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1 Addressing temporal considerations in life cycle assessment

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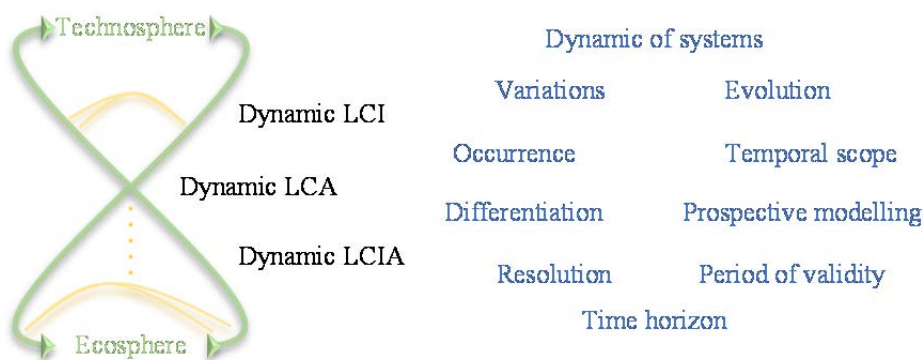
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16 HIGHLIGHTS:

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

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25 **ABSTRACT**

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

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

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

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

47 **KEYWORDS:**

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

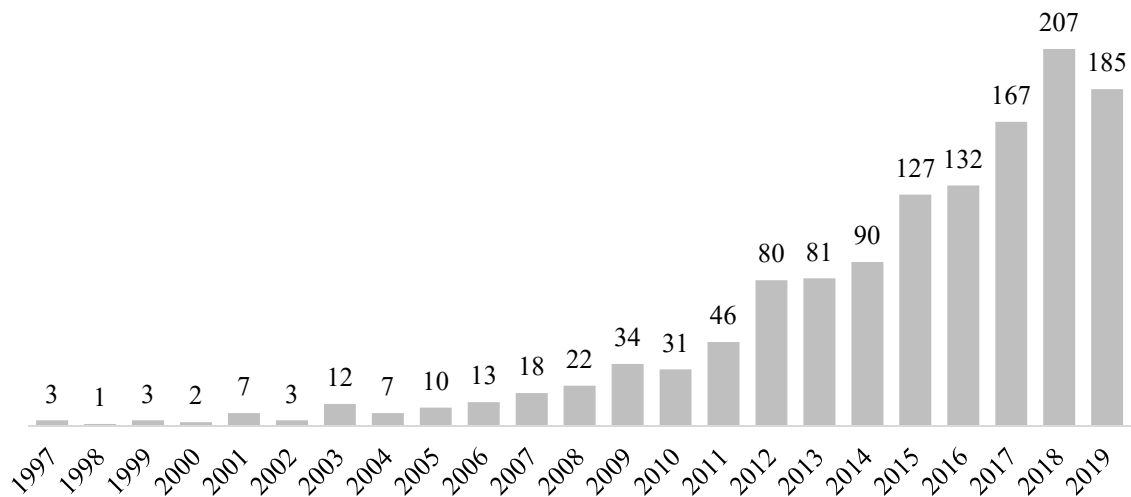
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52 1. INTRODUCTION

53 Disregarding temporal considerations¹ has been identified as an inherent limitations of life cycle assessment
54 (LCA) (ISO14040, 2006; ISO14044, 2006). Indeed, the importance of properly considering the dynamics of
55 environmental sustainability for the comparison of products, services or systems has been explored, debated and
56 confirmed during the last 20 years by many researchers like Owens (1997a), Herrchen (1998), Reap et al.
57 (2008a; 2008b), Finnveden et al. (2009), Levasseur et al. (2010) and McManus & Taylor (2015), to name a few.
58 In this discussion, Rebitzer et al. (2004), Reap et al. (2008a) and Yuan et al. (2015) have mainly explored the
59 subject of dynamics in human activities. During the same period, Reap et al. (2008b), Shah & Ries (2009),
60 Fantke et al. (2012), Kendall (2012), Levasseur et al. (2012b) and Manneh et al. (2012) have proposed different
61 ideas on the dynamics of environmental responses to human pressures. Additionally, Hellweg et al. (2003b;
62 2005; 2014), Levasseur et al. (2013), Saez de Bikuña et al. (2018) and Yu et al. (2018) have underlined different
63 potential effects from the choice of temporal boundaries in LCA studies. These three general subjects have
64 covered the bulk of the conversation on temporal considerations in the LCA framework and a growing
65 awareness of the LCA community on this topic is shown in figure 1² with a growth in the number of publications
66 where some aspects are addressed.



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.

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

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

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

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

95 approach. Recommendations for current implementation options and further developments are then provided in
96 section 4.

97

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

108 2. PROPOSED GLOSSARY

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

114

115 Table 1: List of proposed terms defining key temporal considerations in the LCA framework. The list is in alphabetical order
 116 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 <i>DLICs</i> . 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 <u>model's component</u> 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 <u>temporal scope</u> or <u>period of occurrence</u> . It results from the <u>dynamic of systems</u> in the ecosphere and can be calendar-specific, relative to the length of the <u>temporal scope</u> , or defined by a <u>TH</u> . <u>Period-specific CFs</u> 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 <u>evolution</u> of systems is thus defined and/or simulated using a list of explicit assumptions regarding the future. <u>Prospective modelling</u> can be applied to both the technosphere and ecosphere and is a subset of the <u>dynamic of systems</u> , which only concerns future forecasts.
Temporal considerations	Any aspects (i.e. information) described in relation to the time dimension or <u>dynamic of systems</u> 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 <u>models' components</u> . 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 <u>granulometry</u> when <u>temporal differentiation</u> 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 <u>period-specific CFs</u> . [Time step]
Temporal representativeness	Qualitative or quantitative assessment of data, processes or LCIA methods in relation to how appropriate their information fits with their <u>temporal scope</u> . [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 <u>models' components</u> . (e.g. definition of <u>temporal scopes</u>)
Time horizon (TH)	Relative <u>temporal scope</u> over which environmental impacts are summed up to provide LCA results.

117 3. TEMPORAL CONSIDERATIONS FOR DIFFERENT PURPOSES

118 Many temporal considerations have been described in previous publications, reports and standards to develop the
119 general LCA framework (ISO14040, 2006; ISO14044, 2006; Joint Research Center, 2010) and its dynamic
120 counterpart. For instance, Sohn et al. (2020) classified 56 DLCA studies by their technological domains and
121 types of assessed dynamism. In this section, the considerations are first regrouped by their purposes. A Venn
122 diagram in figure 2 presents this organisation of temporal considerations where gold, purple and red rounded
123 rectangles respectively highlight the purposes of defining the temporal scope, considering the dynamic of
124 systems and increasing the temporal representativeness. 10 classes of temporal considerations are also presented

125 with rectangles of different colours and linked to the phases of the LCA framework where they most commonly
 126 appear. In figure 2, the interpretation phase is excluded because the identified temporal considerations are first
 127 accounted for in the three mentioned phases and can then be used to analyse the results.

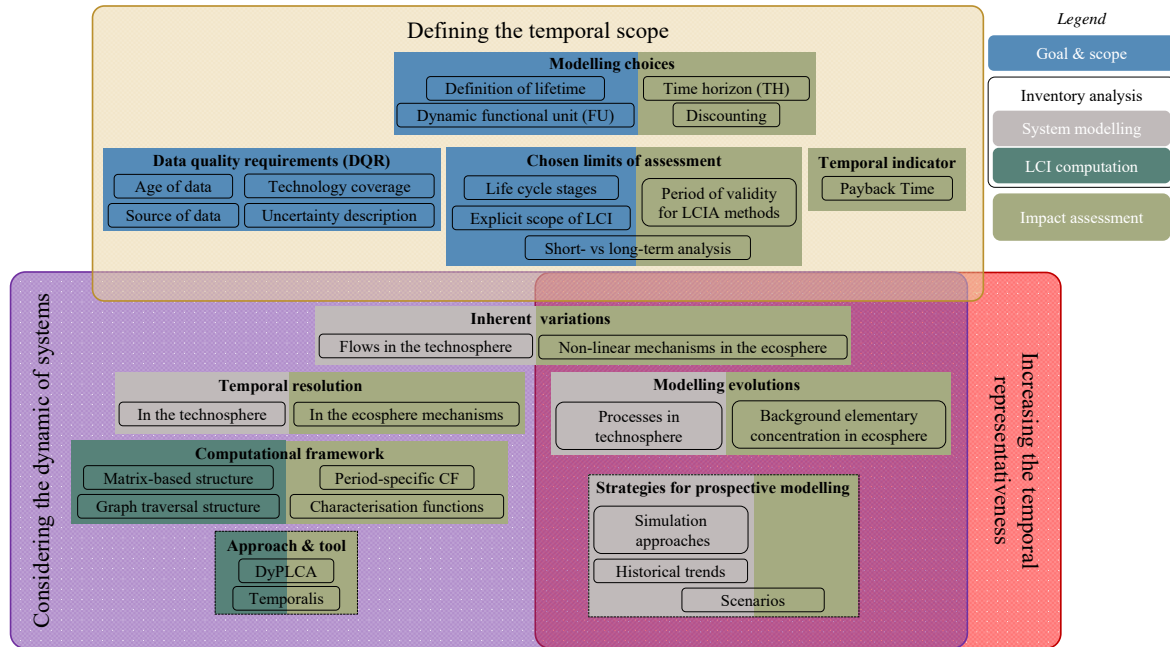


Figure 2: Venn diagram of temporal considerations in relation to their purposes (grey rectangles), the phases of the LCA methodology (coloured rectangles) and 10 classes (Bold titles). Existing connections are presented by arrows.

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

134 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

135

136 3.1. Phase of goal and scope definition

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

141 3.1.1. Modelling choices

142 *Definition of lifetime*

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

153 *Dynamic functional units*

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

161 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
 162 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
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	3.4.1 Modelling 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	

163

164 3.1.2. Data quality requirements (DQR)

165 *Age of data*

166 Some metadata of datasets, which should be defined in the DQR (ISO14044, 2006; Joint Research Center,
167 2010), informs on their age and minimum length of time for data collection. Potential temporal discrepancies
168 between used datasets and the targeted temporal scope of a modelled system can thus be partially evaluated.
169 Such information also provides some insights on the temporal scope of a system model when it represents human
170 activities (Bessou et al., 2013; Yuan et al., 2015). For example, the description of solar energy installations from
171 the 1990s would probably be relevant for LCA of solar energy before 2000. Nevertheless, using such periods of
172 validity require expert opinion, thus limiting the usefulness for this kind of metadata.

173 *Technology coverage*

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

182 *Source of data*

183 The choice of data sources and the qualitative assessment of their overall representativeness provide an indirect
184 assessment of the temporal scope for modelled systems and LCA studies (Rebitzer et al., 2004). For example,
185 when data are sourced from scientific journals, date of publication is the primary indication for its period of
186 validity. More precise temporal information is also often provided in case studies for systems with longer
187 lifetimes or in DLCA studies like (Heeren et al., 2013; Pahari et al., 2015; Sohn et al., 2017a; Vuarnoz et al.,
188 2018). The use of up-to-date LCA databases can bring a false sense of security on the temporal scope and
189 representativeness of the data for recent products or systems. Indeed, database updates do not always follow the
190 changes in market shares or evolution of technology because of the lack of new data.

191 Nevertheless, different temporal metadata is given for most datasets. For instance, ecoinvent guidelines (Wernet
192 et al., 2016) require the definition of the date of generation, the date of review and the period of validity with a
193 start date and end date for any dataset. These temporal considerations fulfil most of the requirements from ISO
194 14044 (2006) except for the definition of the averaging period of dataset inputs. The ILCD handbook (2010) has
195 set further requirements defining temporal properties: the expiring year of datasets and the duration of the life
196 cycle, which respectively relates to the period of validity for LCI datasets and the temporal scope of elementary
197 flows for a dataset. This metadata is available in most datasets of the ELCD (Recchioni et al., 2013). Many of
198 these temporal metadata are more relevant to assess the temporal scopes of studies than the choice of a database
199 and its version, but the place (e.g. in dataset descriptions) and the different definition under which they can be
200 found hinder their use in most LCA studies.

201 *Uncertainty description*

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

210 3.1.3. Chosen limits of assessment

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

215 *Considered stages of the life cycle*

216 LCA studies can limit the temporal scope of their analysed systems and LCIs by considering only a part of the
217 life cycle. Setting the end-of-life outside the boundaries is an example of such a limited temporal scope. The ISO
218 14044 (2006) allows this limitation, but only if they do not significantly change the overall conclusions of a
219 study because such phases are not linked to significant impacts. Most of the LCA reports clearly state the

220 excluded life cycle stages, but they often provide an imprecise description for the limitation of the temporal
221 scope. Moreover, the specification of the considered stages of a life cycle will not explicitly state the temporal
222 scope in which elementary flows are considered (e.g. 2 years) nor offer a calendar-based period of occurrence
223 (e.g. from January 2019 to December 2020).

224 *Temporal scope of life cycle inventories*

225 More specific and precise descriptions of temporal scopes for LCI have been provided in recent scientific
226 publications that focus on some temporal considerations (i.e. DLCA). For example, relative temporal scopes
227 have been used to define the periods of LCIs for many studies on different products, for example considering the
228 lifetime of wood-based products and buildings between 50 and 100 years (Fouquet et al., 2015; Levasseur et al.,
229 2010) including tree growth period over 70 and 150 years (Levasseur et al., 2013; Pinsonnault et al., 2014) ,
230 lifetime of marine photovoltaic of 20-30 years (Ling-Chin et al., 2016) and zinc fertiliser over 20 years crop
231 rotation (Lebailly et al., 2014). In these cases, the LCIs are enclosed within a quantified period of time that can
232 be relevant for some impact categories, but they lack any reference to a calendar year or period. Several DLCAs
233 studies defined calendar-based temporal scopes, but discussions on the potential usefulness of this contextual
234 information could be further enriched. Some were based on reference calendar years of building materials
235 (Collinge et al., 2013b), hourly energy demand in buildings (Vuarnoz et al., 2018), as well as seasonal and
236 annual variations in crop rotations (Caffrey and Veal, 2013). Other studies were based on calendar-specific
237 periods detailing domestic hot water production (Beloin-Saint-Pierre et al., 2017), future biomass production
238 (Menten et al., 2015), the lifetime of buildings (Roux et al., 2016a; Roux et al., 2016b), the energy use in hourly,
239 daily and monthly temporal resolutions (Collinge et al., 2018; Karl et al., 2019), or for introducing back-time
240 horizon (Tirutu-Barna et al., 2016).

241 *Short- vs long-term analysis*

242 Several publications describe the temporal scopes of technosphere models (Dandres et al., 2012; Menten et al.,
243 2015) or LCI (Finnveden et al., 2009; Morais and Delerue-Matos, 2010; Pettersen and Hertwich, 2008; Roder
244 and Thornley, 2016) with adjectives such as short-, medium- or long-term. These qualitative and relative
245 attributes thus inform the considered periods, but are vague. This lack of a precise temporal definition can be
246 partly explained by the lack of consensus on how temporal scopes should be defined.

247

248 3.2. Phase of inventory analysis: system modelling

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

255 Strategies to consider inherent variations and evolution have been proposed by different authors, mainly for
256 energy (Amor et al., 2014; Zaines et al., 2015), transport (Tessum et al., 2012), agriculture (Fernandez-Mena et
257 al., 2016; Yang and Suh, 2015) and waste management (Bakas et al., 2015). For example, the energy share of
258 electricity production in a country varies throughout days, weeks, months and seasons (Beloin-Saint-Pierre et al.,
259 2019; Vuarnoz and Jusselme, 2018). LCA case studies have shown that inherent temporal variations of
260 production can have significant effects on results, mainly when consumption of these products is not constant
261 over time.

262 3.2.1. Inherent variations with flow differentiation

263 Inherent variations can be modelled with temporal differentiation of flows or dynamic modelling. For instance,
264 electricity production (Messagie et al., 2014; Vuarnoz and Jusselme, 2018; Walker et al., 2015) and its use in
265 buildings (Collinge et al., 2013b; Collinge et al., 2018; Karl et al., 2019; Roux et al., 2016b; Roux et al., 2017;
266 Vuarnoz et al., 2018; Walzberg et al., 2019a), cloud computing (Maurice et al. 2014) and wastewater treatment
267 (de Faria et al. 2015) have all been modelled with such approaches. In different ways, all these approaches
268 convert flows into temporal distributions, thus supplementing temporal properties to the core data of the model
269 components in the LCA framework. The applicability of such data in other LCA studies is often limited because
270 the temporal information is valid only for the temporal scope of a given case study. A way to address this
271 limitation is to use a reference “time 0” in the temporal distribution as a period of occurrence relating to a
272 starting period of a process (Beloin-Saint-Pierre et al., 2014; Tiruta-Barna et al., 2016). This “time mark” creates
273 process-relative descriptions, which can be reused in any period of a life cycle or even for different life cycles.
274 Tiruta-Barna et al. (2016) and Pigné et al. (2019) provided process-relative temporal distribution archetypes for
275 ecoinvent v3.2, applicable to foreground and background datasets. As underlined by Beloin-Saint-Pierre et al.
276 (2014), the additional efforts needed to provide temporal information for all the flows of LCA databases are still
277 significant and the prioritisation of data-gathering remains important.

278 3.2.2. Temporal resolution

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

288 3.2.3. Modelling evolutions with process differentiation

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

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

303 3.2.4. Prospective modelling

304 Modelling future evolution of systems is another common example of temporal considerations that is often
305 performed under the umbrella of DLCA studies. Indeed, many DLCA studies have explored different
306 prospective models for a range of products like: photovoltaic panels (Pehnt, 2006; Zhai and Williams, 2010),
307 buildings (Collinge et al., 2013a; Frijia et al., 2012; Scheuer et al., 2003; Sohn et al., 2017a; Sohn et al., 2017b;
308 Su et al., 2017), bioethanol (Pawelzik et al., 2013), passenger vehicles (Bauer et al., 2015; Miotti et al., 2017;
309 Simons and Bauer, 2015), metals (Stasinopoulos et al., 2012) or ammonia (Mendivil et al., 2006). Any temporal
310 assumptions made to define future evolution are thus considered for system modelling and LCI calculations.
311 While major advances have been reached to offer explicit descriptions of assumptions made for temporal
312 considerations in DLCA, *e.g.* (Collinge et al., 2013b; Herfray and Peuportier, 2012; Menten et al., 2015; Pehnt,
313 2006; Roux et al., 2016b), they are currently not the standard. Prospective modelling assumptions can be
314 grouped within three categories that have fundamental differences on how they justify their forecasting.

315 *Simulation approaches*

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

329 The lack of consideration for human behaviour in PEM or GEM has recently been pointed out as a potential
330 issue for the validity of the prospective models (Marvuglia et al., 2015). The use of agent- or activity-based
331 models have therefore been proposed as alternatives to carry out prospective assessments; both in the foreground
332 and in the background systems. Such models have mostly been used in consequential LCAs relating with

333 transport policies (Querini and Benetto, 2015), regional market penetration of electric vehicles (Noori and Tatari,
334 2016), switch grass-based bioenergy systems (Miller et al., 2013), smart buildings (Walzberg et al., 2019b) or
335 raw materials criticality (Knoeri et al., 2013), but could be used to predict future trends. The differences between
336 the use of such simulation approaches in DLCA or consequential LCA studies have been discussed recently by
337 Sohn *et al.* (2020).

338 *Forecasting based on historic trends*

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

347 *Using scenarios to explore potential futures*

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

361 3.3. Phase of inventory analysis: LCI computation

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

365 3.3.1. Computational framework

366 *Matrix-based computation with process differentiation*

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

375 *Graph traversal structure*

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

385 3.3.2. Approaches and tools

386 Some commercial software tools use matrix-based computation (*e.g.* Simapro, Umberto) and could thus work
387 with the process differentiation framework for the calculation of temporally differentiated LCI. To our
388 knowledge, this option has not been implemented comprehensively in DLCA studies because LCA databases do
389 not offer temporal details. The ESPA method has also not been developed into a computational tool and its

390 implementation has been limited to one simplified case study (Beloin-Saint-Pierre et al., 2017). Nevertheless,
391 two options currently exist for full DLCI computations and are introduced in the following sub-sections.

392 *DyPLCA*

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

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

406 *Temporalis*

407 Temporalis (Cardellini et al., 2018) is a free and open source package of the Brightway2 LCA tool (Mutel,
408 2017), using the best-first search strategy. The tool is fully compatible with many existing commercial LCA
409 databases, but temporal descriptions of datasets are currently not provided. Temporalis does not require a fixed
410 and continuous temporal resolution over any system models to provide DLCI or results for the impact
411 assessment. Nevertheless, a DLCIA method for GWP based on the IPCC methodology (2013), is included. A
412 simple case study for the temporal consideration of biogenic carbon flows was carried out with the method of
413 Cherubini et al. (2012; 2011). It has shown that the LCI computation can be resolved on a regular laptop within a
414 short time. Nevertheless, further developments still need to be completed before most LCA practitioners can use
415 the tool easily.

416 3.4. Phase of life cycle impact assessment

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

420 3.4.1. Modelling choices

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

426 *Time Horizon*

427 The choice between a finite or infinite TH is a common type of temporal consideration that sums the
428 environmental effects over a selected temporal scope (e.g. the 100-year TH for the GWP indicator). The
429 consideration of different THs is used, for instance, by the ReCiPe method (Huijbregts et al., 2016), which builds
430 on three cultural perspectives, proposed by Hofstetter et al. (2000). These perspectives are associated with
431 different sets of calculation assumptions, including CFs with different THs for each impact category. For
432 example, the “hierachist” perspective retains a 100-year TH for GWP and other categories, while “individualist”
433 and “egalitarian” perspectives respectively use THs of 20 and 1000 years. Furthermore, very long THs are
434 suggested for some impact categories such as for climate change (i.e. 1000 years) and ionising radiation (i.e.
435 100,000 years). The ILCD handbook (2011) and the SimaPro Database Manual (PRé, 2016) provide additional
436 insights into the use of THs in different LCIA methods, but there is not yet any standard on how to deal with
437 long-term impacts and related uncertainties within all categories. For instance, the 5th IPCC assessment report
438 (2014) removed the 500-year TH due to high uncertainties associated with the assumption of constant
439 background concentrations.

440 To date, the choice of a TH remains a topic of discussion within the LCA community (Dyckhoff and Kasah,
441 2014; Reap et al., 2008b) where three critical aspects are challenging the use of fixed and finite THs in LCIA
442 methods:

- 443 • The first aspect is the inconsistency between the temporal boundaries of the studied systems and the TH of
444 the LCIA methods (Benoist, 2009; Levasseur et al., 2010; Rosenbaum et al., 2015; Yang and Chen, 2014).

445 Indeed, it could be understood that effects from elementary flows beyond the chosen TH should not be
446 considered. However, the effects are ultimately modelled over an invariable temporal scope, even if they
447 occur at different periods during a life cycle (e.g. 100 years). This use of THs may thus lead to
448 misrepresentations of impacts and their period of occurrence (Hellweg and Frischknecht, 2004), for
449 instance, misleading decision-making concerning temporary storage and emission delays (Brandao and
450 Levasseur, 2011; Jørgensen et al., 2015). This issue can be particularly significant for intermitting emissions
451 like pesticides, where arbitrary cut-offs of emissions after pesticide application should influence how each
452 emission contributes to related impacts of human toxicity (Fantke and Jolliet, 2016) and ecotoxicity (Peña et
453 al., 2019).

454 • The second aspect refers to the time integration of substances with highly variable environmental effects
455 over their lifetime in the ecosphere (e.g. aging effects reducing bioavailability of metals (Owsianiak et al.,
456 2015) or transformation of persistent chemicals in the environment (Holmquist et al., 2020)), which can
457 significantly bias the conclusions of LCA studies (Arodudu et al., 2017; Lebailly et al., 2014). In the case of
458 GWP, the weight of forcers with very short atmospheric residence time decreases with an increasing TH
459 (Levasseur et al., 2016; O'Hare et al., 2009), while a shorter TH increases the importance of short-lived
460 gases. For example, methane (CH₄), whose atmospheric lifetime is about 12.4 years, goes from a factor of
461 84 CO₂-eq for the 20-year TH to a factor of 28 CO₂-eq for 100-year TH (Myhre et al., 2013). For further
462 examples on this subject, Levasseur et al. (2016) presented various approaches that have been proposed for
463 TH definition. For toxic substances, Huijbregts et al. (2001) demonstrated that TH variations can change
464 impacts by up to 6.5 orders of magnitude for metal toxicity. In this case, the high dependency between CFs
465 and the chosen TH is due to long residence times (i.e. persistence) in fate models, which increase metal run-
466 offs and leaching potential to global marine and soil compartments.

467 • The third aspect relates to the temporal cut-offs that come with the selection of a fixed and finite THs, which
468 can be ethically questioned in the context of intergenerational equity (Hellweg et al., 2003a). Indeed, these
469 cut-offs raise concerns on the subjectivity of choosing a specific TH to highlight preferences between short-
470 and long-term impact considerations (Lueddeckens et al., 2020). For instance, the 100-year TH in GWP is
471 the most used and recommended option, but this preference is not justified by scientific facts (Reap et al.,
472 2008b; Shine, 2009; Vogtländer et al., 2014) and is implicitly subjective for decision-making (Brandao and
473 Levasseur, 2011; Fearnside, 2002). This 100-year TH is particularly important when temporary/permanent
474 carbon storage or the delayed emissions from biogenic and fossil sources are evaluated or incentivised

475 (Guest and Stromman, 2014; Levasseur et al., 2012a). Moreover, emissions that are delayed after the 100-
476 year scope are then considered to be permanently avoided (BSI, 2011; Joint Research Center, 2011).

477

478 A “simple” solution to remove such time preferences and value choices has been recommended by setting
479 infinite THs in all cases. For instance, some LCIA methods (e.g. EDIP2003 (Hauschild et al., 2006), IMPACT
480 2002+ (Jolliet et al., 2003), ReCiPe 2016 (Huijbregts et al., 2016)) use infinite or indefinite THs as a standard for
481 stratospheric ozone depletion, human toxicity and ecotoxicity. In the case of the land use impact category, THs
482 are generally not explicitly stated in current characterisation models (see e.g. Huijbregts et al. (2016) for
483 biodiversity impacts or Müller-Wenk and Brandão (2010) for climate change). Even if the theoretical
484 frameworks for land use impact assessment discusses changed (Beames et al., 2015) or permanent impacts and
485 therefore the need for defining a TH (Canals et al., 2007; Koellner et al., 2013), permanent impacts are currently
486 not considered in available characterisation models. Current models implicitly correspond to the choice of an
487 infinite TH where impacts of each land use intervention is being integrated over time until the effect factor
488 reaches 0, i.e. until the variations of soil quality after the land use intervention regenerates back to a reference
489 soil quality. Regeneration time then plays a significant role in the effective integration period and in the
490 definition of CFs.

491 *Discounting*

492 This concept was discussed to value time in LCIA (Hellweg et al., 2003a; Pigné et al., 2019; Yuan and Dornfeld,
493 2009; Zhai et al., 2011) and to deal with the uncertainties associated with time preferences and future emissions.
494 The setting of finite THs is an implicit form of discounting for long-term impacts, using a zero discount rate over
495 the TH, and an infinite discount rate beyond the TH. Discounting offers a trade-off between giving a higher
496 value to present or future impacts. A more detailed discussion on this subject is provided by Lueddeckens et al.
497 (2020).

498 3.4.2. Chosen limits of assessment

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

502 *Period of validity for LCIA methods*

503 Stating the period of validity (e.g. 2000 to 2010) or version for chosen LCIA methods in LCA studies is not
504 common practice, but it can provide insights on the expected temporal scope (Bessou et al., 2011; Hauschild et
505 al., 2013; Ling-Chin et al., 2016; Weidema et al., 2012). The choice of THs can also suggest an implicit
506 definition of the considered period of validity. In an ideal world, the temporal scope of obtained LCIs and chosen

507 LCIA methods should be fitted to each other. Such a correspondence is desirable if CFs vary significantly over
508 time, but it is currently difficult to implement in the available databases and software tools.

509 *Short- vs long-term analysis*

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

518 3.4.3. Temporal indicator

519 *Payback time*

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

526 3.4.4. Inherent variations

527 In conventional LCIA methods, CFs are determined with average or marginal approaches that model changes in
528 the impact according to a change in the inventory (Frischknecht and Jolliet, 2016; Hauschild and Huijbregts,
529 2015). With this average approach, the environmental disturbances from different activities are aggregated,
530 historically referred to as “snapshots” of a studied system (Bright et al., 2011; Heijungs and Suh, 2002; Klöpffer,
531 2014; Levasseur et al., 2016; Owens, 1997b; Vigon et al., 1993). For example, most existing models for
532 characterising toxic impacts (Rosenbaum et al., 2008) assume constant environmental conditions for the
533 assessment of health impacts. With this approach, inherent variations of the ecosphere are not considered.

534 *Non-linear mechanisms in the ecosphere*

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

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

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

559 3.4.5. Temporal resolution

560 *Specific temporal resolution for each elementary flow*

561 The temporal considerations within LCIA models may follow specific frequencies (*e.g. yearly changes*), as well
562 as temporal-inherent features deriving from dynamic biogeochemical processes. The frequency can be

563 differentiated, for instance, as responding to episodic (*e.g.* initial land clearing), cyclical (*e.g.* seasonal water and
564 pesticide use), stochastic (*e.g.* 1 in 20 years' waste discharge), or continual (*e.g.* fisheries yields) variations in the
565 studied system (Lenzen et al., 2004). Cyclical or seasonal variations concerning sunlight, temperature and
566 precipitation on the calendar year (*e.g.* winter vs summer time) are other examples of temporal considerations
567 that could be relevant for impact categories like aquatic eutrophication (Udo de Haes et al., 2002), water scarcity
568 (Boulay et al., 2015), human toxicity (Manneh et al., 2012) and photochemical oxidant formation (Shah and
569 Ries, 2009). Such frequencies therefore highlight relevant temporal resolutions for the temporal differentiation of
570 elementary flows in databases and DLCIs. Temporal inherent features may vary with hourly, daily, monthly or
571 yearly constraints depending on temporal patterns or modelling time steps of the characterisation models (Collet,
572 2012; Owens, 1997b).

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

581 3.4.6. Modelling evolutions

582 *Considering variations for concentration substances and the state of the environment*

583 Elementary flows may have varying levels of effect, depending on the timing of emissions (*i.e.* period of
584 occurrence) and the state of the environment (*i.e.* varying substance concentrations). Temporal considerations of
585 environmental mechanisms in LCA studies are challenging because the current state of practice rarely allows to
586 account for the periods of emission occurrences that are related to a product's life cycle (Finkbeiner et al., 2014;
587 Hellweg and Frischknecht, 2004; Jørgensen et al., 2014; Kendall et al., 2009; Levasseur et al., 2010; Reap et al.,
588 2008b). In fact, LCI flows are typically given as simple values that are considered to be a representation of
589 steady or pulsed flows from and to the environment by most LCIA models. For instance, impacts
590 characterisation methods often use an effect factor for a given concentration of pollutants in the background
591 environment (Finnveden et al., 2009; Hauschild, 2005). Thus, the same amount and type of elementary flows
592 (*i.e.* equivalent LCIs) can generate different levels of impacts because they have been emitted at different periods

593 of occurrence (*e.g.* 2016 or 2017), with varying flows (*i.e.* inherent variations) and geographies, requiring both
594 temporal and spatial differentiation. In this case, calendar specifications may be relevant to assess and compare
595 the evolution of impacts and/or background concentrations over time (*e.g.* 1990 Kyoto Protocol and the 1750
596 IPCC reference years for climate change). The inherent variations in the state of the environment can also affect
597 the CFs. For example, temporary changes in the carbon cycle from land use (Vazquez-Rowe et al., 2014) and
598 related changes in the albedo of the land surface are two dynamic aspects that can bring variations in
599 environmental impacts (Bright et al., 2012). Such variations are currently difficult to assess since they are not
600 linked to "standard" elementary flows, which are always the source of impacts in the usual LCA framework.

601 3.4.7. Strategies for prospective modelling

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

604 *Scenarios*

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

612 3.4.8. Computational framework

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

616 *Period-specific characterisation factors*

617 In the last decade, LCA researchers have developed DLCIA methods addressing time dependent impacts as a
618 function of time, yet they are mainly restricted to GWP and toxicity indicators. These DLCIA methods consider
619 the periods of occurrence for emissions by providing different period-specific CFs to assess their impacts. For
620 example, CFs can be calculated for each year over a chosen time horizon or for the month of January 2020.
621 These CFs thus bring consistency between the temporal scopes of DLCI and impacts (Levasseur et al., 2010).

622 Different LCA scholars found that the results based on such DLCIA methods provide useful examples for
623 decision-making, among others, on: “the intensity, extend and frequency of the impacts” (Lebailly et al., 2014),
624 the sensitivity of the results to various TH choices (Levasseur et al. 2012b), and the optimisation options from
625 scenario-bound simulations (Shimako et al., 2017). The DLCIA method developed by Levasseur *et al.*
626 (Levasseur et al., 2010) is currently one of the most recognised and sophisticated approaches, featuring period-
627 specific CFs. In addition, calendar-specifications can be relevant to assess and compare the evolution of impacts
628 and/or background concentrations over time (*e.g.* 1990 Kyoto Protocol and the 1750 IPCC reference years for
629 climate change).

630 *Time-dependent characterisation functions*

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

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

649 3.4.9. Approach and tools

650 As was explained in subsection 3.3.2, some examples of using combined DLCI and DLCIA methods have been
651 published recently for DyPLCA (Shimako et al., 2017; Shimako et al., 2016) and Temporalis (Cardellini et al.,

652 2018) respectively for the toxicity and climate change categories. Still, this type of combination is rare and can
653 only be done for few impact assessment methods with period-specific characterisation factors or time-dependent
654 characterisation functions. Further developments are definitely required here to allow for a comprehensive
655 consideration of the dynamics of impacts in future DLCA studies.

656 4. PROPOSED DEVELOPMENT PATHWAYS

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

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

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

684 4.1. Stepwise approach for temporal considerations with current knowledge

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

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

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

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

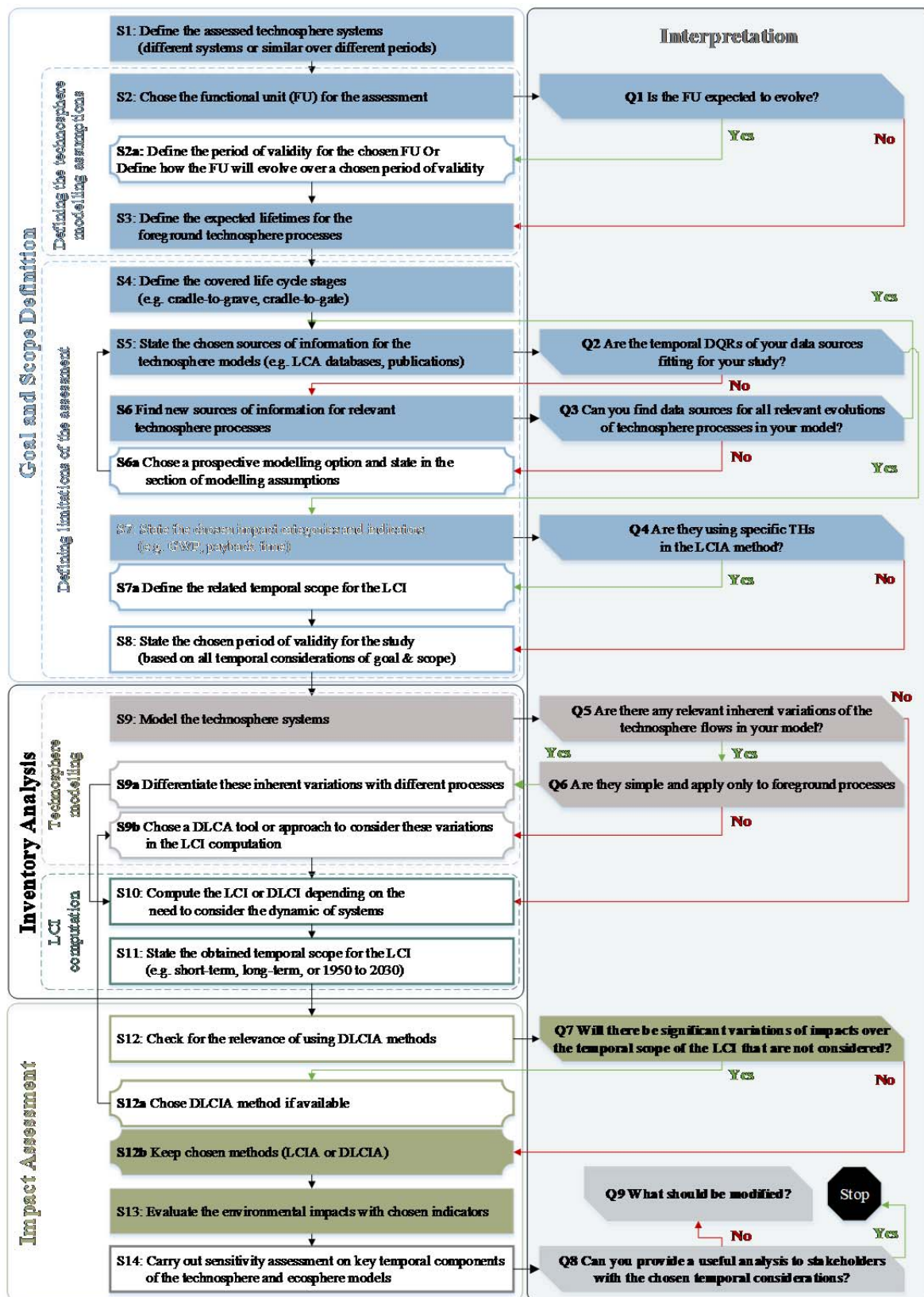


Figure 3: Stepwise approach to identify where and how to include temporal considerations in the LCA framework. S: Steps / Q: Questions / Green = Yes / Red = No

712

713

714 4.2. Temporal considerations in the goal and scope definition

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

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

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

734 4.3. Time dependent modelling of human activities

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

740 Alternatively, DLCA studies start from the assumption that inherent variations, periods of occurrence and
741 evolution need to be accounted. The basic principle is to consider such levels of temporal considerations with
742 process differentiation, which turns out to be challenging due to the large amount of temporal information

743 needed whenever a comprehensive and detailed description of the life cycle is expected. The temporal
744 differentiation of flows with process-relative temporal distributions has also been shown to be feasible, but has
745 not yet been implemented in commercial databases. Given the current challenges and options, the next steps of
746 development for time-dependent system modelling are suggested, as follows:

- 747 1. Carry out a comprehensive review of methodologies and approaches where dynamic modelling is
748 considered in other fields of research to identify strategies that might not yet be proposed for the DLCA
749 framework. For instance, DLCA is intrinsically rooted on modelling the dynamics of systems. Many models'
750 components describe a large system, featuring several thousands of processes in the technology matrix and
751 many hundreds of elementary flows in the intervention matrix. The introduction of timed variables in the
752 matrixes and vectors of calculation can induce non-linear trends in the causal relationships. Delays might
753 appear in the datasets (e.g. storage processes) or in the interventions (buffer zones at technosphere/ecosphere
754 interface). The discontinuities form due to temporal switch between technical flows (e.g. seasonal supply) or
755 abrupt release could also arise. All these aspects cause a real issue for solving, simulating and providing
756 DLCA results under a reasonable computation time. Nonetheless, system dynamics is a well-studied topic in
757 applied mathematics and control theory. The introduction of temporal considerations into the field of LCA
758 would thus benefit from the knowledge of these research areas or disciplines.
- 759 2. Provide more process-relative temporal distributions to describe all flows and use these distributions within
760 new computational tools. The identification of key sources for temporal variability within systems is
761 probably the best way to start this work and will increase our knowledge on this subject in an iterative
762 manner. Furthermore, process-relative descriptions should be combined with calendar-specific processes
763 that change automatically when they are no longer representative of the operating technology or activity
764 over the considered life cycle (i.e. period of validity). Furthermore, the temporal resolution that is sufficient
765 for such distributions should be balanced with the efforts to describe the models (i.e. data management and
766 gathering).
- 767 3. Consider that some technosphere flows or processes might have fixed historical settings when human
768 activities are represented. For example, all elementary flows that are linked to the construction phase of
769 hydro power plants in a country will not have different periods of occurrence if they are linked to past or
770 future products.
- 771 4. Identify and define the temporal correlation of flows in current databases. From a mechanistic point of view,
772 these relationships exist (e.g. carbon content in CO₂ from tailpipe emission depends on fuel consumption)

773 and LCA practitioners can use them when creating datasets. By making these relationships explicit, one
774 could simplify the introduction of temporal considerations in datasets, as some are intrinsically linked over
775 time (e.g. nitrate emissions at the crop level are strongly related to the crop production cycle).

776 5. Find solutions for temporal considerations with co-product management and allocation. Indeed, the avoided
777 product approach raises the question of how avoided product(s) can be modelled in time. Should it be
778 simultaneous to the co-product or following the co-product creation, assuming that the replacement will take
779 place afterwards? A non-physical allocation raises other questions about temporal considerations. For
780 instance, to ensure carbon balance, corrections are made when multi-output processes are split into several
781 single-output processes. Artificial positive and negative CO₂ emissions are added up to match the carbon
782 fixations to the carbon content of a product (Weidema, 2018). This approach is, for example, used in the
783ecoinvent database under “*At Point of Substitution (APOS)*” and “*Cut-off*” system models (Wernet et al.,
784 2016). These allocation options question whether to maintain these flows in DLCIs, and if so, how to
785 position these artificial flows over time. Therefore the period of occurrence will be difficult to justify in
786 DLCA.

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

794 4.4. Inventory calculation: keeping time in the LCI

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

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

802 2. Check the importance of temporal resolution for flows in DLCI. A LCA system can represent many
803 dynamics, because of the size of the system and the inherent temporal variations of the production
804 processes, emissions and resource consumption, as well as of the environmental mechanisms. This issue has
805 already been identified and discussed in some LCA studies where process dynamics are relevant. For
806 instance, Collet et al. (2014) discussed the necessary match between the emission dynamic and the impact
807 category to justify such temporal considerations. Shimako *et al.* (2018) dealt with the time step of
808 simulations regarding the impact features and showed the gap between examples of climate change (year)
809 and ecotoxicity (day). Urban traffic is another example of the time-resolution aspect that shows the
810 relevance of intraday dynamic for commuters since they mainly travel at the beginning and the end of the
811 working period. Moreover, let's consider, for the sake of clarity, that both carbon dioxide and particulate
812 matter have an intraday emission dynamic. If this resolution seems suitable for the fate of particulate matter,
813 it is clearly too short for climate change mechanisms, where a yearly resolution would be sufficient. The
814 transportation activity also needs infrastructure, which is defined over decades, adding an even slower
815 dynamic to the system. Consequently, urban traffic is a good example of a system that merges multiple time
816 resolutions with fast and slow environmental effects. Investigating different systems with varying timescales
817 will thus be relevant to identify temporal consistency in systems.

818 4.5. Dynamics of impact assessment

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

- 823 1. Identify methods to consistently consider THs in DLCA studies for impact categories where it is relevant. A
824 clear definition of the temporal scope covered by the LCIA methods would indeed be useful when impacts
825 have strong time dependency. The choice of a TH should be based on the limits that are set in the goal and
826 scope of a case study. However, to reduce value-laden choices, sensitivity analysis should be encouraged to
827 assess the temporal variability in results. For instance, by determining the use of different THs or setting
828 different end-years in the dynamic results when using period specific CFs.
- 829 2. Propose a clear list of the relevant time scales for each LCIA category to fix database requirements in the
830 definition of elementary flows for any datasets. As explained before, environmental mechanisms for
831 different impacts of substances will occur within diverse temporal scopes. These specific periods for each

832 impact category can therefore provide guidance on the required resolution of temporal distributions to
833 describe the elementary flows of LCIs, while minimising the temporal uncertainty.

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

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

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

846 4.6. Summary of potential development paths for temporal considerations in DLCA

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

850

851 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	+++

852

853 5. CONCLUSIONS

854 Considerable efforts have been made in the last 20 years to include temporal considerations within the LCA
855 framework and to show that accounting for such aspects significantly affects the results of, at least, some case
856 studies. For instance, LCA studies on systems with long lifespan (e.g. buildings) can benefit from models and
857 tools where the dynamics of energy flows are considered with more details (i.e. variations and evolution).
858 Periods of validity for datasets, which represent rapidly progressing technologies (e.g. photovoltaic cells), are
859 important temporal information, provided in some LCA databases. Furthermore, dynamic LCIA methods have
860 now been developed to account for impacts that vary significantly when the timing of emission change. Overall,
861 the suggested approaches, tools and strategies increase the temporal representativeness of LCA studies and

862 decrease the temporal uncertainty of models the technosphere and its impacts. Nevertheless, their uses in current
863 LCA studies are still uncommon, which can be explained mainly by a lack of consistent descriptions and the
864 challenges of gathering temporal information.

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

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