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Defining Temporally Dynamic Life Cycle Assessment: A Literature Review

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Abstract

Durable goods last for years, decades, or even centuries. The environmental implications of the changing social, economic and material conditions in which these goods are embedded can be overlooked by conventional life cycle assessment that assumes a static world. In order to avoid these problems, methods such as Dynamic LCA (DLCA) are increasingly being used. Despite the growing use of DLCA, numerous questions remain. These include how this dynamism is incorporated and what aspects of any given DLCA are dynamic. To answer these questions we perform a review of 56 DLCAs, of which 44 propose a framework for DLCA covering all ISO phases of an LCA or carry out a DLCA. Three types of LCA dynamism are identified and assessed for the reviewed literature: *dynamic process inventory*, *dynamic systems*, and *dynamic characterization*, while a further two types of LCA dynamism, *dynamic scope* and *dynamic weighting*, are proposed, but not applied, in the assessed literature. We found that the implementation of DLCA varies widely, and inventories accounting for dynamic characteristics are by far the most prevalent expression of DLCA. In order to reduce confusion surrounding the discussion of DLCA, we propose a definition of DLCA and its sub-types: Full DLCA, Partial DLCA, and Prospective LCA. It is concluded that, amongst the current array of DLCA definitions, the implementation of partially dynamic LCA (PDLCA), which apply dynamism in only some parts of the LCA, is common and likely to continue. This is because PDLCA offers quantifiable marginal utility, in terms of increased validity of the

assessment, in relation to conventional LCA methods, but caution is needed in applying PDLCA because of potential for introducing bias into the LCA. To avoid this problem, we propose incorporating system dynamism as part of a sensitivity analysis particularly in PDLCA that are limited by missing data.

Keywords: Dynamic Life Cycle Assessment; Prospective LCA; Temporal Differentiation; Time Horizon; Systemic Change

Key Points:

1. The application of dynamism in life cycle assessment varies significantly due to a lack of definition and methodological guidelines.
2. Incorporation of dynamics in a life cycle assessment can significantly alter results.
3. By incorporating dynamism as a type of sensitivity analysis instead of in the reported results, when data is not available to incorporate dynamism in the entire system, inadvertent bias can be avoided while maintaining the benefits of dynamic assessment.
4. We define dynamic LCA as well as three distinct sub-types that we encountered in the literature.

Introduction:

Life cycle assessment (LCA) has become a well-recognized and frequently used tool for the assessment and comparison of the environmental and social impacts of products and product-systems. Since its inception, the purpose and practice of LCA has changed significantly, with the generation of new knowledge, approaches, and understanding of

limitations. The better understanding of how products interact with the economy and surrounding environmental conditions has inspired new dimensions to LCA (e.g. consequential thinking, social impacts, spatial explicitness etc.). There has been much research and discussion regarding market consequences of product use or substitution, attribution or allocation of impacts in the case of co-products and secondary functions, characterization and potentially normalization of impacts to ensure valid results and strengthen decision support, etc. (Reap *et al.* 2008a, 2008b). Although there are continuing differences of opinion, these issues are well documented in literature comparing consequential and attributional LCA, e.g. in Ekvall and Weidema (2004), as well as in innumerable discussions regarding characterization factors and normalization methods (Hauschild *et al.* 2013; Owsianiak *et al.* 2014). However, there has been less work to ensure that the product system models themselves are adequately developed to deal with an ever-increasing range of products and systems. Namely, practitioners often have to grapple with how to model systems that operate and require inputs for decades (Reap *et al.* 2008b). One major piece of this development is the application of temporal system dynamism, that is to say dynamic assessment methods.

Compounding this present lack of exploration is that LCA's initial developers intended that the tool be used in the comparison of individual energy production methods and 'simple' product comparisons, such as packaging alternatives (Curran 2006). This origin, and prioritization of comparative product LCA, has resulted in a tool well developed to model products with a short service life (relative to the assessed time horizon) and/or that have no ongoing inputs e.g. packaging, coatings, or consumables. On the other hand, the LCA techniques for durable products/services with resultant ongoing inputs, such as

building insulation, urban infrastructure, and machinery, are less advanced (Levasseur *et al.* 2010; McManus and Taylor 2015). Furthermore, the application of LCA to the buildings and infrastructure in cities, such as in Goldstein *et al.* (2013), makes such a discussion even more relevant.

This background supports a current practice where temporal dynamism is often either ignored, or accounted for to varying levels, without adequate standards or acknowledgement of the ramifications of decisions made for its modeling. This non-standardized way of handling dynamism results in an inconsistent application of the methods to incorporate dynamism in recent LCAs, potentially generating incorrect conclusions. For example, this type of assessment with incorrect conclusions could stem from the incorporation of a dynamic inventory quantifying ongoing inputs that does not account for temporal variations in characterization factors, or it could stem from incorporating dynamism in the foreground system while omitting dynamism in the background system and marginal products or vice versa.

These partial implementations of dynamic LCA (DLCA), whether applied in consequential or attributional LCA (further discussed in section 3.4), do not inherently produce incorrect decision support, but such inconsistencies could undermine model validity and potentially lead to unintentionally misleading results. And, as the number of DLCA published is rapidly increasing, with over 1000 articles published and 165 articles hereof published in 2016 alone (Figure 1), it is imperative that we explicitly define DLCA, outline its important attributes and systematize the way in which this emerging tool is applied. In order to address and illuminate the methodological issues related with DLCA, this work aims to evaluate the use of DLCA in order to clarify a best practice for

the LCA of durable products or systems so that the impact of such variability in method might be reduced. Furthermore, we present a definition of DLCA to promote a unification of discussion of said subject.

Methods

LCA is comprised of four phases: goal and scope definition, life cycle inventory, life cycle impact analysis, and interpretation (ISO, 2006). It is possible to treat any one or a multiple of the phases dynamically. For the purposes of this review, DLCAs were analyzed in accordance with three of the four ISO defined phases: the inventory analysis phase, the impact assessment phase, or the interpretation phase. Specifically, we assess three types of dynamism:

- *dynamic process inventory* (DPI), where the potential for future development (viz. technological advances) was incorporated into single unit processes (e.g. the incorporation of increasing efficiency in energy production technologies) to develop a dynamic inventory for individual unit processes,
- *dynamic systems inventory* (DSys), where the potential for future change in components of system processes are accounted for by discretely changing between unit processes or behaviors in a system model (e.g. the shift from coal energy production to natural gas energy production or from gas to electric vehicles) to develop a dynamic inventory for the system,
- *dynamic characterization* (DChar), where characterization factors are adjusted to reflect a difference in temporal scale (e.g. the change in characterization factor for CO₂ eq. released today vs in the future).

These three types of LCA dynamism: DPI, DSys, and DChar, are considered regardless of in which phase of the LCA they occur (Figure 2). We do not include incipient methodological advances lacking concrete application, such as dynamic normalization/weighting (Su *et al.* 2017) and dynamic scope (Østergaard *et al.* 2017), the latter of which is proposed in relation to large scale infrastructural projects (e.g. for buildings constructed at various times within an urban development masterplan) but not yet implemented.

Literature Aggregation and Analysis

This literature review is not intended as an exhaustive study but rather as a representation of the state of the art. First, to assess the trend in publication regarding dynamic life cycle assessment, a topic search in Web of Science using the term “dynamic life cycle assessment” was carried out for the years 1991-2016, returning 1071 results (Figure 1). Then, to gather a sampling of literature for assessment, we then performed a targeted searches of titles containing the phrases “Temporal Life Cycle Assessment”, “Temporal LCA”, “Dynamic Life Cycle Assessment”, and “Dynamic LCA”. These were chosen because the authors feel they were likely to include a sampling of DLCA where authors were specifically attempting to include issues pertaining to DLCA. This search returned 62 distinct results, of which, 6 did not pertain to life cycle assessment (e.g. articles from information sciences). We analyzed the remaining 56 articles to determine if they included a fully implemented LCA or a framework for the implementation of a full LCA, thus covering all ISO phases of an LCA. The 44 articles that met the former criterion were then compared in regards to which types of dynamism were present, DPI, DSys,

and/or DChar respectively, and all 56 DLCA articles were characterized according to their dynamic attributes (SI Table 1).

Limitations of the literature review

One of the primary limitations of this work is that the review of DLCA papers is only representative. While it would be ideal to undertake a complete review of all DLCA, processing the resultant articles would pose a significant challenge that the authors consider insurmountable. This is in part due to many articles incorporating elements of DLCA are not titled or described accordingly, so identifying them amongst all LCA would be a near impossible task. Thus, it would require actively assessing all publications where LCA is carried out in order to unequivocally claim that all DLCA have been assessed, and based on a web of science search, the number of articles including “life cycle assessment” in their title was greater than 500 in 2015 alone. The Authors consider such an undertaking far outside the scope of this work. Another significant limitation of this review is that it covers both articles where an LCA is carried out as well as articles that propose new LCA methodologies or frameworks. Because of this, some articles are shown that propose methodological changes within one specific dynamic LCA part (e.g. dynamic characterization factors). While these papers are excluded from most of the figures on analysis of inclusion of specific dynamic parts of LCA, they are also an important indicator of issues that are presently being taken on in scientific literature, and are thus included in some of the analysis.

Also, the decision to break dynamism into three parts (DPI, DSys, and DChar) could have been done in other ways. The authors chose to break the dynamic parts in this way, as it closely mirrors the way systems exhibit dynamism in the real world. It would be

possible to envision other ways making a distinction between the dynamic parts such as between foreground systems, background systems, and characterization factors. Such a method would more closely follow the way LCA practitioners treat their models, but we feel it is likely that the conclusions drawn in such an analysis would be similar to what was shown with the chosen method. The authors suggest that, while it is out of the scope of the present manuscript, confirming this through additional analysis would be a useful follow up to this work.

Discussion and Results

The assessment of literature indicates a wide range in DLCA practices. Figure 3 displays the different application rates of DLCA amongst the ISO phases in which they are found. The prevailing trend, with 73% of assessed DLCA studies, is that LCA practitioners use only dynamic inventories while omitting other potential dynamic elements. Figure 4 expands this comparison, showing the parts of assessed LCA literature in which dynamic principles were applied. This is further displayed in Figure 5, where trends amongst technological domain or framework type can be seen.

Amongst all the assessed literature (omitting partial-frameworks), a partially-dynamic LCA (PDLCA), i.e. a DLCA that does not exhibit dynamism in all phases or parts, is most common (93%). For example, Sohn et al. (2017) analyzed different insulation materials with a DSys that incorporated a shift in background energy grid (i.e. from coal to natural gas) but did not incorporate either DPI (i.e. technological improvement within individual technologies) or DChar. While in that case it was likely that the omission had no material impact on the results, cases where that would not hold true can easily be envisioned. For example, it would be possible to create a model that improperly favors a

particular emerging technology by incorporating a partially dynamic inventory that includes dynamism for the emerging technology and omits it for the background system, thus over-stating the benefits of the emerging technology over time. More specifically, an example of this can be envisioned for an assessment done on a new form of biopolymer production to replace an existing technology. In this scenario, a learning curve is applied reducing the inputs necessary for the new technology over time as the process is refined but not applied to the replaced polymer production. This is done because the practitioner is using data for the existing technology from a database in aggregated form, making it difficult to apply a learning curve. Thus, any potential improvements to the existing process would not be accounted for in the inventory while reductions in energy consumption for the new technology would be, making the comparison improperly favor the new technology.

While this problem of improperly-implemented partial DLCA whether duplicitous or simply from naïveté is a possibility, there are many cases where a PDLCA provides better decision support than a static LCA while avoiding the increased work demands of a fully-implemented dynamic LCA (i.e. a DLCA that covers dynamism in all applicable phases of the LCA for all unit processes). This is particularly important in cases where it is nearly impossible or impractical to implement such a full dynamic LCA due to data demands, increased model complexity, or lack of established method, as well as in situations where the dynamic properties of a process or system are so uncertain that it is better omitted. In order to allow for the appropriate use of PDLCA, a standard for use should be established outlining standards for implementation and reporting.

Definition of dynamic life cycle assessment

Thus, in order to facilitate the discussion of DLCA, and given a general dearth of concrete definitions for DLCA, we propose the following definitions for DLCA and its sub-types:

Dynamic life cycle assessment: an LCA that incorporates elements of temporally induced changes that affect results and interpretation of the modeled system.

Full dynamic life cycle assessment: an LCA where temporally induced changes are incorporated in all phases of the assessment. This includes (i) Dynamic goal and scope (e.g. temporally induced changes in service life), (ii) Dynamic inventory analysis (including temporally induced changes in all systems), (iii) Dynamic impact assessment (e.g. temporally differentiated characterization factors), (iv) Dynamic interpretation (e.g. temporally differentiated weighting factors)

Partial dynamic life cycle assessment: an LCA where temporally induced changes are incorporated in some phases of the assessment. May also include instances of temporal change unevenly applied across elements of the assessed system (e.g. only assessing temporal differentiation in the inventory of foreground processes).

Prospective life cycle assessment: an LCA where the assessment is made for a single point in the future. May include comparison with status quo. The future assessment may or may not include temporally differentiation in all phases of the assessment.

Given the large requirement for data and the relatively minimal returns in regard to validity, the theoretically possible full dynamic LCA is we consider it unlikely that such

would ever be implemented in practice except in an illustrative simplified case. Thus, most DLCA will be either PDLCA or PLCA, and in this context will be referred to as either DLCA or as their more specific form PDLCA or PLCA respectively.

Incorporation of Dynamic Phases in LCA

In the assessed literature, there are three ISO phases of LCA that include dynamism: inventory analysis, impact assessment, and interpretation. While the three assessed dynamic parts of an LCA naturally occur in their corresponding specific phase of an LCA, this does not necessitate that they are applied in their respective natural locations (Figure 2). This is primarily because dynamism in either or both the inventory and the characterization of impacts might be explored in the inventory analysis and impact assessment phases respectively or might alternatively be addressed in a sensitivity analysis, which would take place in the interpretation phase of an LCA. This latter option of incorporating dynamics in a sensitivity analysis can offer a significant portion of the benefits of DLCA while avoiding some potential drawbacks of PDLCA such as inadvertent prejudicing of results in an assessment that is limited by incomplete data. This can be accomplished by exploring the impacts of dynamism in one part of the system and acknowledging the ramifications in discussion as part of a sensitivity analysis, which allows for recognition of the issue without skewing the comparisons made in the reported results of the LCA.

Dynamic Process Inventory

Dynamic process inventory is the most common expression of DLCA in the assessed literature, with 70% of the assessed DLCA having incorporated DPI and 32% having

exclusively incorporated DPI. A typical expression of this type of dynamism is presented in the incorporation of variations in an energy production system (Björk & Rasmuson 2002), which explores the effect of parameter shift within a unit process for drying within the energy production system. This type of dynamism can be agent-based depending on external factors (e.g. economic merit-based decision-making practices) or development based (e.g. technological improvement within a system or process). Regardless of which type, it can play a significant role in the relative impacts of processes within a system. For example, in the aforementioned energy production system, environmental impacts within the energy production process could vary over 50% with an approximately 8% variance in the economics of the system (Björk and Rasmuson 2002). While this type of variance can be straightforwardly implemented in foreground processes developed by the LCA practitioner, implementing such variation can be more difficult in background processes where representative unit processes from existing databases that are difficult to modify might be used, such as was carried out in Sohn et al. (2017a, 2017b, 2017c). The distinction between DPI and DSys can become rather fine, as in Miller et al (2012), where changes in a particular type of production are modeled as discrete processes which are then implemented to various degrees by the technology adopters. This causes this expression of dynamism to be classified as DSys, but it could have been modelled as improvement on an existing technology (single unit process) and thus have been classified as DPI instead.

Dynamic Systems

Dynamic systems inventory can be one of the most readily implementable elements of DLCA because it relies on change in unit process type within the product system rather

than change within unit processes themselves. This means that, in its simplest form, dynamic systems can be implemented while utilizing unedited database unit processes. Despite this, it is only employed in 45% of the assessed literature. In cases where it was implemented, DSys tends to be developed in one of three ways: scenario-based models, trend analysis, and agent-based models (Miller *et al.* 2012). It can be of significant importance, particularly in systems incorporating biomass, where it can effect results by over 10% (Pinsonnault, Lesage and Levasseur 2014) and when assessing overall energy systems, where it has been reported resulting in impact changes up to 219% (Ben *et al.* 2014). Because DSys can incorporate variation in the background systems, such as energy grid composition, it can be incorporated in a wide variety of time scales. For example, hourly resolution might be important in some cases (Ben *et al.* 2014; Messagie *et al.* 2014), while annualized change in system composition might be important others, such as in analysis of an overall energy grid (Sohn *et al.* 2017a). And, though changes in unit processes (DPI) are not accounted for in DSys, oftentimes the effects of such changes (e.g. electricity generation plants becoming more efficient over time) are well understood and can thus be estimated and accounted for in sensitivity analysis. This type of implementation in the sensitivity analysis could allow for the implementation of DSys even when lack of data or variable levels of uncertainty in such development across different processes would make direct utilization inappropriate.

Dynamic Characterization

As LCA is used for products and systems with ongoing inputs as well as in increasingly long time horizons, temporally variant characterization factors for specific elemental flows can be developed to avoid incorrectly equating the environmental impacts of

temporally disparate emissions (Shah and Ries 2009; Levasseur *et al.* 2010; Dyckhoff and Kasah 2014). For example, a variable characterization factor for photochemical ozone formation has been proposed with up to two orders of magnitude difference between the characterization factor for months with greatest impact and those with least (Shah and Ries 2009). DChar is also particularly important in product systems incorporating biogenic carbon from sources with long regrowth period, such as wood (Guest and Strømman 2014). It is also of great importance in product systems where present expenditures of impact are used to prevent future impacts that may happen long into the future and where impact payback times are great. The analysis of building insulation for near net-zero energy housing in Sohn *et al.* (2017a), for example could benefit greatly from such an addition. The incorporation of dynamic characterization factors, however, can be especially challenging, as they are not readily implemented in many existing LCA software packages. Such software development would significantly aid the LCA practitioner, but barring demand for such development, it is unlikely that it will be implemented (Chastek 2002). Despite wanting tools, alternative methods of temporal impact adjustment, such as impact discounting methods (Zhai, Crowley and Yuan 2011; Yuan *et al.* 2015), can be readily applied in a spreadsheet application, however the application of such methods relies on assumptions that introduce very high levels of uncertainty and are often considered controversial.

Further Dynamism

There were two further dynamic parts of DLCA, namely dynamic scope and dynamic weighting, which were identified but not assessed among the reviewed articles, as they were never utilized in an LCA, only proposed as part of future frameworks. Despite a

lack of application in literature, their utility in the ever-broadening application of LCA is evident.

In cases where the implementation of an assessed system will happen over a long time-period (i.e. decades), such as in urban development masterplans or phased implementation in a large production system, the length of the use phase of a product or system has the potential of changing drastically throughout the course of the system's implementation. Østergaard et al. (2017) describe this process in assessing an appropriate scope (sc. service life, life span, or temporal scope) for the assessment of buildings. In relation to this, one could imagine developing e.g. temporally differentiated expected service lives for buildings in an urban development project. Since DLCA results are often very sensitive to the chosen time horizon (Dyckhoff and Kasah 2014), refining scope in such a dynamic way has the potential to offer more accurate results in some cases relative to conventional LCA practice.

Dynamic Weighting, on the other hand, should not have a direct effect on the results of an LCA, as weighted results should be delivered with reference to unweighted results (International Organization for Standardization 2006). However, in practice end consumers of LCA reports (e.g. policy makers and corporate executives) are often unable, due to lack of understanding the technical details or time constraint, to understand the nuance between what is shown at the midpoint impact level and a single score result. To account for this, Su et al. propose incorporating the objectives, location, and time horizon of the assessment in making dynamic weighting factors (2017). Incorporation of this type of dynamic perspective in a distance-based multiple attribute decision making method for use in obtaining single scores such as that proposed by Kalbar et al. (2016)

could greatly increase ability for the LCA to provide relevant decision support. However, the potential to incorrectly assess future perspectives is significant and should be noted in regards to any conclusions drawn from dynamic weighting techniques (Herrchen 1998). As such, interpretation of the weighting as well as any assumptions made in its derivation should be disclosed in a manner appropriate to the intended audience to prevent improper inclusion of bias.

Data Availability – Ramifications on DLCA

One of the largest challenges in developing DLCA (and perhaps LCA in general) is adequate data. Some system elements more easily lend themselves to forecasting, such as DSys for energy grids, where government policies or strong historic trends indicate realistic future developments with a relatively high level of confidence. However, potential bifurcations abound with other elements, where multiple, possible futures preclude the accurate characterization of a single, dominant system down the road. This means that the LCA practitioner can either present several scenarios that encompass a ‘best’ and ‘worst’ case scenario, resulting in an impact range. For example, one could develop characterization factors for climate change impacts that mirror the different emissions pathways outlined by the IPCC in their climate change report (IPCC 2014). Due to its utility in modelling processes that cannot be easily predicted, the use of Monte Carlo simulation might be useful developing this type of scenario based impact projection (Kroese et al. 2014). Alternatively, the practitioner could select a ‘likely’ scenario amongst available scenarios. This latter solution, however, is essentially controlled conjecture, and could pose significant issues, particularly if alternative pathways and their relative impacts are not disclosed.

Another issue in relation to data for future development scenarios is that developing such a model inherently creates a more complex system that requires greater data input than conventional LCA methods. Particularly if one takes the case of a consequential LCA, the number of unit processes can be greater relative to an attributional LCA. So, if all of these unit processes must also become dynamic, then the data demands of such a model could quickly become overwhelming. In such a case, the development of a clear cutoff metric is necessary to allow for the implementation of such an analysis.

Dynamism in Consequential and Attributional LCA

A primary issue that should be addressed when speaking of temporal dynamism issues in LCA is the differentiation that is made between DLCA and consequential LCA. The ILCD handbook differentiates consequential and attributional LCA primarily via the life cycle model's interaction with a 'dynamic' technosphere that reacts to additional supply and demand or a 'static' technosphere that remains unchanged by the life cycle model being embedded in it (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010). However, while consequential LCA deals with system reactions, and thus incorporates some 'dynamic' aspects, a consequential LCA is not necessarily dynamic in the same way as DLCA. Thus, consequential LCA need not incorporate temporal issues within the direct assessment of the functional unit, as it instead places focus on the input-output structure and territoriality of the resultant production-consumption system. That is to say, that consequential LCA might be used to assess a product that could also be assessed using attributional LCA without any temporal information, e.g. comparing food-packaging alternatives. The issue of assessing market change independent from the proposed system or product alternatives within the scope of

an LCA is not addressed in the aforementioned ILCD definitions for either consequential or attributional LCA, but some of the language used regarding attributional LCA might lead one to believe that attributional DLCA would be precluded from such an assessment. In practice, however, both consequential and attributional LCA methods are used in developing DLCA as seen amongst the assessed DLCA (e.g. Sohn et al. (2017a) used an attributional approach while Roux et al. (2016) take a consequential approach). The application of attributional and consequential approaches in DLCA is also further discussed by Collinge et al. (2013b), wherein they describe the concept that in a DLCA the application or function of the system studied, the supply chain, and environmental effects of an emission can vary independently – thus allowing both consequential or attributional approaches.

In some cases, attributional LCA might be preferred over consequential LCA in practical application, as the data demands of a dynamic consequential LCA of a complex system can become unwieldy should the LCA practitioner not want to employ some method of cutoff in assessing the temporal dynamics of the system. However, the implementation of a well-defined cutoff metric that is transparently applied would follow other standard practices in consequential LCA, and it would make DLCA as easily implementable in consequential LCA as in attributional LCA, with the potential drawback of adding another element with the potential for reducing comparability across studies (e.g. in the case that different metrics are used).

Future Outlook for DLCA

Because DLCA is becoming more prevalent (Figure 1), there are a number of opportunities and challenges for the development of DLCA in the coming years. These

include computing solutions such as software and databases, an increasing need for reporting standards and development of methodological standards, as well as the incorporation of big data and the internet of things, etc.

As the models used in DLCA become more complex, the computational demands become much greater. In most cases, this is not an issue, as recent improvements in computing power mean that it is not usually a limitation on LCA practitioners' ability to perform an LCA. But, as additional layers of dynamism and uncertainty are added, the features in LCA software design could play a role in widespread implementation of DLCA. For example, in most widespread LCA product system modelling software (e.g. SimaPro, GaBi, OpenLCA, etc.), it can be challenging to incorporate dynamic elements such as variable time horizons and their related effects on system development or dynamic characterization factors. Furthermore, particularly in consequential LCA where the background system can expand significantly (relative to attributional LCA), modelling system development manually, e.g. through parameterized inputs, for all processes throughout the system could take a disproportionately large amount of effort relative to the marginal benefits over a conventional LCA. In order to rectify this issue, logical cut-off points on this type of expanded dynamism would need to be established. To help alleviate this problem, LCA product system modelling software development could play a significant leading role, creating the opportunity for more structured full-implementation of time differentiated product system, characterization, and interpretation models. Such projects as Brightway, a python-based open source LCA software (Mutel and Hellweg 2019), are beginning to pave the way for this, but lack the general ease of

access to make them available to the general LCA practitioner populous due to the lack of GUI.

Furthermore, the need for standardization in how dynamism is treated becomes apparent, as some instances of dynamism (e.g. increasing efficiency in established technologies) appear to only contribute small differences ($\pm$ ca. 2%) while others (e.g. temporally differentiated characterization factors or development of emerging technologies) can contribute orders of magnitude difference. Also, as elements such as dynamic scope or cutoff metrics become incorporated in DLCA, presently available standards will be challenged to adequately support practitioners in creating a uniform implementation. As such, it is apparent that new standards will need to be written encompassing the implementation methods and reporting necessary for carrying out DLCA.

Application of DLCA

In order to better understand how the definition of DLCA presented in this manuscript might be applied; an explanatory case is described here through classification in terms of DLCA definitions. This case describes the dynamic life cycle assessment as carried out in Sohn et al. (2017a). In this assessment, the authors aimed to determine an optimal level of insulation for Danish residential application, based on construction at the time of publication. According to the definition framework of DLCA, as set out in this manuscript, this assessment was carried out as a PDLCA, as only DSys was included. The authors, recognizing the shifting nature of the energy mix used to provide residential heat, sought to elucidate the effect of such change on the impacts of a single family home. In order to achieve this, the authors modelled the changing energy production types (DSys) from political projection and included a static assessment as a point of

comparison. Other elements necessary to complete a full DLCA were omitted, and the authors noted the impacts of some of these.

For example, DPI would have been useful to the assessment, but citing lack of data, it was omitted. Despite this, the authors qualitatively note the effects on the results of the assessment from its inclusion. This helps to ensure that the results do not mischaracterize the system despite the omission of DPI. DChar could have also been applied with incremental value-add to the assessment, however, data was lacking for such implementation. Given the more complicated nature of the effect of implementing DChar relative to DPI, in this instance, it would also have been difficult for the authors to expound qualitatively on the impact of the omission of DChar. This was not addressed by the authors, and could ideally have been broached in the manuscript to help avoid influence on the results. Conversely, dynamic scoping would not have been appropriate for application in this study, as the decision context only included construction at the time of publication with no projection for the future. Ideally, the authors when formulating the PDLCA could have made such a statement. Furthermore, the authors did not approach the concept of dynamic interpretation. This latter could potentially shed light on elements of the study, especially on the interpretation of future heat provision impacts, particularly in concert with dynamic characterization, however lack of data to support such projections might hinder any such efforts. Based on this analysis, it can be determined that this case represents an effective implementation of PDLCA where DLCA might have been prohibitively difficult to implement. However, some elements, such as the inclusion of reasoning for omitted elements, might have been improved by implementing the DLCA definition framework as proposed in this manuscript.

Conclusions

Despite assessing only a subset of all articles incorporating DLCA, some conclusions can still be drawn about the implementation of DLCA in present literature. Overall, the application of dynamic parts in DLCA is varied. Moreover, although it offers the most holistic view and takes advantage of the synergies that can be developed in a dynamic LCA that incorporates dynamism in all parts, only 7% of assessed literature incorporated all three assessed parts of DLCA. This is indicative of the varied implementation of PDLCA, and although this is not inherently problematic, appropriate measures must be taken to ensure that the use of PDLCA does not skew results. A possible solution for this issue when PDLCA are carried out due to missing data is to show the effect of estimated DPI and DSys in sensitivity analysis, thus avoiding influence on the results through accidental omission while giving the opportunity for discussion and perhaps further research to fill determined data gaps. Furthermore, while dynamic characterization factors are important, present implementation with existing software can be difficult. This issue, as well as other dynamic modelling issues, should be able to be overcome with future software development. But, it is necessary that demand for such dynamic capability become greater for this type of software development to be likely. Despite these challenges, it is important that the effects of temporal dynamism be accounted for when they are available, as they can have significant impacts on the results of an LCA and its associated decision support.

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Figure 1: Count of articles appearing in Clarivate Analytics Web of Science Core Collection on the topic of DLCA by year from 1991 to 2016.

Figure 2: Application of additional dynamic LCA parts associated with the related phases of an LCA in the ISO Life Cycle Assessment Framework (2006) as well as potential alternative application of dynamic LCA parts.

Figure 3: Inclusion of dynamism in the inventory and impact assessment phases of an LCA in the assessed DLCA where a full LCA was carried out or a full framework for LCA was discussed. Articles presenting a partial framework for DLCA as classified in Table 1G were omitted.

Figure 4: Inclusion of dynamic LCA parts in the assessed DLCA articles where an LCA was carried out or a full framework for LCA was discussed. Articles presenting a partial framework for DLCA as classified in Table 1G were omitted. DPI-Dynamic Process Inventory, Dsys-Dynamic System Modelling, DChar-Dynamic Characterization.

Figure 5: Inclusion of DLCA parts by technological domain/type and year in count of occurrence in all assessed articles. BLDG-Building, CC-Carbon Capture, EP-Energy Production, FF-Full Framework including all ISO LCA phases, ITU-Infrastructure, Transportation, and Urban Issues, MAN-Manufacturing, PF-Partial Framework including only some of the ISO LCA phases.