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Ten questions concerning prospective LCA for decision support for the built environment

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ABSTRACT

It is essential to provide quantitative decision support when pursuing environmental impact mitigation efforts, particularly when considering resource and energy-demanding sectors such as the built environment. Life cycle assessment (LCA) provides widely recognized quantitative decision support regarding environmental performance. However, for long-lived products such as buildings, the usefulness of conventional LCA is limited as it relies on databases that only give a current or past representation of industrial processes. The emerging field of prospective LCA (pLCA) allows us to evaluate the results at a future point in time based on technological and socio-economic projections. This article builds on a systematic literature screening, ongoing discussions in the pLCA academic community, and hands-on experimentation with available software. The goal of the study is to 1) understand implications of how pLCA is conducted, and how it relates to the built environment; 2) Improve the documentation and credibility of pLCA and applied scenarios; And 3) identify practical tools and workflows that can make pLCA more accessible to practitioners. The study raises ten relevant questions when considering how to use pLCA for decision support in the built environment. This list of questions is not exhaustive nor definite, and recommendations are possible answers suggested by the authors. Using scenario narratives from energy and Integrated Assessment Models allows for systematic and consistent transformation of LCA databases to represent possible futures. However, there is a need for pLCA practitioners to improve documentation to ensure that the goal and scope of the LCA are compatible with the chosen future scenario. In the case of built environment, it is relevant to consider different projection years when modeling construction, operation, renovation, and demolition phases, respectively, as they span several decades. Not doing so can misestimate the effects changing socio-economic and technological contexts have on the life-cycle impact of buildings.

1. Introduction

Due to the global focus on sustainable development and emissions reduction, providing qualitative and quantitative decision support is becoming increasingly relevant. Regarding environmental impacts, life cycle assessment (LCA) is a widely recognized methodology for the said task [1]. The accuracy of LCA results for decision support is a challenge of significant importance, especially in the built environment, which faces issues of high resource and energy consumption – 30% of the final energy demand in 2022 only for the operation of buildings [2]. Furthermore, the long service life of buildings raises problems regarding the temporal over-simplification applied in practice and hence the validity of LCAs covering temporal ranges of decades or centuries [3,4]. The field of prospective LCA (pLCA) is receiving increasing attention as a methodological improvement that can ameliorate the validity of decision support, specifically regarding the inclusion of emerging technologies [5–9]. This paper focuses on prospective LCA's practical applicability and relevance, focusing on its application to the built environment. By raising ten relevant questions and discussing possible answers, the paper presents methodological challenges associated with applying pLCA to systems with long service lives. The article presents a systematic literature screening with hands-on application, experimentation with current tools, and discussion with the community of developers and users to identify questions, challenges, and potential solutions to applying pLCA to the built environment. The objective is to give the authors' perspective on the emerging field of pLCA and guide future research, especially within the built environment and other products with long service lives. This paper is primarily targeting LCA

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modelling experts and researchers of pLCA.

LCA systematically accounts for the environmental burdens induced by the product system under study through each of the product's relevant life-cycle phases (i.e., from raw materials extraction and production to the use and disposal of the product). LCA most often includes some form of temporal dimension that is, to a varying extent, oriented towards the future. This "glance" into the future may be different in its nature and in the way the future-orientation is handled in practice: predictive, explorative or normative [10]. The integration of future aspects in LCA becomes increasingly relevant when considering large-scale decision support and products with long service lives, for instance as seen in the built environment.

The built environment accounts for 40% of global resource use and waste generation and 33% of anthropogenic greenhouse gas emissions [11]. In this context, LCA is widely used to quantify the environmental performance of buildings [12]. As buildings are usually estimated to have a service life of approximately 80 years [13], it becomes relevant to consider dynamic (time-dependent) aspects, as systems supporting the use phase of buildings (e.g., electricity and heat networks) may change during this period. The LCA methodology has, however, usually a "flat" representation of time (e.g., emissions from all life-cycle phases occur at once, as a pulse emission), and inventory data are static throughout the service life of the building, despite technological and market changes.

Hence dynamic and temporal aspects are often cited as a limitation in LCA studies [14,15]. The research field of dynamic LCA (DLCA) has emerged to deal with such issues. For instance, some studies consider systemic aspects (e.g., seasonal variations in energy supply and hourly variations in operational energy of buildings) to identify possible optimizations [16]. Other researchers in the field consider discounting through weighting and temporally dependent characterization factors to account for the variation of impacts occurring at different points in time [8]. Others consider system changes in the form of changes to the foreground and background systems in the life cycle inventory, such as supply mixes for electricity and emerging technologies [17]. Prospective LCA, anticipatory LCA, and ex-ante LCA consider systemic changes over time. According to the literature found in this study (see supplementary information), the term *prospective* in relation to LCA was first used in 2002, however does not get traction before 2015. Many recent studies still find the terminology and methodology to be inconsistent [5,8,10,18]. A critical literature review by Ref. [9] noted that despite efforts to propose definitions of future-oriented LCA on emerging technology, the terminology in the field is inconsistent to a degree that inhibits a properly structured meta-analysis. They identified that dynamic, anticipatory, ex-ante, and prospective LCA focus on temporal aspects that can affect the performances of emerging technologies and products yet to be produced at scale. In this study, we simplify the discussion by referring to future-oriented LCA with the term "prospective LCA", or pLCA.

2. The ten questions

The following ten questions were formulated with the three objectives in mind: 1) Understand implications of how pLCA is conducted, and how it relates to the built environment; 2) Improve the documentation and credibility of pLCA and applied scenarios (a need identified by several studies); And 3) identify practical tools and workflows that can make pLCA more accessible to practitioners.

2.1. Question 1: How can future environmental impacts be assessed?

Prospective LCA can be useful for assessing the environmental impacts of products in future contexts. Nevertheless, projecting the future comes with limitations and uncertainties, which this section discusses.

As pointed out by Ref. [19]; pLCA induces inherent uncertainty. Uncertainty may originate from the possible performance deviation of the system or product under study (i.e., lab-scale performance versus future industrial-scale performance). Another significant source of uncertainty may come from changes at the scenario level which may indirectly affect the system performances (i.e., change in the carbon-intensity/climate change impact of the electricity supply), but also from the fact that not all scenarios have the same likelihood to unfold. Hence, pLCA is considered an explorative rather than predictive methodology. In this respect, the scenario-based uncertainty and sensitivity assessments pLCA can provide are essential: the process allows exploring future pathways and assessing their effects on the performance of the systems studied. It is desirable to provide the decision-maker with a good understanding of the risks of an emerging technology underperforming because of factors unrelated to its development (e.g., background systems such as energy conversion technologies). Such technology could rely on future low-carbon electricity, as with electric vehicles [20] and operational energy for buildings. Considering large-scale decision support, those uncertain factors about the future warrants a thorough uncertainty analysis based on various scenarios to explore possible future outcomes.

Different methods for uncertainty analysis are described by Refs. [21,22], and ranges from simple Monte-carlo analysis which aggregates parameter uncertainties; to more advanced methods such as local and global sensitivity analysis, investigating the effect of changing certain parameters. The latter methods are more relevant in a context of understanding implications in decision support. Igos and colleagues find that more advanced methods should consider an exhaustive list of uncertainties and their correlations. For pLCA this can in theory be done via simulation tools for the foreground system. In practice, it is difficult concerning the entire background system. Hence the output of models projecting future background data can be collected in pre-defined scenarios. E.g., assessing the background systems according to several different future scenarios from IPCC (see more in section 2.4) can be considered as advanced uncertainty analysis.

A systematic literature screening (see details in supplementary information) of case studies applying pLCA was conducted for this paper. Search engines ScienceDirect and Scopus were used with the search terms *(temporal OR future OR prospective OR dynamic OR dynamism) AND (lca OR life AND cycle AND assessment OR life AND cycle AND analysis) AND scenario)*, yielding 2011 results. After screening, 38 case studies and nine literature reviews remained relevant.The screening of the case studies found 50 different approaches used for scenario development. The general picture is that 29 approaches are used across 38 papers. The most widely used approaches in the analysis are summarized in Table 1. They occur 4 to 5 times each and are used by 25 of the 38 papers reviewed. The reader should refer to the Supplementary Information material for more details on the literature screening.

Forecasting based on author assumptions and historical trend projections are some of the most popular approaches. This prevalence is likely due to its simplicity and flexibility in terms of implementation. Such practices achieve higher credibility when based on scientific literature and industry reports. However, "literature" is an ambiguous term, and the results can differ depending on the referenced literature. Hence, there is a risk of (un)intended bias when applying the most popular scenario development approach identified in this paper. Projections from energy agencies or similar institutions can leverage assessment credibility, although these projections still entail the same challenges regarding bias.

Scenario narratives are relatively frequently occurring in the screening. They aim to provide a higher consistency through high transparency and documentation. Being based on consensus gives them credibility. Scientific models from different fields combined with policy pathways form the basis of narratives. We find that they are often based on scenarios from the International Energy Agency (IEA) or the United Nations in the form of the Shared Socioeconomic Pathways (SSP). The SSPs will be discussed further ins section 2.4.

Table 1
Most occurring approaches in the systematic literature screening. They occur in 25 of the 38 screened papers.

Approach	Description	Occurrence	
Author forecast	They are qualified forecasts and assumptions defined by authors. Can be vaguely supported by "what-if" scenarios.	5	[23] [24] [25] [26] [27]
Historical trends projection	They are an extrapolation of historical trends used for future projections.	5	[28] [29] [30] [26] [27]
Scientific literature	It refers to projections from the relevant scientific literature, implying the risk of bias.	5	[31] [32] [33] [34] [35]
Reduction targets	They are projections based on pathways to reach policy reduction targets, such as the Paris agreement.	5	[36] [37] [29] [16] [34]
RCP Transition pathways	Same as above but based on the Representative Concentration Pathways (RCP) (see section 2.4).	4	[38] [32] [30] [39]
Energy Agency projections	Projections from Energy Agency reports.	4	[28] [26] [40] [41]
TIMES cost-optimization models	Future energy grid evolution based on variants of the *TIMES* cost-optimization models.	4	[32] [42] [29] [41]
IMAGE-based narratives	Projections based on narratives using the *IMAGE* integrated assessment model for quantification (see section 2.6).	4	[43] [20] [17] [39]

2.2. *Question 2: How are temporal dependencies accounted for in prospective LCA?*

A literature review by Ref. [44] investigated the dynamic elements of LCA. The study defines pLCA as assessing a product system for a single future point (i.e., a chosen target year), which is often compared to the status quo. They find that pLCA might include dynamism in all ISO-defined stages of an LCA (i.e., goal and scope, inventory, impact assessment, and interpretation). However, Sohn and colleagues consider that dynamism is unlikely ever to be implemented fully in all these stages of an LCA due to extensive data and modeling requirements and relatively minimal returns in terms of validity.

The literature screening conducted in this article found that most studies consider dynamic LCI (i.e., including dynamism in the inventory stage as defined by the ISO 14040 standard, see more in section 2.4). Sixty-eight percent (68%) of the studies do not consider other dynamic aspects than the LCI, as shown in Fig. 1e [44]. found that the LCI can be either a dynamic process inventory (DPI) or a dynamic system (DSys). DPI considers dynamic changes in the foreground system of the life cycle inventory, whereas DSys additionally accounts for changes in the background system. Including the background system enables pLCA to assess a product's or service's performance in a future context, considering the expected changes across the sectors that support the life cycle. Exemplifying using the built environment, DSys allows us to evaluate the environmental performance of constructing a building in 2030, renovating it in 2070, and demolishing/dismantling it for reuse in the year 2100. In this case, the performance of systems in the background (e.g., electricity grid, transportation, production processes, disposal treatment) would differ for each life cycle phase.

2.3. *Question 3: How is the goal and scope definition adjusted when conducting prospective LCA?*

The literature screening conducted in this study reveals that most (18 of 37) pLCA studies use the future target year of 2050. Ten studies consider earlier target years, whereas nine papers consider later target years, with the farthest being 2100 (see Fig. 1a). Most of the studies are recent, with only two articles published before 2013 and more than half of the papers published in 2018 or later. By subtracting the publication year from the target year, we find that most studies have a time horizon stretching 25–35 years into the future (see Fig. 1b). Relative to the service life of a building, this time horizon is considered too short to consider the full life cycle from cradle to grave.

The functional unit (FU) of an LCA is crucial for the results. However, when considering the future, uncertainty may very well be connected to the reference flows estimated to fulfill the FU and the possibility of multifunctionality and co-production. Our observations are that retrospective LCAs (with extensive time horizons) can define a static FU, but the reference flows are inherently dynamic through time – hence, the same applies to the future. For example, the average Danish citizen's demand for transport changes regarding distance and means of transportation. Similarly, for buildings, the type of housing, size, and level of comfort change over time.

Prospective LCA is conducted both as consequential and attributional LCA. These two methods answer different questions, and the reader can refer to Ref. [21] for a comparison. Software (further described in section 2.6) that systematically modifies the background system is currently only available for the attributional version of the ecoinvent database [45]. The literature screening conducted in this paper reveals that less than a fifth of the assessed pLCA studies followed a consequential approach.

2.4. *Question 4: How to estimate foreground and background systems of the future?*

Nearly half of the pLCA studies in the literature screening implement the future scenarios exclusively in the foreground system of the LCI. In contrast, approximately a third of the studies consider only the background system. Four of the 38 studies consider both foreground and background systems (see Fig. 1f). As found by Refs. [17,43]; the outcome of an "electric vs. fossil-fuel vehicle" decision varies depending on the scenario used for the modification of the background system, suggesting that pLCA must include changes in the background system. Furthermore, it is essential to apply consistent background system modification to achieve a common basis for comparison across studies [46]. When conducting pLCA within the built environment, aligning the background systems with the temporal scope of the study is essential for several reasons. First, construction materials (e.g., cement, stone wool, bricks) are energy-intensive and responsible for environmentally-harmful emissions today. However, sector-wide mitigation efforts should reduce their environmental footprint in the future (e.g., a decrease of clinker used in cement, an increased use of alternative fuels and cementitious materials, and hydrogen-based direct reduction of iron for steelmaking) [47,48]. Second, heat and electricity systems engaged throughout the service life of buildings should also undergo efficiency (e.g., low-temperature district heating) and structural (e.g., large-scale high-temperature heat pumps) changes. Finally, the standard practices of handling construction waste by the end-of-life of the building may be different from today's (e.g., accelerated carbonation of concrete before reuse, which could be relevant for e.g. 3d printed concrete elements, that is designed for optimal CO2 sequestration [49]). These aspects are typically not modeled by the practitioner but are part of the background LCA database. They have the potential to affect the life cycle impacts of a building significantly, and it is, therefore, essential that background systems reflect such sector-wide mitigation efforts.

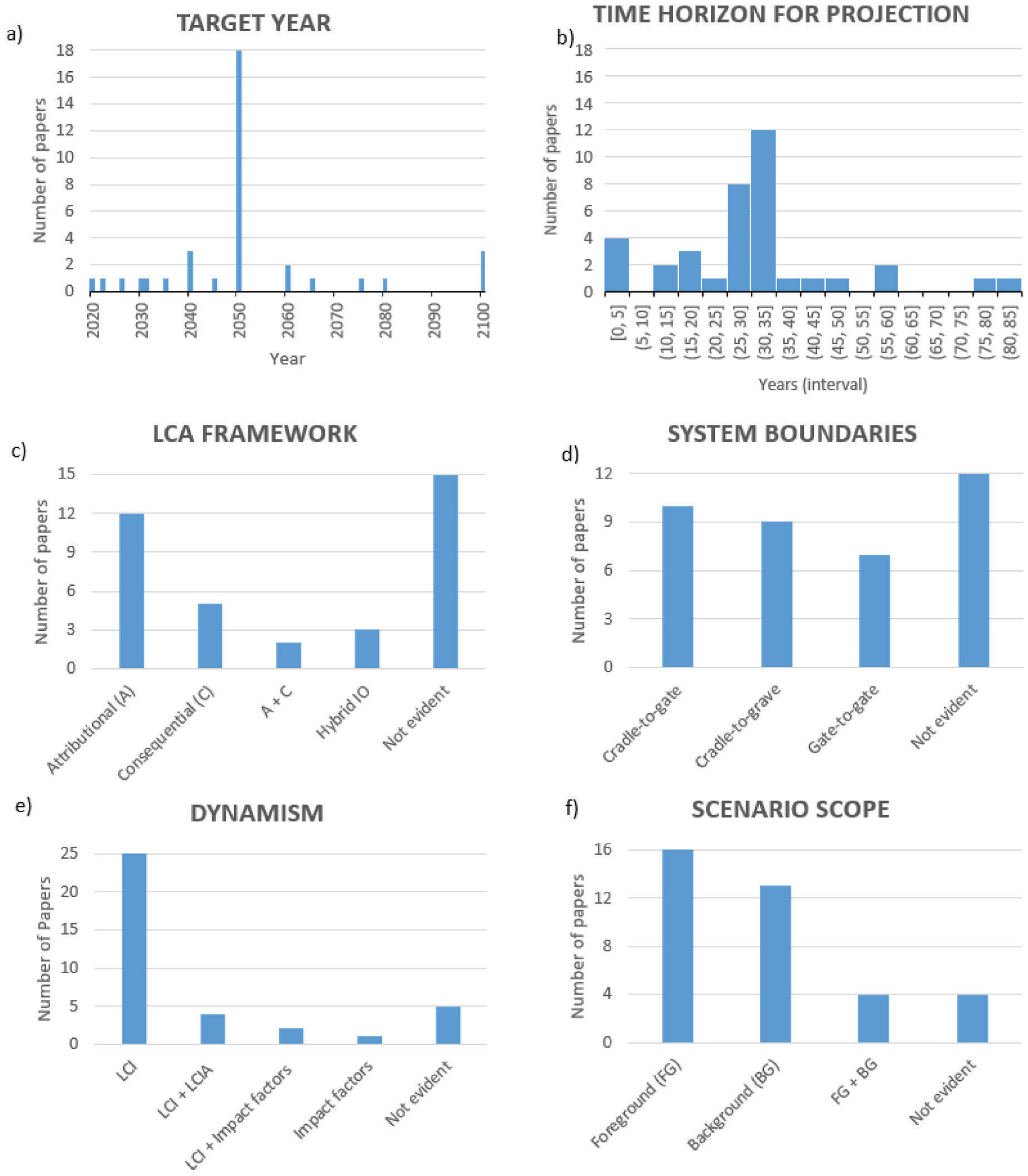

Fig. 1. Basic LCA-specific information for the 38 screened papers. A) Target year of LCA, b) temporal scope (target year minus publication year), c) applied LCA framework, d) system boundaries, e) types of dynamism implemented, and f) LCI system modeling scope of future scenarios.

[9] suggest including experts and stakeholders as well as learning curves and custom scenarios to solve the challenge of foreground system modeling. For prospective background system modeling, they propose Integrated Assessment Models (IAMs) to transform LCI databases in line with the Shared Socioeconomic Pathways (SSPs). The scientific background of the SSPs is briefly summarized in the following paragraph.

In the late 2000s, research groups started developing new and up-to-date climate change scenarios up until 2100. It resulted in a set of Representative Concentration Pathways (RCPs) describing different concentrations of greenhouse gasses and resulting warming of the climate that might occur in the future [50]. To complement this, O'Neill and others developed the SSPs, which consider five scenarios of how the world might develop in the absence of climate policy, including factors such as population, economic growth, education, urbanization, and the rate of technological development [51]. A different narrative of the future defines each of the five SSP scenarios [52]. The SSPs were published in 2016 and used for the Coupled Model Intercomparison Project version 6 (CMIP6) in preparation for the IPCC's sixth assessment report [53].

2.5. *Question 5: How are future scenarios integrated into LCAs?*

The SSP scenarios are quantified trajectories for societal demand, technology change, and resulting environmental impacts (often limited to climate change). IAMs, which are computer models analyzing a broad range of physical, economic, and social data to aid decision-making are used to elaborate SSPs. Within climate research, IAMs provide guidelines to reach specific political emission targets given socio-economic scenarios [54]. The literature screening finds that, often, so-called *soft-linking* is used to implement scenarios into LCA. *Soft-linking* indicates that the LCA practitioner manually implements changes in the life-cycle inventories. For example, most pLCA studies reviewed consider the evolution of the electricity supply through *soft-linking*. However, *soft-linking* is prone to errors when applied to background systems and is difficult to document and reproduce. An example of soft-linking is found in Ref. [55]; where SSP scenario data from International Institute for Applied Systems Analysis (IIASA) [56] is implemented manually in the foreground system. This study is furthermore an example of modelling an advanced foreground system, using building simulation and future weather projection tools for the years 2020, 2050, and 2080 given different climate, demography, and socioeconomic scenarios.

It should furthermore be noted that the SSP's contain regional data (e.g. population growth, demographic trends, etc.) which must be taken into account for when soft-linking. Furthermore, data from other sources might include greater local details, for instance on a city-level. For instance Ref. [57], conducted an LCA-study in which SSP's were downscaled (i.e. regionalized) to Texas based on auxiliary data and models. Another study by Ref. [32] conducted prospective LCA on buildings using RCP's downscaled to France. A third study by Ref. [58] estimated the long term impact of the Swedish building stock, using LCA with eight scenarios of four variables describing regional changes in technology and sectorial practices. One of the systematic hard-linking methods (as opposed to soft-linking) has the benefit of automatically regionalizing the processes (which are affected by the future projections) based on a geographical harmonization between data from the IAMs and ecoinvent [39].

Fig. 2 shows the different implementation methods (i.e., how practitioners implemented the scenarios in LCA). Note that each paper used only one implementation method (see overview in supplementary information). Our review identifies twenty-two distinct practices. Grouping into broad categories reveals that manual (soft-linking) are more frequently represented than systematic (hard-linking) methods. The manual methods are easy to implement, as they simply modify the inputs and outputs of the database processes (e.g., ecoinvent, in most cases). These can benefit from being parametrized, possibly allowing for better maintainability. Eight studies do not disclose how the scenarios were implemented; however, simple process modifications were likely used.

Systematic methods are needed to minimize human error and increase results' reproducibility. Ideally, these rely on integration of scenarios and LCA software (hard-linking). In practice, hard-linking is challenging for several reasons, ranging from handling different data formats to matching variables between the projection model and the LCA database. The following question will discuss promising solutions.

2.6. Question 6: Which software can facilitate/support pLCA in practice, and to which extent?

To facilitate the systematic modification of inventory datasets (i.e., alignment of LCI databases with a scenario narrative) [59], developed the Python-based tool "Wurst", which allows filter-based search and editing of datasets in the LCA database. The capabilities of Wurst were later extended by Ref. [39] who developed the *premise* (PRospective EnvironMental Impact asSEment) framework. The framework uses Wurst together with the IAMs REMIND, REgional Model of Investment and Development [60], and IMAGE, Integrated Model to Assess the Global Environment [61], to systematically modify the ecoinvent database according to SSP projections (i.e., scenario narratives) for any year between 2005 and 2100.

premise is currently the most developed and maintained database modification tool for prospective LCA and allows for the integration of expected transformations within five major energy-intensive sectors: power generation, cement and steel production, freight and passenger road transportation, and supply of conventional and alternative fuels [39].

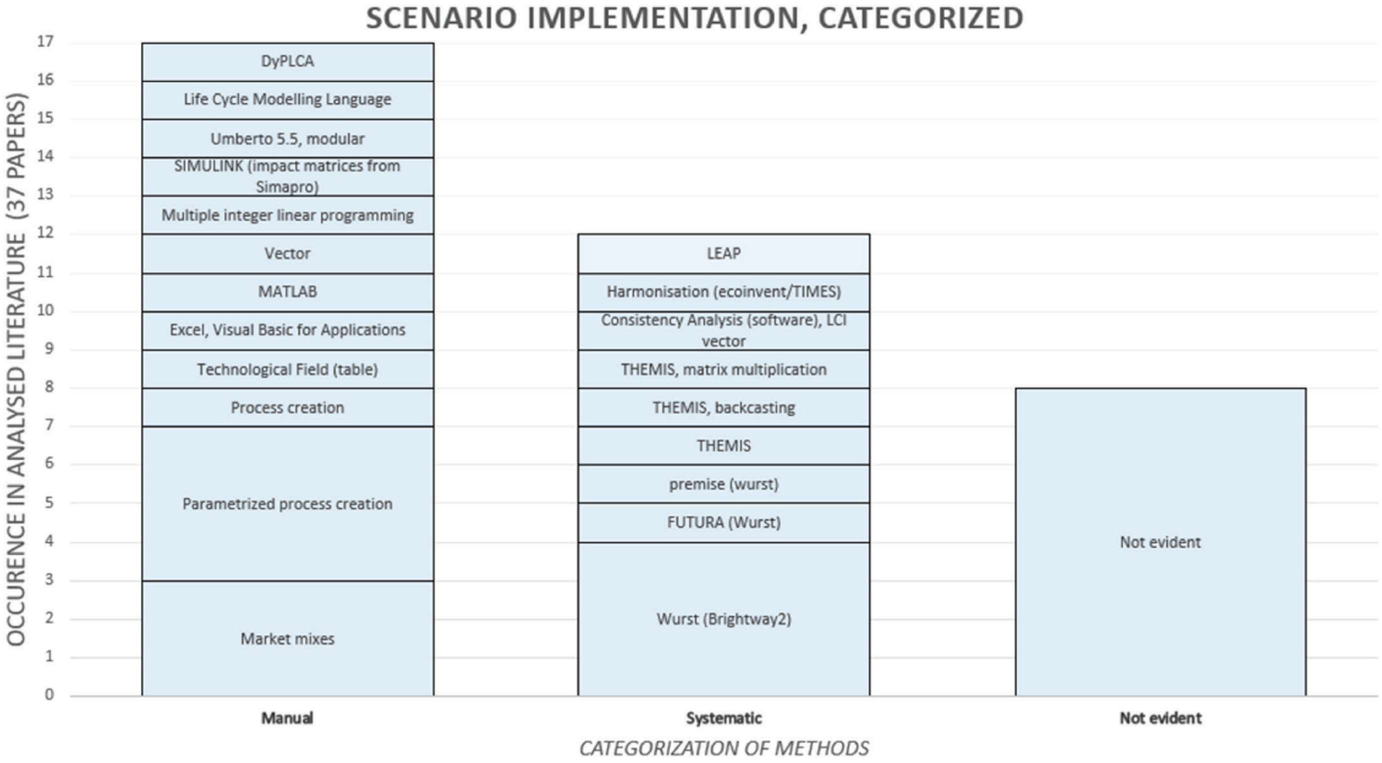

Fig. 2. Overview of implementation approaches for future scenarios. Vertical axis: number of occurrences in screened literature. Horizontal axis: General implementation approach categories.

The documentation of *premise* and the principal author's experimentation with the software helps identify several limitations. First, because *premise* cannot export modified databases back to their original Ecospold2 format [62], popular product system modeling software OpenLCA or Umberto [63,64] cannot import *premise* databases. It is possible to import *premise* databases into SimaPro using text files. Currently, *premise* targets users of the open-source LCA framework Brightway2 [65], which was recently improved by adding a graphical user interface called Activity Browser [66], increasing the user-friendliness of the software. However, Brightway2 and Activity Browser requires a basic skill level within Python programming and use of GitHub and opensource software, which can be a barrier to many LCA practitioners.

Further, *premise* currently only supports the ecoinvent database in its "cut-off" system model version, preventing it from integrating advanced allocation rules, e.g., those recommended by Ref. [11] or [67] for modeling circular economy systems. Ongoing work aims to add support for the consequential system model version of ecoinvent [68]. The construction sector relies heavily on data from Environmental Product Declarations (EPD) modeled after the cut-off system model [69,70], thus pLCA is software-wise within reach for the built environment. However, the software is not ready yet to bring the concepts of circular economy and consequential LCA into prospective studies, which are relevant to the residential sector in general, and bio-based construction materials in particular.

Another promising tool for systematically modifying the LCA database is *Futura* [46]. Here the focus is put on user-friendliness and reproducibility. A scenario recipe can be saved and shared, allowing LCA practitioners to reproduce third-party scenario modifications without sharing the underlying database, which is often under a restrictive license. According to the code repository, version 0.0.4 of *Futura* was released in March 2022 without further updates since, suggesting that the development may have stalled.

2.7. Question 7: Which dynamic elements of pLCA are relevant for the built environment?

As described in Section 2.3, 25 of the 38 identified pLCA studies exclusively considered dynamism as an initiative altering the inventory modeling (see Fig. 1e). One can question whether projecting the inventory to a future point in time qualifies as a dynamic approach or if it should instead be considered a new static approach. Considering long-lived products such as buildings, it might be relevant to increase the dynamism of the LCA. As mentioned earlier, the inventory could be divided into several time horizons, considering that construction, renovation, and demolishing will occur at different time points and in various technological and societal contexts. Life-cycle inventories should consider this aspect, as a substantial part of a conventional building's emissions occur during its service life (i.e., due to energy consumption for heating, cooling, and ventilation). Although it should be noted that this would differ for near-zero emission buildings with low energy consumption but higher embodied energy in materials [16, 71–73]. Some studies consider hourly variations in energy supply [16]. In contrast, others propose discounting dynamic characterization and weighting factors to manage impacts at different points in time [8]. This is supported by Ref. [74]), who find that the impact from buildings' operational electricity is usually significantly lower when using dynamic inventory data. However, the impacts showed no significant difference when comparing an hourly and daily resolution of this dynamic data. Lueddeckens and colleagues also establish that there are distinct types of time horizons. For example, most often, the temporal scope of an LCA will differ from the time horizon of the LCI (i.e., the inventory data applied are not 100% representative of the temporal scope of the LCA). They find that extended time horizons are impractical to implement in LCA. This statement is relayed by Ref. [75]; who find that dynamic LCI often is conducted by collecting data at different timesteps. As discussed in a network meeting of the prospective LCA academic community [76], it is desirable to include dynamic elements in all ISO stages; however, only the inventory stage has reached some (practical) maturity. In other words, this is the starting point, and it is the desire to extend the dynamic aspects to all four ISO-defined LCA steps.

Splitting the inventory modeling into several timesteps is possible for buildings with currently available tools. In the case of operational energy, it could, for instance, be modeled in 10-year intervals (see Fig. 3), thus assuming that changes to the energy grid only will have significant LCA result implications on a decadal scale. Given a service life of 80 years, the operational energy would comprise eight datasets, which modeled mix would reflect the deployment of renewables over time. Although it is suggested by Ref. [3] that developing a dynamic inventory dataset requires further research, applying this stepwise approach can provide an immediate solution. Brightway2 can handle several databases simultaneously, and customized scripts can provide some degree of automation for splitting life cycle inventories into intervals without extensive manual work. The building-specific LCA tool, LCAbyg [77], uses a similar stepwise approach for the operational energy of buildings. In this case, a consultancy firm laid out future projections for electricity and district heating emission factors based on data from the Danish energy agency. The projections were based on currently available technology and assume that after 2040 the efficiency and emission factors will remain constant [78].

2.8. Question 8: Are IAM-based scenarios suitable for considering other indicators than climate change?

When projecting databases to future years, one must understand that the underlying scenarios and IAMs are based on climate-focused models. When a scenario projects the efficiency of a technology to increase in the future, *premise* adjusts the efficiency of the process accordingly. The caveat is that this does not capture mechanisms relevant to other impact categories than global warming. For instance, increased demand for batteries may lead to a change in lithium extraction technologies, changing the extent to which surrounding areas are affected by the release of polluting substances.

Climate-focused models can formulate scenarios leading to a burden-shifting from climate change to other impact categories, such as resource depletion. This issue is regularly discussed in the prospective LCA community, although few academic studies have looked into it [79,80]. LCA practitioners unfamiliar with the underlying IAM scenarios may be unaware of the low reliability of the results for indicators other than climate change [10]. emphasize the need for LCA practitioners to be well-versed in scenario theory, as well as a need for solid coherence between the applied scenarios and the goal and scope of the LCA. Hence, pLCA based on IAM scenarios integration falls short of supporting decisions for environmental indicators other than climate change.

According to the development team of *premise*, the underlying IAM scenarios provide coherent projections for the indicators of climate change, land, energy, and metals use. The latter is based on conservative projections as IAMs do not provide information on collection and recycling rates of metals – except for steel. These indicators are highly relevant to the built environment. However, the European standard EN 15804 "sustainability of construction works" requires the reporting of the following environmental indicators: climate change (fossil, biogenic, and related to direct and indirect land use change); ozone depletion; acidification; eutrophication (marine, freshwater, and terrestrial); photochemical ozone formation; mineral and metal depletion; fossil resources depletion; and water use [69]. Therefore, there is a discrepancy between the European Union construction sector standard and the indicators that can be reasonably calculated from pLCA using *premise*-generated databases.

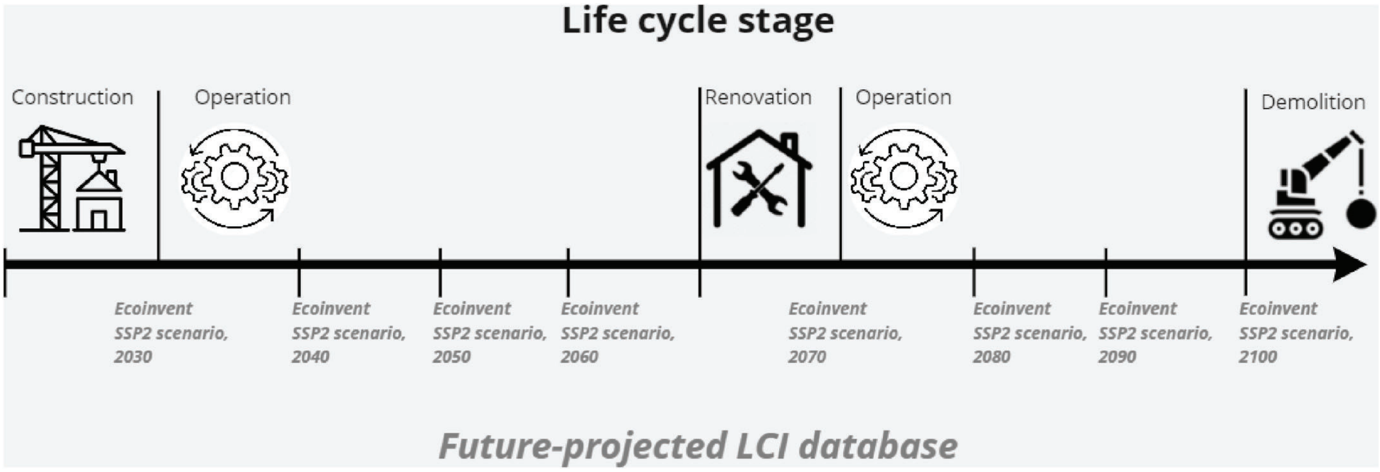

Fig. 3. Stepwise dynamic inventory modeling for a building's life cycle. Inventory modeling example with 10-year intervals.

2.9. Question 9: Which scenario narratives are readily available for LCA integration?

Currently, *premise* is the most consistent way of conducting changes to the background system of an LCI. *premise* offers future database projections based on the SSP2 scenario considering four different climate policy scenarios: RCP 1.9 (global temperature change limit 1.5 °C by 2100 compared to pre-industrial levels); RCP 2.6 (temperature change less than 2 °C); RCP 4.5 (reference scenario, also known as NPi - National Policies implemented); and RCP 6.5 (Counter-factual scenario with no stringent climate policy). Most IAMs formulated these scenarios when reporting the IPCC's latest assessment report. It should be noted that the RCP's are merely representing different trajectories of climate policy. It can be debated if these are realistic projections of future GHG emissions. Due to this uncertainty, it is relevant for pLCA studies to report results based on several differing RCP's.

The following narrative from Ref. [52] describes the scenario SSP2, also nicknamed "the middle of the road":

> "The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain."

It could however be a topic for debate whether the SSP2 scenario is a realistic representation of how the future might unfold. Hence when conducting pLCA, it is also relevant to consider other SSP scenario narratives, for instance, SSP1 "Taking the Green Road" or SSP5 "Fossil-fueled Development – Taking the Highway". However, only the dataset for SSP2 is currently available with the software package [81]. Concerning the built environment, these different narratives could be relevant, as the construction practices might differ, e.g., the share of timber versus concrete constructions.IIASA's 1.5 °C Scenario Explorer [56] holds a repository of all IAM scenarios considered for the IPCC's "Global Warming of 1.5C" report [82]. However, the IAMC time-series data template commonly used for that purpose prevents their integration into *premise*, as needed input variables are presented with a high level of aggregation.

As mentioned in section 2.6, the IAM's REMIND and IMAGE are used to quantify the SSP's and RCP's for prospective transformations of ecoinvent. It is also possible to use data from other models as input. For instance, the Swiss Federal Office for Energy have developed a scenario for Swiss carbon neutrality by 2050 [83]. This scenario has been implemented as a custom scenario in *premise*. Another scenario for cobalt-specific scenario based on [84] have been developed, as well as a ammonia-specific scenario based on [85]. The mentioned scenarios are available at a public repository [86].

2.10. Question 10: What could be standard procedures and workflows to increase the consistency and credibility of prospective LCA?

First of all, it is relevant to consider who is the target group of the pLCA methodology. That is, who do we expect will utilize this methodology? In the built environment, architects are often interested in applying LCA aspects in their design. This however requires simplified tools, which can often be overwhelming to understand all details and implications of. Hence, it is not considered meaningful to implement pLCA for this target group, nor to replace current tools, such as LCAbyg or EPDs. One way to implement prospective considerations for said target group, could be to provide simple impact factors based on pLCA - i.e., informing the architect about how much the carbon intensity per kWh of electricity is projected to decrease by 2050, essentially enabling them to consider this in their design.

Currently, pLCA requires a high degree of expertise within its specific research field. This paper intends to guide research in a direction, that makes pLCA generally more accessible to a broader target group of LCA practitioners with a certain degree of expertise, both in industry and academia. Ideally, pLCA should be utilized by experts for large-scale decision support, possibly as a kind of uncertainty analysis. According to Ref. [21]; uncertainty can be analyzed numerically (I.e. Monte Carlo simulations evaluating a confidence interval for the final results based on combinations of known parameter uncertainty ranges). Hauschild and colleagues also discuss that in some cases where the uncertainty is unknown or difficult to quantify, it makes more sense to consider several different scenarios. In this light, pLCA can be considered as an uncertainty analysis for LCA's considering future uncertainty. In the context of decision support, it then becomes increasingly relevant to consider different scenarios (I.e. SSP's and RCP's) – maybe one decision can have significantly different recommendations in the different scenarios, as was the case in a study investigating electric vehicles by 2050 [17].

A conference workshop report [6] concludes that prospective LCA benefits from a multidisciplinary approach but that a shared foundation regarding methods, data, best practices, and software solutions is lacking [7]. suggest valuable data sources, including experts outside the LCA community, patents, scientific articles, and laboratory and simulation results. Arvidsson and colleagues propose to model both the foreground and background systems separately and report how modifications in each of the two systems change the results. This way, the influence of respective background and foreground systems is transparently reported, mitigating uncertainties related to the difficulty of assessing the generic scale-up of emerging technologies and predictions of future scenarios. As discussed in section 2.7, pLCA can further be improved by considering dynamism in all ISO-stages of the LCA, e.g., dynamic characterization factors. However, pLCA is currently an emerging research field, and the community is currently focusing on the LCI ISO-defined stage and management of prospective inventory databases.

A scenario-based approach is generally agreed to be beneficial for prospective LCA (i.e., thus maintaining the perspective in the assessment that the future is not one specific development but several development options). The exhaustive literature review by Ref. [10] suggests maintaining the current and case-specific complexity when combining LCA and future scenarios. On the downside, this complexity might cause inconsistencies regarding pLCA modeling and documentation mentioned by several studies [5,9,10].Standardized methods for future scenario implementation in prospective LCA will improve the extent to which studies are uniform, comparable, and reproducible. They will also require less knowledge about future scenario theory from the LCA practitioner, making pLCA generally more accessible. Currently, the most promising option to increase the consistency of pLCA is to use IAM and other energy models' projections to bring sector-wide changes to the LCA database, as *premise* and previous works [6,17,20,43,87] have done with ecoinvent. In contrast, the foreground system can benefit from a more tailored approach, including experts and stakeholders. This approach requires detailed and transparent documentation from the LCA practitioner, which could eventually make pLCA more costly in a commercial setting. The pLCA community is currently putting an effort into facilitating an increased data quality as well as documentation and reproducibility hereof. One of such efforts are the current work streamlining database transformations with *premise*, as well as sharing these transformations between LCA practitioners. This becomes increasingly relevant considering data quality requirements needed to achieve certain labels or standards (e.g., EPDs). As ecoinvent is updated annually, it is furthermore relevant to be able to apply prospective transformations with minimal effort.

[10] highlighted the importance of ensuring coherence between the goal and scope of an LCA and the applied scenario. A potential lack of coherence resonates with the pLCA community's discussion on the importance of choosing scenarios that satisfy the goal and scope of the LCA: Is the pLCA, for instance, supposed to examine all possible future outcomes or just the result of one particular scenario? Hence, the very reasons to conduct pLCA condition how, which and how many scenarios should be interpreted. The literature screening reveals that pLCA documentation often lacks clear goals and scope according to the relevant ISO standards. Hence, improving this in the community of pLCA practitioners should be a general priority.

3. Conclusions

This article presents, elaborates on, and answers ten questions concerning pLCA for decision support within the built environment. Some questions are specific to the built environment, whereas others have a more general pLCA applicability. We conclude by providing short answers to each question. Note that the answers pertain to the authors' viewpoints and are not exhaustive nor definite but suggestions to guide future research.

3.1. Answer 1: How can future environmental impacts be assessed?

Prospective LCA is an emerging methodology that assesses a product's or service's environmental impact following the context set by a target future year. Evaluating a product system across one or several scenarios addressing future technological and socio-economic contexts helps evaluate the uncertainty introduced by the unknown future. Prospective LCA can be considered relevant for the built environment due to the high energy consumption that characterizes its use phase of buildings (e.g., heating, ventilation), as it is projected to change significantly over the long service life of a building. For infrastructure, i.e., bridges, this would typically not be the case. However, if there are substantial emissions from maintenance, this could be accounted for with pLCA.

3.2. Answer 2: How are temporal dependencies accounted for in prospective LCA?

Prospective LCA does, in most cases, merely provide an (alternative) static view, just like conventional LCA – although considering future projections of technological evolvement and socio-economic changes for a chosen target year. This temporal dimension is relevant for buildings, as construction, operation, and demolition happen at different points over an extended time horizon.

3.3. Answer 3: How is the goal and scope definition adjusted when conducting prospective LCA?

Thirty-seven identified pLCA case studies most often consider a relatively short future time horizon of a magnitude of 25–35 years and apply an attributional modeling framework in most cases reviewed. This time horizon is, however, relatively short compared to the typical 80 years of service life for buildings. The reviewed studies consider either the whole supply chain (i.e., cradle-to-grave) or selected parts hereof (i.e., gate-to-gate, cradle-to-gate). Besides the time horizon, a substantial portion of the studies lack clear documentation of their system boundaries.

3.4. Answer 4: How to estimate foreground and background systems of the future?

To provide a realistic assessment through the application of pLCA, both foreground and background systems of the LCI should be coherent with the temporal scope of the study. Foreground system modeling can be aided by knowledge from stakeholders and experts. Generally, projections for background system modeling using scenario narratives such as the SSPs are more extensive and coherent. The foreground system is essential for pLCA in the built environment because of changes in construction practices (i.e., leading to different materials need), whereas the background system is essential due material's production having high embodied energy as well as the provision of energy during the operation phase.

3.5. Answer 5: How are future scenarios integrated into LCAs?

Scenario narratives such as the SSPs can, through IAMs (such as REMIND and IMAGE), be applied as input for an LCA. However, many reviewed pLCA studies do not provide detailed information about how the scenarios are coupled and implemented in the LCA software. This lack of details suggests that most of these efforts rely on soft-linking and manual modification of processes in the LCA software. These methods are prone to error and hamper reproducibility.

3.6. Answer 6: Which software can facilitate/support pLCA in practice, and to which extent?

The open-source software *premise* is currently the most promising tool facilitating pLCA (by systematic and automated background database modifications). It can transform the ecoinvent database according to a target year between 2005 and 2100, considering the SSP2 socio-economic pathway, quantified by either REMIND or IMAGE, across four climate policy scenarios. The output is a future-projected database for background system modeling in SimaPro or Brightway2. *premise* currently supports the cut-off system model version of the ecoinvent database, which the construction industry standard for EPD recommends. However, *premise* is not yet able to integrate a consequential modeling framework (especially relevant for e.g., timber-based buildings and biobased materials), nor advanced allocation-based methodologies proposed by the field of circular economy. We do not consider the many identified simulation models (e.g., cost optimization models such as TIMES) as "tools", but rather as data generators. We consider the tool as a program/code that facilitates more automatic implementation. Other relevant, but not widely used, tools include DyPLCA, THEMIS, and Futura. Short descriptions and references are given in supplementary information.

3.7. Answer 7: Which dynamic elements of pLCA are relevant for the built environment?

In its current emerging state, pLCA rarely considers other dynamic elements than projecting the inventory to a future year. Hence pLCA, in its prevailing form, merely delivers an alternative static snapshot in time. Concerning the built environment, life-cycle inventories can be split into relevant timesteps and associated with different target years to assess the impacts of construction, operation, and demolition processes.

3.8. Answer 8: Are IAM-based scenarios suitable for considering other indicators than climate change?

The SSP scenarios and IAMs used to couple them with LCA have a focus on costs, energy, and greenhouse gas emissions. Hence, deriving scores for indicators other than climate change (e.g., toxicity, eutrophication) comes with the risk of under or overestimating them. This lack of details for different types of environmental impact poses a substantial challenge in decision support, as it might shift the burdens across impact categories to an unknown extent. *premise* provides reasonable projections for climate change, energy use, land use, and metal depletion. Relevant standards for the built environment require several impact categories that *premise* might misestimate.

3.9. Answer 9: Which scenario narratives are readily available for LCA integration?

Currently only the SSP2 scenario is available for use with *premise*. However, the dataset provides four distinct scenarios of climate policy in the socio-economic context of SSP2. As *premise* supports custom scenarios, it is theoretically possible to reconstruct the remaining four SSP narratives via data from the IIASA IAMC data explorer. However, currently, the needed variables for *premise* integration are not supplied. The authors consider it relevant to include the remaining SSP scenarios, which are more "extreme", but suggest that constructing such datasets is a job for experts. Other narratives could be highly relevant considering futures with pronounced timber constructions and associated competition for land and wood resources.

3.10. Answer 10: What could be standard procedures and workflows to increase the consistency and credibility of prospective LCA?

Several (overlapping) literature reviews on pLCA find inconsistencies in the terminology and methods to be a general limitation. Scenario narratives can help improve consistency, with *premise* being a viable tool for the background system. The foreground system typically being more customized, thus requiring thorough documentation by pLCA practitioners. It is furthermore essential that the goal and scope of the pLCA are well-defined and compatible with the applied scenario(s).

4. Expertise of the authors

Morten Birkved is professor and head of SDU Life Cycle Engineering, which is a research center devoted to method development and advanced application of the LCA methodology. He has spent parts of his career, in both academia and industry, exploring numerous ways to improve the LCA methodology in terms of reliability, validity and realism. His scientific contribution includes numerous scientific papers and book chapters primarily within the field of LCA-oriented method development as well as teaching of life cycle assessment. Morten has through his participation in many nationally and internationally funded projects further demonstrated that the lack of consensus within the area of prospective LCA, is pivotal for LCAs predicting novel technologies and thus to the societal development. Demonstrating early in his career that the temporal dimension of LCA was not addressed appropriately despite being of fundamental importance to LCA results, he has spent two decades of his academic career exploring and improving LCA of long-lived services and products, primarily buildings and cities.

Romain Sacchi joined the Technology Assessment Group at the Paul Scherrer Institute in June 2019 as a Postdoctoral Researcher, to contribute within the field of prospective life cycle assessment (LCA), with a focus on future mobility technologies. More specifically, Romain develops tools and methods to integrate projections from Integrated Assessment Models and energy models into LCA.

Ciprian Cimpan is currently an associate professor at SDU Life Cycle Engineering, working on topics addressing challenges of societal transitions and policy support towards circular economy. Previously, as postdoc at NTNU (Norwegian University of Science and Technology), he used economy-wide approaches to measure future effects of circularity interventions in the European plastics sector.

Simon Bruhn is currently writing his PhD with the title "Refining the Inclusion of the Temporal Dimensions in Life Cycle Assessment Based Decision Support". He serves as specialist engineer in two commercial projects: In *Circle Bank*, he quantifies the future viability of circular economy in the built environment; and in *Black Transition of Urban Life* he conducts historical LCA on buildings and other consumption segments to map personal carbon footprints and its evolution since 1860.

CRediT authorship contribution statement

Simon Bruhn: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romain Sacchi:** Writing – review & editing, Validation, Software, Resources. **Ciprian Cimpan:** Writing – review & editing, Supervision. **Morten Birkved:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Simon Bruhn reports a relationship with Innovation Fund Denmark, Velux Foundation, and EU Horizon 2020 that includes: funding grants. Romain Sacchi reports a relationship with EU Framework Programme for Research and Innovation Societal Challenges that includes: funding grants. Although Romain Sacchi is the main developer of premise, it should be noted that this did not influence the design of the paper or the ten questions. Initial dialogue between SB and RS was initiated after the study had identified premise as the most viable tool facilitating pLCA. Eventually, RS joined the study as co-author to provide deep knowledge on the implications of using premise.

Data availability

provided in supplementary information.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110535.

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