCA modelling to simulate potential future evolution to assess direct and indirect consequences of decisions (e.g. climate policies) on large scale systems. Nevertheless, the current focus of using these models to assess consequences of changes in LCA studies should not hide their potential to offer possible development paths in prospective assessments. PEM generally focuses on one particular economic sector with a higher level of detail (i.e. technology rich), while GEM covers the whole economy with a lower level of detail (typically 30–50 economic sectors). For instance, PEMs have been used to model the energy sector in France (Albers et al., 2019c; Menten et al., 2015), or biogas production in Luxembourg (Marvuglia et al., 2013) and GEMs have been used to evaluate the consequences of different energy scenarios on the whole economy in Europe (Dandres et al., 2011). PEMs have also been coupled with GEMs to model the consequences of energy policy scenarios in an integrated manner (Igos et al., 2015) and they have been used in combination with dynamic models of biogenic and soil organic carbon for a similar purpose (Albers et al., 2020; Albers et al., 2019b).

The lack of consideration for human behaviour in PEM or GEM has recently been pointed out as a potential issue for the validity of the prospective models (Marvuglia et al., 2015). The use of agent- or activity-based models have therefore been proposed as alternatives to carry out prospective assessments; both in the foreground and in the background systems. Such models have mostly been used in consequential LCAs relating with transport policies (Querini and Benetto, 2015), regional market penetration of electric vehicles (Noori and Tatari, 2016), switch grass-based bioenergy systems (Miller et al., 2013), smart buildings (Walzberg et al., 2019b) or raw materials criticality (Knoeri et al., 2013), but could be used to predict future trends. The differences between the use of such simulation approaches in DLCA or consequential LCA studies have been discussed recently by Sohn *et al.* (2020).

Forecasting based on historic trends

Some data sources (*e.g.* statistics on energy production) describe historic trends from which forecasting is made by extrapolation, assuming paradigm shifts will not occur. For instance, regression analysis was used to assess the evolution of energy systems (Pehnt, 2003a; Pehnt, 2003b; Pehnt, 2006; Yang and Chen, 2014) and the construction sector (Sandberg and Brattebø, 2012). The main strength of this approach is its simplicity and the potential to assess the observed level of variability of historic trends. It can thus provide averaged future trends and the expected variability (uncertainty). The main weakness, on the other hand, is the implicit assumption that historic trends are representative of the future, which is not always the case, particularly for emerging systems and technologies.

Using scenarios to explore potential futures

Scenario-based modelling has been used in many sectors like waste management (Hellweg et al., 2005), water consumption (Pfister et al., 2011), bioenergy (Choi et al., 2012; Daly et al., 2015; Dandres et al., 2012; Earles et al., 2013; Igos et al., 2014; Menten et al., 2015), renewable electricity (Hertwich et al., 2015; Pehnt, 2006; Viebahn et al., 2011), transport (Cheah and Ieee, 2009; Garcia et al., 2015; Pehnt, 2003a; Pehnt, 2003b), chemicals (Alvarez-Gaitan et al., 2014) and buildings (Roux et al. 2016b). A general idea behind modelling scenarios is that exploring many potential futures may be simpler to justify than offering predictions on what the future will look like for a system as complex as human activities. For instance, Pesonen *et al.* (2000) defined that the scenarios describe possible future situations based on assumptions about the future and include developments from the present to the future. The authors distinguished between “what-if” and “cornerstone” scenarios (Pesonen et al., 2000), depending on the need to consider short- or long-term planning. "What-if" scenarios are often based on the field-specific expertise of LCA practitioners. Cornerstone scenarios explore many options with very different assumptions on the future to identify potential development paths. Another category is legally bound scenarios that explore future paths under the restriction of regulations.

3.3. Phase of inventory analysis: LCI computation

The computation of LCI transforms the information of a technosphere model into a set of elementary flows whose quantities are in relation to the FU of the assessed systems. The computation traditionally aggregates all flows of the same type over the entire life cycle.

3.3.1. Computational framework

Matrix-based computation with process differentiation

The conventional matrix-based computational approach can be used to calculate DLCIs, but with larger technosphere and ecosphere matrixes (Heijungs and Suh, 2002). Collinge et al. (2012; 2013b) used this approach on foreground processes to calculate the DLCI for each year of a building's life cycle. They concluded, similarly to Heijungs and Suh (2002), that the implementation brings significant challenges in data management when background databases are used. The challenges of this approach are twofold. Firstly, the temporal description of a system needs to be re-informed when the periods of assessment differ (*e.g.* 1980-2000 vs 2005-2025), if considered impacts are calendar-based. Secondly, the amount of data and the computational efforts depend on the required temporal precision (*e.g.* day vs. year) to describing all flows.

Graph traversal structure

The Enhanced Structure Path Analysis (ESPA) approach (Beloin-Saint-Pierre et al., 2014) is one type of graph-based computational framework that convolves process-relative temporal distributions (see subsection 3.2.1) to propagate the temporal descriptions of flows. The general concept behind the ESPA framework (Beloin-Saint-Pierre et al., 2014; Maier et al., 2017) relates to one strategy of graph traversal algorithms (i.e. breadth-first), but other options have been explored. The depth-first search strategy (Tiruta-Barna et al., 2016) recommends a different traversal of supply chains, which is normally linked to lower memory requirements. The best-first search strategy (Cardellini et al., 2018) is another option that propagates the temporal information by prioritising the temporal distribution with higher contributions to impacts. All these options use process-relative temporal distributions, thus profiting from their reusability and the potential for higher temporal precision.

3.3.2. Approaches and tools

Some commercial software tools use matrix-based computation (e.g. Simapro, Umberto) and could thus work with the process differentiation framework for the calculation of temporally differentiated LCI. To our knowledge, this option has not been implemented comprehensively in DLCA studies because LCA databases do not offer temporal details. The ESPA method has also not been developed into a computational tool and its implementation has been limited to one simplified case study (Beloin-Saint-Pierre et al., 2017). Nevertheless, two options currently exist for full DLCI computations and are introduced in the following sub-sections.

DyPLCA

DyPLCA has been implemented as a web tool (available at http://dyplca.univ-lehavre.fr/), originally presented by Tiruta-Barna et al. (2016), which uses the depth-first graph search strategy. The main parameters that balance accuracy vs. computation time in this tool are the temporal resolution of function integrals and the back time span. Common values for both are respectively 1 day and −50 years (i.e. 50 years before the period of occurrence for the FU). The computational intensity of the DLCI calculation has thus been resolved by a trade-off between accuracy and cut-offs. The process-relative temporal distributions can have different levels of detail to describe the flows in the system models. For instance, they can be detailed for foreground processes, as presented in Shimako *et al.* (2018), and can be rather generic for the background datasets.

DyPLCA currently works with a temporal differentiated ecoinvent v3.2 (Pigné et al., 2019), providing generic temporal descriptions to most background inventory processes. The DLCI results can be further used with static or DLCIA methods, as shown in studies on bioenergy production from microalgae (Shimako et al., 2016) and on grape production (Shimako et al., 2017).

Temporalis

Temporalis (Cardellini et al., 2018) is a free and open source package of the Brightway2 LCA tool (Mutel, 2017), using the best-first search strategy. The tool is fully compatible with many existing commercial LCA databases, but temporal descriptions of datasets are currently not provided. Temporalis does not require a fixed and continuous temporal resolution over any system models to provide DLCI or results for the impact assessment. Nevertheless, a DLCIA method for GWP based on the IPCC methodology (2013), is included. A simple case study for the temporal consideration of biogenic carbon flows was carried out with the method of Cherubini et al. (2012; 2011). It has shown that the LCI computation can be resolved on a regular laptop within a short time. Nevertheless, further developments still need to be completed before most LCA practitioners can use the tool easily.

3.4. Phase of life cycle impact assessment

In the LCIA phase, temporal considerations affect many aspects that are linked to all phases of the LCA framework. For instance, the selection of a TH and changes of environmental mechanisms (i.e. impact pathways) over time are key modelling choices to characterise impacts in a DLCA framework.

3.4.1. Modelling choices

LCIA is a complex task that requires many assumptions (e.g. the future state of the environment) and choices, which sometimes limit the validity of results to a specific temporal scope and introduce bias in the results. One of the most explicit and commonly used temporal considerations in LCIA methods is the TH, restricting the impact assessment to a specific period. Discounting is another modelling choices that can affect LCA results in similar ways to TH with links to its potential subjectivity (Lueddeckens et al., 2020).

Time Horizon

The choice between a finite or infinite TH is a common type of temporal consideration that sums the environmental effects over a selected temporal scope (e.g. the 100-year TH for the GWP indicator). The consideration of different THs is used, for instance, by the ReCiPe method (Huijbregts et al., 2016), which builds on three cultural perspectives, proposed by Hofstetter et al. (2000). These perspectives are associated with different sets of calculation assumptions, including CFs with different THs for each impact category. For example, the "hierachist" perspective retains a 100-year TH for GWP and other categories, while "individualist" and "egalitarian" perspectives respectively use THs of 20 and 1000 years. Furthermore, very long THs are suggested for some impact categories such as for climate change (i.e. 1000 years) and ionising radiation (i.e. 100,000 years). The ILCD handbook (2011) and the SimaPro Database Manual (PRé, 2016) provide additional insights into the use of THs in different LCIA methods, but there is not yet any standard on how to deal with long-term impacts and related uncertainties within all categories. For instance, the 5th IPCC assessment report (2014) removed the 500-year TH due to high uncertainties associated with the assumption of constant background concentrations.

To date, the choice of a TH remains a topic of discussion within the LCA community (Dyckhoff and Kasah, 2014; Reap et al., 2008b) where three critical aspects are challenging the use of fixed and finite THs in LCIA methods:

- The first aspect is the inconsistency between the temporal boundaries of the studied systems and the TH of the LCIA methods (Benoist, 2009; Levasseur et al., 2010; Rosenbaum et al., 2015; Yang and Chen, 2014). Indeed, it could be understood that effects from elementary flows beyond the chosen TH should not be considered. However, the effects are ultimately modelled over an invariable temporal scope, even if they occur at different periods during a life cycle (*e.g.* 100 years). This use of THs may thus lead to misrepresentations of impacts and their period of occurrence (Hellweg and Frischknecht, 2004), for instance, misleading decision-making concerning temporary storage and emission delays (Brandao and Levasseur, 2011; Jørgensen et al., 2015). This issue can be particularly significant for intermitting emissions like pesticides, where arbitrary cut-offs of emissions after pesticide application should influence how each emission contributes to related impacts of human toxicity (Fantke and Jolliet, 2016) and ecotoxicity (Peña et al., 2019).

- The second aspect refers to the time integration of substances with highly variable environmental effects over their lifetime in the ecosphere (e.g. aging effects reducing bioavailability of metals (Owsianiak et al., 2015) or transformation of persistent chemicals in the environment (Holmquist et al., 2020)), which can significantly bias the conclusions of LCA studies (Arodudu et al., 2017; Lebailly et al., 2014). In the case of GWP, the weight of forcers with very short atmospheric residence time decreases with an increasing TH (Levasseur et al., 2016; O'Hare et al., 2009), while a shorter TH increases the importance of short-lived gases. For example, methane (CH_4), whose atmospheric lifetime is about 12.4 years, goes from a factor of 84 CO_2-eq for the 20-year TH to a factor of 28 CO_2-eq for 100-year TH (Myhre et al., 2013). For further examples on this subject, Levasseur et al. (2016) presented various approaches that have been proposed for TH definition. For toxic substances, Huijbregts et al. (2001) demonstrated that TH variations can change impacts by up to 6.5 orders of magnitude for metal toxicity. In this case, the high dependency between CFs and the chosen TH is due to long residence times (i.e. persistence) in fate models, which increase metal run-offs and leaching potential to global marine and soil compartments.
- The third aspect relates to the temporal cut-offs that come with the selection of a fixed and finite THs, which can be ethically questioned in the context of intergenerational equity (Hellweg et al., 2003a). Indeed, these cut-offs raise concerns on the subjectivity of choosing a specific TH to highlight preferences between short- and long-term impact considerations (Lueddeckens et al., 2020). For instance, the 100-year TH in GWP is the most used and recommended option, but this preference is not justified by scientific facts (Reap et al., 2008b; Shine, 2009; Vogtländer et al., 2014) and is implicitly subjective for decision-making (Brandao and Levasseur, 2011; Fearnside, 2002). This 100-year TH is particularly important when temporary/permanent carbon storage or the delayed emissions from biogenic and fossil sources are evaluated or incentivised (Guest and Stromman, 2014; Levasseur et al., 2012a). Moreover, emissions that are delayed after the 100-year scope are then considered to be permanently avoided (BSI, 2011; Joint Research Center, 2011).

A “simple” solution to remove such time preferences and value choices has been recommended by setting infinite THs in all cases. For instance, some LCIA methods (e.g. EDIP2003 (Hauschild et al., 2006), IMPACT 2002+ (Jolliet et al., 2003), ReCiPe 2016 (Huijbregts et al., 2016)) use infinite or indefinite THs as a standard for stratospheric ozone depletion, human toxicity and ecotoxicity. In the case of the land use impact category, THs are generally not explicitly stated in current characterisation models (see e.g. Huijbregts et al. (2016) for biodiversity impacts or Müller-Wenk and Brandão (2010) for climate change). Even if the theoretical frameworks for land use impact assessment discusses changed (Beames et al., 2015) or permanent impacts and therefore the need for defining a TH (Canals et al., 2007; Koellner et al., 2013), permanent impacts are currently not considered in available characterisation models. Current models implicitly correspond to the choice of an infinite TH where impacts of each land use intervention is being integrated over time until the effect factor reaches 0, i.e. until the variations of soil quality after the land use intervention regenerates back to a reference soil quality. Regeneration time then plays a significant role in the effective integration period and in the definition of CFs.

Discounting

This concept was discussed to value time in LCIA (Hellweg et al., 2003a; Pigné et al., 2019; Yuan and Dornfeld, 2009; Zhai et al., 2011) and to deal with the uncertainties associated with time preferences and future emissions. The setting of finite THs is an implicit form of discounting for long-term impacts, using a zero discount rate over the TH, and an infinite discount rate beyond the TH. Discounting offers a trade-off between giving a higher value to present or future impacts. A more detailed discussion on this subject is provided by Lueddeckens et al. (2020).

3.4.2. Chosen limits of assessment

The periods of validity for chosen LCIA methods and discussions on the short- or long-term nature of impacts are two types of temporal considerations that can inform on the temporal scope of a LCA study, whether this selection is voluntarily made by the practitioner or not.

Period of validity for LCIA methods

Stating the period of validity (e.g. 2000 to 2010) or version for chosen LCIA methods in LCA studies is not common practice, but it can provide insights on the expected temporal scope (Bessou et al., 2011; Hauschild et al., 2013; Ling-Chin et al., 2016; Weidema et al., 2012). The choice of THs can also suggest an implicit definition of the considered period of validity. In an ideal world, the temporal scope of obtained LCIs and chosen LCIA methods should be fitted to each other. Such a correspondence is desirable if CFs vary significantly over time, but it is currently difficult to implement in the available databases and software tools.

Short- vs long-term analysis

Much like it has been said in the definition of the goal & scope (subsection 3.1.3), the adjectives of short- and long-term have been used to describe the temporal scope of LCIA methods (Arodudu et al., 2017; Chowdhury et al., 2017; Reap et al., 2008b). This lack of a precise temporal definition when stating short-, medium- and long-term can be partly explained by the differences in time scales of life cycles and environmental impacts for different systems. Furthermore, a commonly accepted standard does not yet exist to deal with long-term impacts and related uncertainties within all categories. For instance, the 5th IPCC assessment report (Myhre et al., 2013) removed the previously published 500-year TH due to the high uncertainties associated with the assumption of constant background concentrations.

3.4.3. Temporal indicator

Payback time

Payback times have been created to provide a temporal scope that informs on temporality of impacts. The basic idea is to calculate the necessary period to compensate for the "cradle-to-gate" impacts of any system. It has been mostly used to evaluate the time it takes to produce an amount of electricity that is equivalent to the primary energy use from the manufacturing of photovoltaic installations (Espinosa et al., 2012; Fthenakis and Alsema, 2006; Knapp and Jester, 2001), but it can be applied to energy use in many types of product (Elshout et al., 2015) or could also give payback time for other impact categories.

3.4.4. Inherent variations

In conventional LCIA methods, CFs are determined with average or marginal approaches that model changes in the impact according to a change in the inventory (Frischknecht and Jolliet, 2016; Hauschild and Huijbregts, 2015). With this average approach, the environmental disturbances from different activities are aggregated, historically referred to as "snapshots" of a studied system (Bright et al., 2011; Heijungs and Suh, 2002; Klöpffer, 2014; Levasseur et al., 2016; Owens, 1997b; Vigon et al., 1993). For example, most existing models for characterising toxic impacts (Rosenbaum et al., 2008) assume constant environmental conditions for the assessment of health impacts. With this approach, inherent variations of the ecosphere are not considered.

Non-linear mechanisms in the ecosphere

The marginal approach addresses an impact resulting from a small change to a given background concentration. The impact is therefore positioned in relation to the current environmental state. For example, studies of human health impacts from exposure to fine particulate matter ($PM_{2.5}$), where indoor, outdoor, urban and rural locations have shown significant differences in $PM_{2.5}$ background levels (Fantke et al., 2017). A non-linear exposure-response model thus accounts for these differences in $PM_{2.5}$ levels, reflecting a slope for low concentrations that are substantially higher than for high concentrations (Fantke et al., 2019).

Impact assessment models are representations of complex environmental mechanisms that depend on a long list of parameters, such as the lifetime of substances in the environment and the sensitivities of ecosystems over different temporal scopes (Lenzen et al., 2004). In many LCIA methods, CFs are defined from generic parameters values in stationary conditions (e.g. intervention quantity, baseline for target substances, and profiles of the soil composition) or for a given TH. Subsequently, impacts are assumed linearly proportional to the inventoried emissions, which enable the scaling of impacts to any functional unit. In reality, the involved environmental mechanisms are dynamic and often highly complex (Arbault et al., 2014). They depend on the physical, chemical and biological phenomena and non-linear interaction occurring in nature and are consequences of the elementary flows generated by human activities.

Time-dependent characterisation has been performed in some cases by modelling the dynamics for one or more of the three factors influencing an impact (i.e. environmental fate, exposure, and effects), thus creating a type of DLCIA methods. Effect data are typically not easily linked to temporal properties, allowing for temporal considerations in effect modelling (e.g. dose response for human effects or concentration response for ecological effects). Hence, time-dependent characterisation is usually only facilitated by considering the dynamics of systems in the fate and exposure factors of an impact pathway, which is usually enabled by models of the underlying mass balance for a given impact pathway. This has been implemented, for example, in toxicity-related impacts (Lebailly et al., 2014), where the system dynamics of the environmental fate factor are either solved via numerical integration (Shimako et al., 2017), or via matrix decomposition (Fantke et al., 2013).

3.4.5. Temporal resolution

Specific temporal resolution for each elementary flow

The temporal considerations within LCIA models may follow specific frequencies (*e.g. yearly changes*), as well as temporal-inherent features deriving from dynamic biogeochemical processes. The frequency can be differentiated, for instance, as responding to episodic (*e.g.* initial land clearing), cyclical (*e.g.* seasonal water and pesticide use), stochastic (*e.g.* 1 in 20 years' waste discharge), or continual (*e.g.* fisheries yields) variations in the studied system (Lenzen et al., 2004). Cyclical or seasonal variations concerning sunlight, temperature and precipitation on the calendar year (*e.g.* winter vs summer time) are other examples of temporal considerations that could be relevant for impact categories like aquatic eutrophication (Udo de Haes et al., 2002), water scarcity

(Boulay et al., 2015), human toxicity (Manneh et al., 2012) and photochemical oxidant formation (Shah and Ries, 2009). Such frequencies therefore highlight relevant temporal resolutions for the temporal differentiation of elementary flows in databases and DLCIs. Temporal inherent features may vary with hourly, daily, monthly or yearly constraints depending on temporal patterns or modelling time steps of the characterisation models (Collet, 2012; Owens, 1997b).

The temporal scope of impact assessment itself may be aligned with the dynamics of governing biogeochemical processes to more accurately represent certain fate dynamics. For instance, Liao et al. (2015 found that common seeding-to-harvest assessment periods in agricultural LCAs do not correspond to the actual dynamics of fertilising substances, some of which contribute to eutrophication during the next crop rotation. The same concerns agricultural pesticides, where the time between the application and crop harvest drives related residues leading to human exposure (Fantke et al., 2011). Such fate dynamics can still be analysed and parameterised to fit steady-state models and associated impact pathways, such as human toxicity (Fantke et al., 2012; Fantke et al., 2013).

3.4.6. Modelling evolutions

Considering variations for concentration substances and the state of the environment

Elementary flows may have varying levels of effect, depending on the timing of emissions (i.e. period of occurrence) and the state of the environment (i.e. varying substance concentrations). Temporal considerations of environmental mechanisms in LCA studies are challenging because the current state of practice rarely allows to account for the periods of emission occurrences that are related to a product's life cycle (Finkbeiner et al., 2014; Hellweg and Frischknecht, 2004; Jørgensen et al., 2014; Kendall et al., 2009; Levasseur et al., 2010; Reap et al., 2008b). In fact, LCI flows are typically given as simple values that are considered to be a representation of steady or pulsed flows from and to the environment by most LCIA models. For instance, impacts characterisation methods often use an effect factor for a given concentration of pollutants in the background environment (Finnveden et al., 2009; Hauschild, 2005). Thus, the same amount and type of elementary flows (*i.e.* equivalent LCIs) can generate different levels of impacts because they have been emitted at different periods of occurrence (*e.g.* 2016 or 2017), with varying flows (*i.e.* inherent variations) and geographies, requiring both temporal and spatial differentiation. In this case, calendar specifications may be relevant to assess and compare the evolution of impacts and/or background concentrations over time (e.g. 1990 Kyoto Protocol and the 1750 IPCC reference years for climate change). The inherent variations in the state of the environment can also affect the CFs. For example, temporary changes in the carbon cycle from land use (Vazquez-Rowe et al., 2014) and related changes in the albedo of the land surface are two dynamic aspects that can bring variations in environmental impacts (Bright et al., 2012). Such variations are currently difficult to assess since they are not linked to "standard" elementary flows, which are always the source of impacts in the usual LCA framework.

3.4.7. Strategies for prospective modelling

As is the case for technosphere models, it is, in principle, possible to forecast the environmental responses of the ecosphere to elementary emissions with the use of scenarios.

Scenarios

An alternative form of temporal considerations in LCIA is increasingly performed on scenario-driven case studies. It has been applied to water use impacts by means of scenario-bound CFs, where each scenario represents a different prospective TH (Núñez et al., 2015). It is a step towards considering the temporal variability of environmental indicators, as most LCIA methods make the implicit assumption that the environment and its properties will not evolve over the studied life cycle. Another common example is the case of metal leaching in ground that has been forecasted with different scenarios (Huijbregts et al., 2001; Pettersen and Hertwich, 2008).

3.4.8. Computational framework

Recently, some DLCIA methods have been developed with different computational frameworks. These approaches are key to understand the links between DLCIs and DLCIA methods, while offering potential pathways for future developments.

Period-specific characterisation factors

In the last decade, LCA researchers have developed DLCIA methods addressing time dependent impacts as a function of time, yet they are mainly restricted to GWP and toxicity indicators. These DLCIA methods consider the periods of occurrence for emissions by providing different period-specific CFs to assess their impacts. For example, CFs can be calculated for each year over a chosen time horizon or for the month of January 2020. These CFs thus bring consistency between the temporal scopes of DLCI and impacts (Levasseur et al., 2010). Different LCA scholars found that the results based on such DLCIA methods provide useful examples for decision-making, among others, on: “the intensity, extend and frequency of the impacts” (Lebailly et al., 2014), the sensitivity of the results to various TH choices (Levasseur et al. 2012b), and the optimisation options from scenario-bound simulations (Shimako et al., 2017). The DLCIA method developed by Levasseur *et al.* (Levasseur et al., 2010) is currently one of the most recognised and sophisticated approaches, featuring period-specific CFs. In addition, calendar-specifications can be relevant to assess and compare the evolution of impacts and/or background concentrations over time (*e.g.* 1990 Kyoto Protocol and the 1750 IPCC reference years for climate change).

Time-dependent characterisation functions

Recent works (Shimako et al., 2017; Shimako et al., 2018; Shimako et al., 2016) have proposed to come back to the origins of impact simulation tools and adapt them by adding temporal information in the LCIA phase. The idea is to consider the opportunities of using DLCIs as inputs for DLCIA models. Such a DLCIA model has been proposed to assess toxicity impacts (human and ecotoxicity) by Shimako *et al.* (2017) and has been applied in a full DLCA study. The model reintroduces the time dimension for fate modelling of substances in the environment, providing the temporal distributions of substances in different environmental compartments. The physical parameters for the calculation of fate, exposure and effect factors were taken from the USEtox model. This method doesn't propose period-specific CFs, but directly calculates the impacts by coupling the impact model with all the available information in DLCIs.

The definition of ecotoxicity according to time also allows to evaluating the intensity of the impact for different periods of occurrence, which supports the identification of critical periods for potential impacts. The cumulated toxicity then represents the total damage generated over a TH. When compared with conventional USEtox results, obtained in steady state conditions, the DLCA results are systematically lower, but toxicity tends towards the conventional results for an infinite TH. Non-persistent substances (generally organic) generate almost all their hazard potential during their periods of emission and disappear more or less rapidly due to the degradation or transfer to sink compartments (removal). In contrast, persistent substances accumulate in environmental compartments during the emission periods and their toxicity potentials remain high after the emissions stop, potentially affecting many human generations.

3.4.9. Approach and tools

As was explained in subsection 3.3.2, some examples of using combined DLCI and DLCIA methods have been published recently for DyPLCA (Shimako et al., 2017; Shimako et al., 2016) and Temporalis (Cardellini et al., 2018) respectively for the toxicity and climate change categories. Still, this type of combination is rare and can only be done for few impact assessment methods with period-specific characterisation factors or time-dependent characterisation functions. Further developments are definitely required here to allow for a comprehensive consideration of the dynamics of impacts in future DLCA studies.

4. PROPOSED DEVELOPMENT PATHWAYS

It is rather straightforward to define key temporal considerations within the DLCA framework when the challenges of data availability and management are overlooked. Indeed, the general goal can be summarised by a desire to reach the highest level of temporal representativeness and to provide useful information for analysis, when considering the dynamic of systems in all of the model components. It would then seem relevant to:

- Clearly define calendar-based temporal scopes for all flows of a DLCI to outline the periods of elementary flow occurrences that justify the choice for DLCIA methods with specific temporal scopes or THs. This temporal information would also set a clear temporal frame of reference for all stakeholders who want to identify when their decisions will have effects. Moreover, a period of validity for the results of a LCA study should be set as mandatory information to offer an explicit estimation of the period when results can be considered representative and when updates would be necessary.
- Use comprehensive calendar-specific information for the models of the technosphere and ecosphere systems. It would thus be possible to clearly explain when historical data is considered representative. Prospective data based on forecasting strategies and CFs representing future impacts could also be reported explicitly to substantiate the basis for evolution of processes and their temporal scopes. A clear separation between historic and future-related results would then show the proportion of impacts that can only be based on forecasting assumptions.
- Describe the inherent variations of all flows and CFs over a life cycle with the necessary level of detail to minimise the temporal uncertainty of results. Temporal distributions of flows would be defined relative to systems' components for a common framework of assessment, which considers the dynamics of system and impacts that need to be modelled.

Reaching such a comprehensive and complex representation for temporal considerations in the LCA framework would considerably increase our ability to differentiate the impacts of different systems by removing most of the temporal uncertainties from simplifications, but it is probably out of reach and might not be necessary for most comparisons. Consequently, the current challenge lies more in finding the right balance between additional efforts for data collection, modelling complexity and sufficient temporal representativeness. The search for such a “simple but complex enough” implementation strategy is therefore the key to propose the next development steps for temporal considerations in DLCA.

4.1. Stepwise approach for temporal considerations with current knowledge

While many developments can be proposed (see following sub-sections), it is important to recognise that we can already build a strategy from previous ideas and discussions on temporal considerations LCA (section 3). We thus suggest the following 14 steps and 9 questions within the four standard phases of the LCA framework to help practitioners in the identification of where and how temporal considerations could be included.

Figure 3 presents this stepwise general approach, which can be used for any study or system. Sector specific additions have been proposed for some cases like the building sector (Collinge et al., 2013b; Negishi et al., 2018; Pittau et al., 2019) and biogenic carbon (Breton et al., 2018; Guest et al., 2013), which could be used in some DLCA studies.

The colour code is the same as the one used in figure 2 to highlight connections where solid- or white-filled boxes respectively present common and rarer temporal considerations in current LCA studies. Some other remarks are important to use this stepwise approach. First, the chosen technosphere systems in step 1 (S1) is important to identify potential temporal discrepancies and sectors where DLCA is more often useful as explained in the introduction (e.g. buildings, energy). Second, the white-filled box of the goal & scope are mostly providing further information on different temporal scopes that are usually not explicitly defined in LCA studies. Third, step 9 (S9) and question 5 (Q5) are the initial places where the need to use a DLCA approach might be identified. Step 12 (S12) and question 7 (Q7) might also highlight such a need. In both cases, different options are available (i.e. S9a, S9b, S12a) depending on the aimed level of detail.

The final step (S14) of sensitivity analysis on temporal parameters is certainly useful but currently difficult to implement comprehensively, like what has been proposed by Collet et al. (2014), mainly because there is still a need for deeper investigation of this aspect for all impact categories. Nevertheless, some analyses on technological parameters of the technosphere models are possible and have been carried out for buildings (Asdrubali et al., 2020; Hu, 2018), photovoltaic installations (Louwen et al., 2016) and other renewable energy sources (Pehnt, 2006). A more complete analysis of ecoinvent v2.2 also showed the important variations of GWP when a DLCA was conducted for processes related to wood, biofuels, infrastructure and electricity (Pinsonnault et al., 2014). These examples show that potential technological improvements and increased lifetimes should be investigated in many DLCA studies, but it is not yet possible to provide a full overview of relevant temporal parameters in models.

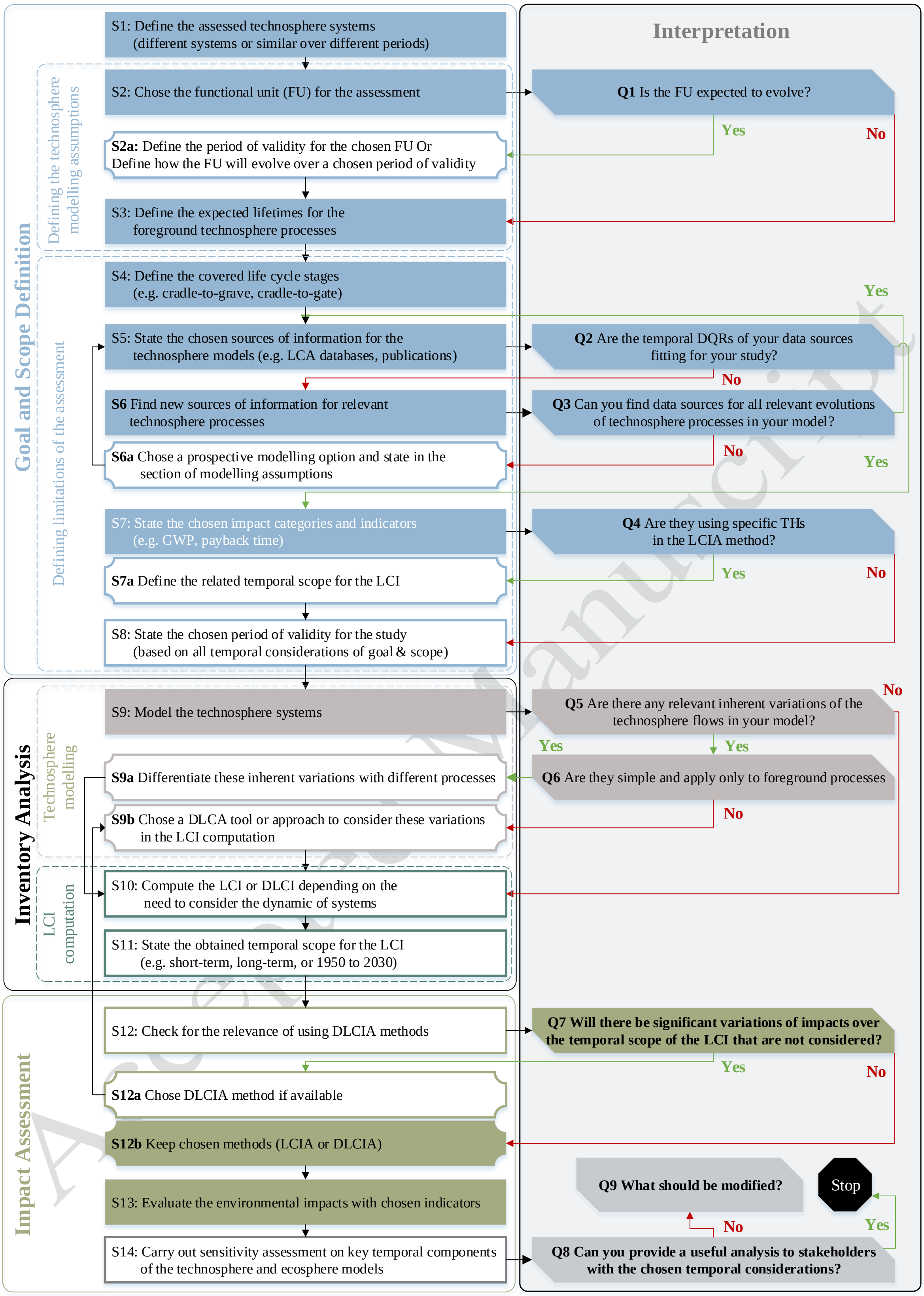

Figure 3: Stepwise approach to identify where and how to include temporal considerations in the LCA framework.
S: Steps / Q: Questions / Green = Yes / Red = No

4.2. Temporal considerations in the goal and scope definition

Temporal considerations, presented in section 3.1, mostly offer partial, implicit and qualitative information about when LCA studies are temporally representative or for when potential impacts are occurring. Temporal scopes of results in LCA studies are sometimes more explicitly defined, but they are not commonly provided, which hinders transparent and fair comparisons among results of different studies (Caffrey and Veal, 2013; Dandres et al., 2012; Huang et al., 2012; Woo et al., 2015). Lack of consistency in the vocabulary that describes the models' components and the linked LCIs or LCIA methods also brings some issues to simplify the exchange of temporal information. These obstacles should be addressed to access the wealth of information and metadata that is currently provided in LCA databases and studies. Two propositions are thus made for potential development pathways:

1. Recognise and use a common structure and vocabulary to discuss and exchange on the subject of temporal considerations in the DLCA framework, databases and studies (see section 2 for propositions).
2. Employ common metadata formats to automate the exchange of temporal information and thus provide access to the wealth of temporal information that is currently provided in LCA databases and studies, as well as to manage the expected significant increase in data requirements for this subject.

A specific example for automation is the development of guidelines to define the different temporal scopes consistently and periods of validity that should be provided in LCA databases for all datasets and studies for all processes. The authors are well aware of the challenge in asking a community to accept a common framework for such a broad subject, but data providers would benefit from the identification of common patterns and of "translation" options between data format.

4.3. Time dependent modelling of human activities

Strategies to account for inherent variations and future evolution of systems and impacts have always been implicitly considered in LCA. The mere goal of summing elementary flows over the full life cycle is a testament of this. Nevertheless, most of the current studies show an implicit assumption that human activities and associated elementary flows will not change significantly over their temporal scopes or that such changes do not have to be considered to differentiate the environmental impacts of two products with equivalent functions.

Alternatively, DLCA studies start from the assumption that inherent variations, periods of occurrence and evolution need to be accounted. The basic principle is to consider such levels of temporal considerations with process differentiation, which turns out to be challenging due to the large amount of temporal information needed whenever a comprehensive and detailed description of the life cycle is expected. The temporal differentiation of flows with process-relative temporal distributions has also been shown to be feasible, but has not yet been implemented in commercial databases. Given the current challenges and options, the next steps of development for time-dependent system modelling are suggested, as follows:

1. Carry out a comprehensive review of methodologies and approaches where dynamic modelling is considered in other fields of research to identify strategies that might not yet be proposed for the DLCA framework. For instance, DLCA is intrinsically rooted on modelling the dynamics of systems. Many models' components describe a large system, featuring several thousands of processes in the technology matrix and many hundreds of elementary flows in the intervention matrix. The introduction of timed variables in the matrixes and vectors of calculation can induce non-linear trends in the causal relationships. Delays might appear in the datasets (e.g. storage processes) or in the interventions (buffer zones at technosphere/ecosphere interface). The discontinuities form due to temporal switch between technical flows (e.g. seasonal supply) or abrupt release could also arise. All these aspects cause a real issue for solving, simulating and providing DLCA results under a reasonable computation time. Nonetheless, system dynamics is a well-studied topic in applied mathematics and control theory. The introduction of temporal considerations into the field of LCA would thus benefit from the knowledge of these research areas or disciplines.
2. Provide more process-relative temporal distributions to describe all flows and use these distributions within new computational tools. The identification of key sources for temporal variability within systems is probably the best way to start this work and will increase our knowledge on this subject in an iterative manner. Furthermore, process-relative descriptions should be combined with calendar-specific processes that change automatically when they are no longer representative of the operating technology or activity over the considered life cycle (i.e. period of validity). Furthermore, the temporal resolution that is sufficient for such distributions should be balanced with the efforts to describe the models (i.e. data management and gathering).
3. Consider that some technosphere flows or processes might have fixed historical settings when human activities are represented. For example, all elementary flows that are linked to the construction phase of hydro power plants in a country will not have different periods of occurrence if they are linked to past or future products.
4. Identify and define the temporal correlation of flows in current databases. From a mechanistic point of view, these relationships exist (e.g. carbon content in CO_2 from tailpipe emission depends on fuel consumption) and LCA practitioners can use them when creating datasets. By making these relationships explicit, one could simplify the introduction of temporal considerations in datasets, as some are intrinsically linked over time (e.g. nitrate emissions at the crop level are strongly related to the crop production cycle).

5. Find solutions for temporal considerations with co-product management and allocation. Indeed, the avoided product approach raises the question of how avoided product(s) can be modelled in time. Should it be simultaneous to the co-product or following the co-product creation, assuming that the replacement will take place afterwards? A non-physical allocation raises other questions about temporal considerations. For instance, to ensure carbon balance, corrections are made when multi-output processes are split into several single-output processes. Artificial positive and negative CO_2 emissions are added up to match the carbon fixations to the carbon content of a product (Weidema, 2018). This approach is, for example, used in the ecoinvent database under "*At Point of Substitution* (APOS)" and "*Cut-off*" system models (Wernet et al., 2016). These allocation options question whether to maintain these flows in DLCIs, and if so, how to position these artificial flows over time. Therefore the period of occurrence will be difficult to justify in DLCA.

6. Offer more explicit and complete list of choices made for prospective (or retrospective) modelling and the use of scenarios. The reason for using such modelling approach is to provide results with future (or historic) perspectives that fit more with the objectives of LCA practitioners. It is important to recognise that it is currently challenging to find a consensus on a "best" option for any case study. In such a context, a more achievable goal is to improve the transparency of modelling choices. It would also be useful to separate the elementary flows that are linked to past and present processes from the ones that are based on prospective models. This would clarify the share of impacts issued from modelling assumptions in prospective models.

4.4. Inventory calculation: keeping time in the LCI

The recently developed conceptual frameworks and tools (see subsections 3.3.1 and 3.3.2) employ a common computational structure based on graph search algorithms to calculate DLCIs. This structure uses process-relative temporal distributions to describe the flows within system models. Such a consensus suggests that the computational structure for DLCA and the corresponding tools could become a standard, but implementation challenges are still limiting their use. It thus seems relevant to:

1. Carry out more DLCA studies with these tools to increase the understanding of the LCA community and to develop the use of process-relative descriptions in LCA databases.

2. Check the importance of temporal resolution for flows in DLCI. A LCA system can represent many dynamics, because of the size of the system and the inherent temporal variations of the production processes, emissions and resource consumption, as well as of the environmental mechanisms. This issue has already been identified and discussed in some LCA studies where process dynamics are relevant. For instance, Collet et al. (2014) discussed the necessary match between the emission dynamic and the impact category to justify such temporal

considerations. Shimako *et al.* (2018) dealt with the time step of simulations regarding the impact features and showed the gap between examples of climate change (year) and ecotoxicity (day). Urban traffic is another example of the time-resolution aspect that shows the relevance of intraday dynamic for commuters since they mainly travel at the beginning and the end of the working period. Moreover, let's consider, for the sake of clarity, that both carbon dioxide and particulate matter have an intraday emission dynamic. If this resolution seems suitable for the fate of particulate matter, it is clearly too short for climate change mechanisms, where a yearly resolution would be sufficient. The transportation activity also needs infrastructure, which is defined over decades, adding an even slower dynamic to the system. Consequently, urban traffic is a good example of a system that merges multiple time resolutions with fast and slow environmental effects. Investigating different systems with varying timescales will thus be relevant to identify temporal consistency in systems.

4.5. Dynamics of impact assessment

Temporal considerations in methods for impact characterisation can be introduced with the choice of specific THs. The recent developments in DLCIA methods have focused on the impact categories of climate change, toxicity and ozone depletion, but there is the need to further explore temporal considerations in the phase of impact assessment for the following subjects:

1. Identify methods to consistently consider THs in DLCA studies for impact categories where it is relevant. A clear definition of the temporal scope covered by the LCIA methods would indeed be useful when impacts have strong time dependency. The choice of a TH should be based on the limits that are set in the goal and scope of a case study. However, to reduce value-laden choices, sensitivity analysis should be encouraged to assess the temporal variability in results. For instance, by determining the use of different THs or setting different end-years in the dynamic results when using period specific CFs.

2. Propose a clear list of the relevant time scales for each LCIA category to fix database requirements in the definition of elementary flows for any datasets. As explained before, environmental mechanisms for different impacts of substances will occur within diverse temporal scopes. These specific periods for each impact category can therefore provide guidance on the required resolution of temporal distributions to describe the elementary flows of LCIs, while minimising the temporal uncertainty.

3. Update the considered background concentrations in ecosphere models (i.e. impact assessment methods) when they substantially change the obtained CFs for an impact category. Sensitivity analyses could be performed on past and current concentration levels in order to assess temporal variability of CFs, and to propose, if necessary, updated values for prospective and/or retrospective studies.

4. Propose strategies for transparent use of prospective assumptions in ecosphere models. Identifying the parameters that were or will be affected by historic or future modifications of the environment could be particularly relevant in the context of forecasting system evolution. Temporal parameters may be based on, for example, projections of population density, or scenario-bound background concentrations. A clear identification and transparent disclosure of the temporal parameters that most affect the calculation of CFs could indeed be an important added value for impact assessment methods.

Collaboration between experts of LCA databases, LCI computation and LCIA methods should be strengthened to develop a common framework for temporal considerations in any impact assessment methods.

4.6. Summary of potential development paths for temporal considerations in DLCA

Table 4 presents a summary of the proposed developments from sections 4.2 to 4.5 with their main purposes along the different phases of the LCA framework and a qualitative assessment of the expected level of challenge to reach these targets. This assessment goes from + (i.e. basic efforts) to +++ (significant efforts).

Table 4: Summary of proposed development paths for temporal consideration in a DLCA framework

Proposed development paths	Purposes of the targets			Challenge level
	Defining the temporal scope	Considering the dynamics of systems	Increasing the temporal representativeness	
4.2 Time in the goal and scope definition				
1. Use of a standard glossary to describe temporal considerations in DLCA databases and studies	X	X		++
2. Use of common metadata descriptions to automate the exchange of temporal information	X	X		++
4.3 Time dependent modelling of human activities				
1. Investigate how other fields of research are modelling the dynamic of systems		X		+
2. Provide more process-relative temporal distributions in DLCA studies to describe flows		X		++
3. Identify the fixed historical nature of some technosphere processes	X	X	X	++
4. Describe the temporal correlation of flows in datasets of LCA databases		X		++
5. Find solution(s) for allocation that can be accepted by the LCA community		X	X	+++
6. Offer more explicit and complete list of choices made when prospective modelling is used	X	X	X	+++
4.4 Inventory calculation with temporal properties				
1. Carry out more DLCA studies with current approach and tool to increase understanding		X	X	++
2. Evaluate the importance of temporal resolution in the description of DLCIs for DLCIA		X		+++
4.5 Dynamics of impact assessment				
1. Consistent use of THs in DLCA studies with sensitivity assessment	X		X	+++
2. Provide lists of relevant time scales for each impact category	X			++
3. Update CFs when changes in background concentration have substantial effects			X	+
4. Offer more explicit and complete list of choices made when prospective modelling is used	X	X	X	+++

5. CONCLUSIONS

Considerable efforts have been made in the last 20 years to include temporal considerations within the LCA framework and to show that accounting for such aspects significantly affects the results of, at least, some case studies. For instance, LCA studies on systems with long lifespan (e.g. buildings) can benefit from models and tools where the dynamics of energy flows are considered with more details (i.e. variations and evolution). Periods of validity for datasets, which represent rapidly progressing technologies (e.g. photovoltaic cells), are important temporal information, provided in some LCA databases. Furthermore, dynamic LCIA methods have now been developed to account for impacts that vary significantly when the timing of emission change. Overall, the suggested approaches, tools and strategies increase the temporal representativeness of LCA studies and decrease the temporal uncertainty of models the technosphere and its impacts. Nevertheless, their uses in current LCA studies are still uncommon, which can be explained mainly by a lack of consistent descriptions and the challenges of gathering temporal information.

With that in mind, we offer some propositions for the next steps of developments in the DLCA framework. A glossary is proposed to build a common and consistent understanding on the key concepts that often come up in discussions on the subject. This common understanding should then help in the use of the already available information that can be found in LCA databases and studies under different names. The consistent description of this metadata should also simplify the automated exchange of information between different software options and practitioners. The temporal boundaries of DLCIs (i.e. temporal scope) should be defined within a calendar-based description (e.g. between 1990 and 2020) to improve the potential for representativeness of the impact assessments and the fairness of comparison between systems. In addition, our overview on temporal considerations in the LCI phase suggests that a preferred pathway seems to emerge in the computational approach (i.e. graph search algorithms) for DLCA, but it will require the use of process-relative temporal distributions to describe flows in datasets (i.e. input format). This information should then provide temporal distributions for all elementary flows. A balance between necessary data collection efforts and reduction of uncertainties should define the temporal resolution of such distributions. It will also be important to consider the chosen DLCIA methods when selecting the temporal resolutions of flows. Lastly, the current development of the DLCIA methods should continue by pursuing the estimation of uncertainty and variability that comes up in all impact categories when temporal information is not provided to describe the input LCI. It is then recommended to identify a relevant level of temporal resolution that would minimise the temporal uncertainty of the models for impact assessments.

6. ACKNOWLEDGEMENTS

The authors want to thank both the Empa and IFPEN institutes for funding their work, which allowed time to work on the bulk of this review paper. The first author would also like to highlight that some of this work stems from his time at MINES ParisTech when he was under the supervision of Isabelle Blanc.

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