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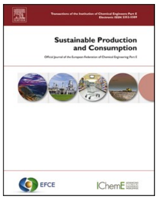

Review Article

Emerging technologies upscaling: A framework for matching LCA practices with upscaling archetypes

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ABSTRACT

Society asks engineers and designers, though sustainability targets, to be highly concerned with socio-technical and environmental consequences generated by the technology they develop and deploy in society. Life Cycle Assessment (LCA) as a methodology can be a tool for assessing the sustainability of technological change of scale, however, the diversity of LCA approaches hinders their adoption by engineers, including LCA practitioners in product design teams.

Therefore, clarifying LCA approaches available in the literature is necessary to deal with the environmental assessment of emerging technology upscaling. To this end, this research paper carries out a literature review of LCA practices and characterises them with conceptual and operational characteristics. This characterization provided the basis for matching the available LCA approaches with the different facets (also known as archetypes) of a technology upscaling to be environmentally assessed, based on their common characteristics.

This literature review produced three main results: first, fifteen LCA modes are characterized by definition, addressed questions, studied objects, the expertise required, scope specificities, and structuring references. Second, guidelines have been extracted from selected case studies or reviews from different engineering fields (*e.g.* chemistry, energy, transport). This constitutes a generic LCA framework to environmentally assess each upscaling archetype. Third, the LCA references are ranked by the related engineering fields. Finally, the challenges of extending these three results are discussed, especially concerning the emergence of new LCA modes in reaction to specific needs for environmental assessments (*e.g.* transition LCA) and in an eco-design perspective based on environmental upscaling assessment.

This work paves the way for two kinds of further research: first, to refine theoretical and practical LCA modes compatibility based on developments by LCA experts. Second, to produce operational guidelines for engineers and designers practicing LCA to transfer ongoing and future LCA developments. This would bring comprehensiveness to the environmental assessment of emerging technology upscaling and a sustainability vision of technology development and production.

1. Introduction

Given the daunting environmental challenges our societies face and the ensuing need for radical change (*e.g.* climate change (IPCC, 2022), biodiversity erosion (Ceballos et al., 2015), material depletion (Vidal et al., 2021 *etc.*), multiple organizations develop transition scenarios for sustainability. The scale of these scenarios can be sectorial (IRENA, 2019; RTE, 2022; Sims et al., 2017), national or continental (ADEME, 2021; AEE, 2019) or international scale (IEA, 2020; IPCC, 2022). These scenarios offer a wide range of sustainability pathways but all have in common being supported by technological developments. Paradoxically, “clean/climate/green technologies” and all technologies that are supposed to be beneficial regarding the reduction of environmental negative impact are often so-called “emerging”, meaning that their effects on the environment have not yet been observed on an extensive scale and sometimes, therefore, are hypothetical (Buyle et al., 2019; Cucurachi et al., 2018). Under these circumstances, the estimation of environmental benefits of immature product systems comes from anticipative environmental Life Cycle Assessments (LCA) by engineers or design teams. LCA practice is, therefore, crucial to assess the environmental sustainability potential of a technology before its upscaling.

Thus, on the one hand, the LCA literature related to upscaling and emerging technology has not stopped being enriched since the 2010s to

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Abbreviations

AESA	Absolute Environmental Sustainability Assessment
BIPV	Building Integrated Photovoltaics
DfS	Design for Sustainability
EAU	Environmental Assessment for Upscaling
ETV	Environmental Technology Verification
EV	electric vehicle
FCE	Final Consumption Expenditure
GHG	greenhouse gas
GIB	Green Incentive-Based
IO-LCA	Input-Output LCA
IoT	Internet of Things
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
MFA	material flow analysis
PB	planetary boundaries
PEFCR	Product Environmental Footprint
PSS	Product Service System
PV	photovoltaic
SOS	Safe Operating Space
SoSOS	Share of Safe Operating Space
TRL	Technology Readiness Level

deal with LCA applied to prototypes, also called 'ex-ante LCA'. Cucurachi et al. (2018), for instance, emphasize in that context the importance of referring to an incumbent technology or service. Therefore, the studied emerging technology has to be compared to existing technologies or services, by conventional methods and guidelines (ISO 14040, 2006). Arvidsson et al. (2018) develop the theoretical basement of ex-ante LCA by raising specific challenges, such as temporal correlation and scenario management. Bergerson et al. (2020) point to the interaction between technological maturity and the maturity of the target market and the associated LCA results uncertainties. The authors therefore identify four situations that combine a level of maturity for the technology (techno-economic uncertainties) and the market it fits (socio-economic uncertainties). Bergerson et al. develop then uncertainty management strategies according to the situation, *e.g.* comparing the prototype with an incumbent technology, producing scenarios, or studying potential social acceptance with agent-based models to simulate the emergence into a market. Thonemann et al. (2020), and Moni et al. (2020) complete these developments with structuring review articles presenting methodological guidance for ex-ante LCA. These works contribute to the clarification of the new methodological requirements (*e.g.* uncertainty challenges and technology maturity elicitation) associated with such LCA mode. In parallel, authors focused on practical aspects such as data availability and uncertainty management (Buyle et al., 2019; van der Giesen et al., 2020; Santos et al., 2022), task organizations and integration in the design process (Tan et al., 2018; Tsoy et al., 2020) or maturity technology management (Tsoy et al., 2020). These works will be discussed in detail in this paper. They, however, focus only on aspects of the upscaling identified in design and engineering literature, *i.e.* the upscaling archetype "from laboratory to industrial scale" (Riondet et al., 2024, 2022). These guidelines, for instance, do not provide information on how to analyse the interactions (expected or not) between the technology upscaled and territories or socio-technical societies. Another point is that guidelines focus on one unit of product/technology. These methodologies do not give insights into cumulative effects resulting from future product/technology massification. Guidelines do not explain either how to characterize the scope of the study for a given deployment strategy or a purposed use. These considerations (anticipating socio-technical interactions and extending the boundary system beyond product level), by contrast, are considered necessary for designing sustainable systems (Ceschin and Gaziulusoy, 2019). These findings show that the upscaling assessment in the literature on LCA confers some methodological lacks. Conversely, many LCA approaches have been designed to address these upscaling properties, but are not identified as enabling analysis of a technology's upscaling. Hauschild (2015) for instance, goes further the classic LCA approach by questioning the absolute sustainability paradigm of the technology development. Absolute sustainability refers to the planetary boundaries that should not be crossed to warrant a safe operating space for humanity. The applicability of this theoretical framework at the product level with LCA is referred to as the Absolute Environmental Sustainability Assessment (AESA). Few articles present an overview of the diversified approaches and the context in which each can be used. Guinée et al. (2018) categorise 8 LCA "modes" in a synthetic three-page article titled "Digesting the alphabet soup of LCA": *attributional, consequential, backcasting, decision, integrated, anticipatory, prospective and scenario-based LCA*. The authors intended to clarify general definitions and associated theoretical principles (*e.g.* used allocation method and scope). Onat et al. (2017) reviewed with a bibliometric analysis the life cycle sustainability assessment literature, for educational purposes. Authors called for defining common vocabulary and then interconnections and feedback between LCA practitioners of different approaches (social, environmental and economic assessments). Ventura (2022b) is a third example of an article covering multiple LCA approaches. This paper develops a new approach so-called "Transition LCA", dealing with environmental aspects of a transition applied to a territory. This is supported by properties of other LCA approaches (*e.g. attributional, consequential, hybrid, input-output, organizational, and territorial LCA*) examined and synthesized by the author. This paper therefore contextualizes and elaborates on the future development of LCA based on a retrospective review. It provides also examples of the application of a Transition LCA to illustrate the novelty of the approach and the associated constraints (*e.g.* stakeholders identification, data collection, scenario management). These examples of structuring literature in LCA (Guinee et al., 2022; Ventura, 2022a) are not, however, specifically oriented to the assessment of a technology upscaling. Second, similar resources are not always purposed to design teams of emerging technologies, more and more interested in environmental upscaling assessments, but rather to LCA experts. Our research work has therefore targeted groups of design teams (*e.g.* engineers, technology experts, and team managers), including LCA practitioners. Thus, this paper aims to address LCA practitioners need for clarification on the different LCA approaches within an upscaling assessment perspective, structured with the formalism of "upscaling archetypes" (see Table 1 in "Method" section) proposed for design communities (Riondet et al., 2022). This research paper aims to answer the question: *how LCA could help to assess or anticipate the environmental sustainability of the upscaling of a technology*, using the archetype formalism of Riondet et al. (2022)? This research question can be partitioned into two sub-questions: (RQ1) *Which existing LCA approaches, available in the literature, are related to upscaling properties?* And (RQ2) *how should design teams be equipped to carry out or anticipate the upscaling of an emerging technology with regard to environmental sustainability?* Section 2 details the literature review methodology and the formalism to answer these two research questions. Section 3.1 presents the collection, definition and characterization of relevant LCA approaches for upscaling assessment to address RQ1. It concludes with a synthesis enabling LCA practitioners and technology designers to identify the expertise and resources required to apply a particular LCA mode. Section 3.2, to answer RQ2, illustrates LCA practices by examining case studies for each of the five upscaling archetypes. Illustrations from several engineering fields are given to exemplify

Table 1
Synthesis of upscaling archetypes definitions, adapted from (Riondet et al., 2024, 2022).

Upscaling archetype	Definition	Usual goal	Upscaling subject	Focus associated with the scope	Illustration
Archetype 1 Scaling-up, from laboratory to industrial scale	Phenomenon generating a "prototype" at industrial or commercial scale.	Maximize maturity (often associated with productivity)	Technology or service upscaled	Technology upscaled	Research and development of a new material or technology to be commercialized (*e.g.* electrical vehicle, emerging renewable energy, superconductor).
Archetype 2 Mass-producing, industrializing	Phenomenon adapting a technology to be mass-produced.	Maximize producibility	Technology or service upscaled in manufacture	Standard performances of the technology upscaled	Development of a value chain and adaptation of the technology to be mass-produced.
Archetype 3 Reaching a level of cumulated service, deploying a technology	Phenomenon translating transition requirements into technology sector perspective.	Reaching a sufficient level of cumulated service	Technology upscaled and boundary of analysis	The cumulated service provided by the group of produced technology	Planning and management of the industrial capacity to reach a cumulated service for a given time horizon (*e.g.* reaching a terawatt of installed capacity for electricity production in 2030, covering the mobility park for electric vehicles in 2040).
Archetype 4 Integrating a complex (socio-technical) system	Integration phenomenon of a technology as a part of a larger and complex system.	Maximize the efficiency of a complex system	Boundary of analysis	The technology interoperability to support its systemic integration	Management of interactions at variable geographical and temporal scales between the designed technology and other technologies or systems (*e.g.* identification of energy stockage requirements to annually support photovoltaic deployment in France).
Archetype 5 down-limiting, downscaling the planetary boundaries to the technology level	Phenomenon tending to restrict technologies according to sustainability considerations.	Assess the sustainability of a technology or associated service	Science-based limit of the domain (socio-environmental limit)	The sustainability of a service provided by one or several products, or systems	Defining the sustainability of a technology (*e.g.* is an energy production system (and its life cycle) sufficiently carbon-free to comply with the Paris agreements?)

archetype specificities (see subsections 3.2.1 to 3.2.5). Based on this review, subsection 3.3 presents guidelines for design teams to help them select the most appropriate LCA "modes" regarding the upscaling specificities (*i.e.* upscaling archetype). Methodological and practical requirements are expressed. Then, subsection 3.3.1 analyses the literature reviewed in terms of engineering fields to stress the "disciplinary" bias of current upscaling archetype assessments. Finally, subsection 3.4 deals with the integrative role of LCA in ecodesign practices for technology upscaling and section 4 sums up the contributions of this article regarding the environmental upscaling assessment.

2. Methods

2.1. Formalism of upscaling archetypes

In previous research, we proposed a framework to define the "upscaling of a technology" in a design and engineering paradigm (Riondet et al., 2024, 2022). A technology upscaling is therefore defined as a techno-economic phenomenon involving the development and deployment of a technology in society to meet societal imperatives (*e.g.* sustainability) (Riondet et al., 2024). This research work, additionally, splits the upscaling definition into five *facets*, so-called "archetypes", identified in the design and engineering literature. The upscaling archetypes reflect different visions of a technology upscaling based on techno-economic expertise and engineering field perspectives. Table 1 introduces the names of each upscaling archetype, their definitions, along with their respective usual goals, subjects and focuses. This synthesis provides also an illustration for each archetype. Thus, the five archetypes are identified as follows: (1) *scaling-up* (from laboratory to industrial scale), (2) *mass-producing* or *industrializing*, (3) *reaching a level of cumulated service* or *deploying a technology*, (4) *integrating a complex system*, and (5) *down-limiting* or *downscaling the planetary boundaries to the technology level*.

As shown in Table 1, archetypes embody mainly techno-economic and engineering visions of a technology upscaling and are not specifically associated with sustainable assessment. LCA engineers, however, have to be sensitized to techno-economic vision and models to be able to properly define the "goal and scope" phase (*i.e.* system boundary and functional unit) and to collect data during the lifecycle inventory step of the LCA. In other words, LCA practitioners, in the case of a technology upscaling, have to cooperate with other experts (technical and economic experts for instance) to define a robust environmental model. Moreover, most of the "new" approaches in LCA (consequential, territorial, absolute, transition) do not necessarily hinge on the same system boundary or functional unit as in a classic LCA (attributional retrospective LCA). This means that using "upscaling rules" directly on the inventory is not sufficient. LCA practitioners have to use a systemic vision to adapt the system boundary, the functional unit and the corresponding lifecycle inventory. This paper aims therefore to guide design teams towards LCA approaches and practices likely to provide an environmental assessment of the upscaling archetype they are focusing on.

2.2. Literature review process to match LCA approaches with upscaling archetypes

To question the potential alignment between available LCA approaches and the upscaling archetypes, a three-step literature review was carried out.

First, search queries were applied on Web of Science and Elsevier over the years 2022 and 2023 with the keywords "LCA" OR "Life Cycle Assessment" AND "emerging technologies" OR "emerging technology" AND "upscaling", "scaling-up", "scale". This first step was dedicated to pointing out the LCA practices in the literature already identified as suitable to assess a technology upscaling. The suitability of the identified practices was checked by comparing their study objectives, subject and scope with the goal, subject and focus of the upscaling archetypes. Case studies have been set apart in this step, and review articles and methodological discussions were preferred. This step brought out 14 references on emerging technology environmental assessment.

As these references were mainly focused on archetype 1 (*scaling-up, from laboratory to industrial scale*), the reference selection criteria have been relaxed to include LCA approaches suitable for environmentally assessing the other archetypes. The second step of the literature review therefore looked for additional LCA approaches. Two review articles summarising the variety of LCA approaches (Guinée et al., 2018; Ventura, 2022a) were mobilized and additional keywords were included in the research queries in combination with “LCA”, such as “deployment”, “industrial scale”, “absolute sustainability”, “prospective”, “ex-ante”, “anticipatory”, “transition”, “AESA”, “territorialized”, “consequential”, “parametrized”, “spatialized”, “PB-LCA”, “downscaling”, “planetary boundaries”. Each new LCA approach identified was compared with the characteristics of the archetypes (goal, subject, scope) to determine their compatibility. Complementary references have been compiled, based on our expertise or following discussions with LCA experts from consequential, prospective, territorialized and absolute LCA, leading to a corpus of 100 references with at least two references per LCA approach. This corpus includes review articles and case studies from various engineering fields (chemistry, energy, transport, waste treatment).

Finally, each LCA approach has been characterized based on the diversity of case studies over different engineering fields, the availability of practical tools, software and guidelines and the age of the structuring references). This characterization led to propose the following classification: “classic” or “historical” for LCA practices with a wealth of literature and associated software and guidelines, “LCA modes with a temporal or geographical focus” for LCA approaches developed in the literature but not generalised in practices and addressing issues requiring theoretical and operational developments, and more “emerging LCA approaches” with limited number of structuring references or case studies (less than 10) or with methodologies still maturing, according to the literature or the experts consulted. This third step, based on existing frameworks provided by the authors Arvidsson et al. (2024), Cucurachi et al. (2018), Guinée et al. (2018), and Ventura (2022a) carries out the characterization of each LCA approach with a definition, a generic addressed question and a usual studied object. Moreover, the type of expertise to operate the LCA approach and additional structuring references (*e.g.* references providing guidelines or methodological precisions) complete the literature review process. This characterization led ultimately to the proposal of a LCA framework for design teams to link LCA approaches to the upscaling archetypes depending on their upscaling objectives and study objects. In other words, this framework helps design teams to environmentally assess the upscaling archetype they are interested in.

3. Results and discussion

3.1. LCA modes suitable for upscaling assessment

This section presents the outcomes of the literature review to address RQ1 “*Which existing LCA approaches, available in the literature, are related to upscaling properties*?”. Since the 2000s, different “modes” of LCA have appeared in the literature to meet different objectives based on variable modelling methodologies and scope of application (*e.g.* product or value chain focused, service, regional, global). Several publications intend to guide LCA practitioners in their practice by categorizing these current or under-development “modes”, in a synthetic way (Guinée et al., 2018), for contextualisation of new LCA developments (Ventura, 2022a), or about the future-oriented assessments (Arvidsson et al., 2018; Buyle et al., 2019).

This section details the definitions and characteristics of available LCA approaches in the scientific literature suitable for upscaling assessment. Thus, the following modes can be used to analyse and anticipate the upscaling of a technology: i) *attributional and consequential, ii) prospective, retrospective, ex-ante, post-ante, anticipatory, simplified, streamlined and parametrized, iii) dynamic, iv) regionalised, spatialized, territorialized, v) hybrid, absolute* and *transition one.* The first columns of Appendix 1 provide a synthesis of the definitions of these LCA modes, classified as *classic* or *historical* approaches, approaches *focused on temporal aspects* or *geographical aspects* of the analysis and more emerging approaches, including *hybrid or combined* approaches.

3.1.1. Attributional and consequential LCA

The ISO 14040:2006 standard and the UNEP-SETAC have proposed suitable frameworks for both modes of consequential and attributional LCA (“ISO 14040,” 2006; UNEP-SETAC, 2011). The UNEP-SETAC defined in 2011 a consequential and an attributional approach. The consequential approach is defined as an environmental analysis assessing the impacts resulting (directly or not) from a decision (*e.g.* change in demand for a product) and the attributional approach as environmental assessment methodologies focused on allocating from the global environmental burdens apart to a life cycle of a product or service (UNEP-SETAC, 2011). These two approaches are not in opposition, and Schaubroeck et al. (2021) systematically list the conceptual characteristics they have in common or that differentiate them. Schaubroeck et al. insist on the fact that several conceptual properties between the ISO-14040 and UNEP-SETAC are not always consistent. The practices and LCA modelling choices depend on some practical assessment needs, and on the practitioners' understanding of the theoretical frameworks (Schaubroeck et al., 2021). In other terms, knowing a LCA is attributional or consequential is not sufficient to fully define it and identify for instance on what model it lies. Such standards recommend practitioners provide information about the question addressed in the LCA (Guinée et al., 2018), the system boundary (normatively) chosen, and therefore the mass and value conservation preserved (Weidema et al., 2018).

3.1.2. Prospective, ex-ante, anticipatory and simplified LCA

One can associate the two modes (attributional or consequential) with other properties, for instance, whether future-oriented or not. The terms “prospective” and “ex-ante” are therefore usually opposed to respectively “retrospective” and “post-ante”. The idea is for both terms that LCA aims at studying an object, already existing or not, in a future context, as opposed to a LCA performed on an existing object, at a past or present period (*i.e.* retrospective or post-ante). Both attributional and consequential LCA can be designated as prospective (Arvidsson et al., 2018). Some authors identify these two terms (prospective and ex-ante) as synonyms (Buyle et al., 2019; Guinée et al., 2018), while others emphasize the difference in terms of the object of study considered. van der Giesen et al. (2020) and Cucurachi et al. (2018) define *ex-ante* LCA *as* a particular case of prospective LCA applied to an emerging technology (*i.e.* technology in early-stage of development) and therefore strongly aligned with the Technology Readiness Level (TRL) indicator. The word “anticipatory” is also used in this context, often considered synonymous with ex-ante (Buyle et al., 2019). Both are future-oriented approaches assessing the field of potential futures for immature technologies considering socio-technical hypotheses. However, anticipatory LCA is sometimes differentiated by the notion of organization and integration in a risk management process (Wender et al., 2014; van der Giesen et al., 2020; Cucurachi et al., 2018). According to these authors, differences between ex-ante and anticipatory would not be on the scientific methodological aspect but rather on the articulation of the LCA practice within a decision-making process. In other words, anticipatory LCA focuses on decision theory and the organizational requirements to operationalize LCA practices with a forward-looking perspective. This approach questions the integration of the stakeholders impacted by the assessment into the decision-making. The distinctions between prospective, ex-ante and anticipatory LCA over time are deepened by Arvidsson et al. (2024). In particular, the authors show that the term *prospective* has been more common in the literature since 2018 than *ex-ante* and even more than *anticipatory*. Arvidsson et al. (2018) mention three scenario-based postures of forward-looking perspective:

- *predictive*, purposed to identify the “likely scenario”;
- *exploratory*, aiming at revealing the range of possibilities with a “what if” approach;
- *normative* or *back-casting, i.e.* “start from a vision of the future and develop pathways to it” (Arvidsson et al., 2018);

It should be noted that the theoretical requirements in terms of uncertainty management vary according to the posture, due to the different nature of the associated uncertainties.

Often associated with ex-ante LCA, to map technology candidates in the early stages of development (Hung et al., 2020), simplified approaches like *streamlined* LCA are dedicated to "be used by different actors without the need for expert knowledge on LCA" (Eleftheriou et al., 2022), including *parametric* LCA (Hollberg and Ruth, 2016). *Streamlined* LCA can also be used for redesigning or integrated into a label framework (Perez-Lopez et al., 2021). Nevertheless, *simplified* LCA stands on fewer indicators and its results are less robust than a full ISO 14040 standard-based LCA (Hung et al., 2020). *Streamlined* LCA is not peer-reviewed and cannot be published. It can be seen as a first step to identifying the environmental impact hotspots generated by a process or product under design. Still, to integrate LCA into the design, the second step after conducting a *streamlined* LCA could be about identifying the parametrization of the Life Cycle Inventory (LCI) with design-oriented categories (*e.g.* component level, product level, End-of-Life). Thus, *parametrized* LCA enable designers to control, optimize and monitor the potential environmental impacts resulting from their design choices (Kamalakkannan and Kulatunga, 2021).

3.1.3. *Dynamic LCA*

A LCA can also be referred to as "*dynamic*" if the impacts of the object studied are varying. Impacts can vary due to a time dependency of the LCI data (*e.g.* energy mix consumption or varying input in an industrial process). In this particular case, the term *dynamic LCI* is also used instead of *dynamic LCA*. Most of the time, the results of a(n *attributional*) LCA are presented by life cycle stages, but their implementation assumes that they all take place at the same time, *i.e.* in a static way (Cardellini et al., 2018). The longer the life cycle is, the more dynamic effects would need to be considered. For example, the energy consumed to assemble a product with a lifespan of several decades could be associated with more impact generated, as it is potentially more carbon intensive than the energy consumed to dismantle it at the end of its lifespan (in the same country) due to the decarbonization of the energy mix over time that should be happening. Taking into account the temporal dimension in LCA can also be refined with a dynamic weighting of the impacts (*i.e.* dynamic characterization factor) to represent for instance cumulative effects of successive emissions (Laratte et al., 2014; Ventura, 2022b). However, this approach is usually only applied to one indicator (often greenhouse gas emissions) because it requires supplementary expertise in biochemistry mechanisms. Consequential LCA is sometimes associated in the literature to dynamic or prospective LCA, as it relies on systemic models requiring updates to describe techno-economic causal chains propagating the consequences of a decision or an unusual event over time (Cucurachi et al., 2018; Roux and Peuportier, 2013). This prompts LCA experts (*e.g.* Schaubroeck et al., 2021; Weidema, 2004) to make the temporality of causality modelling explicit for consequential and attributional LCA.

3.1.4. *Regionalized, spatialized and territorialized LCA*

Other properties often mentioned in the literature are "*regionalization*" and "*spatialization*", respectively associated with "describe the representativeness of the processes and phenomena of a given region" (*e.g.* regionalize the inventory based on multiregional input-output tables, material flow analysis, data from institutional bodies or literature data) and "act of assigning a location to" quantities, to represent their spatial variability (*e.g.* associating geographical information systems to environmental impacts) (Patouillard et al., 2018).

In other terms, regionalization, also mentioned as *contextualization,* tends to define more regional properties for the product system (*e.g.* energy mix, raw material providers) while *spatialization* is related to the geography of a site, with, for instance, the associated characterization of material flows from and to the ecosphere (*i.e.* elementary flow). To deepen the regionalization in LCA, refer to the recommendations provided by Mutel et al. (2019). Moreover, the *territorial* approach is defined as the fact of considering environmental impacts on a given geographical area, either to study the geographical area in question (territorial type A) or to study a product that would influence several areas to be identified (territorial type B) (Loiseau et al., 2018). *Territorial* LCA is therefore a subcategory of *regionalized* LCA and mainly concerns the attributional approach.

Ultimately, *dynamic* and *regionalized* modes aim respectively to manage the temporal or spatial uncertainties associated with the inventory (Patouillard et al., 2018), or associated with the characterization factors (Patouillard et al., 2018; Potting and Hauschild, 2006). The *spatialization* intends to represent the spatial attribute geographic information to emission factors for characterization.

3.1.5. *Hybrid, absolute and transition LCA and LCA mode combinations*

The integration of multi-impacts and multistage methodology with other modelling approaches has also been developed. Guinée et al. (2018) refer in these cases to "integrated LCA", while other authors refer to it as *hybrid* LCA. Hybridizing may refer to input-output models (hence the designation IO LCA), or other kinds, such as MFA for instance or technico-social models (*e.g.* IMAGE, REMIND) (Sacchi et al., 2022a; Ventura, 2022a). In that respect, *absolute* and *transition* LCA (see next paragraphs) can be likened to *hybrid* LCAs as they involve external models of life cycle engineering. This category combines distinct modes from the "classic LCA" practices, *i.e. attributional*, *retrospective*, partially *regionalized* and *relative* LCA.

AESA aims to compare the environmental impacts of an object/service or human activity with environmental limits defined by sustainability science and allocation rules (*i.e.* proceeding from an attributional approach) and usually based on the planetary boundaries (Bjørn et al., 2020a). This approach, also mentioned as planetary boundaries (PB) LCA, is opposed to "relative" assessment, *i.e.* comparing the studied object with another technology (often incumbent) and uses the planetary boundary framework as an absolute reference to be compared with the service provided by the studied object. It seeks to move from "better" to "good enough" regarding environmental impact mitigation (Hauschild, 2015). To this end (Ryberg et al., 2020) proposed the AESA to help LCA practitioners select the sharing principles, among those available (Hjalsted et al., 2021), to be applied to the "Safe Operating Space" (SOS, *i.e.* absolute environmental limits on a global scale) in a particular case. This method brings about the definition of Share of the Safe Operating Space (SoSOS) to be used as an absolute reference in the comparison of environmental impacts. It can be considered as a hybrid mode of LCA, as it adds upscaling models and assumptions to an attributional LCA to implement an "absolute" comparison. This results in two main ways to proceed regarding the indicators and associated characterization factors: either by directly using planetary boundary indicators (Ryberg et al., 2018a) or by using carrying capacities, meaning transposed environmental limits in the "classic" LCA indicators (Bjørn and Hauschild, 2015; Sala et al., 2020). Moreover, attention must be paid to the LCI modelling: to be compared to a SoSOS, the reference flow that supplies the inventory is measured in kg per unit of time (usually per year). It reflects the continuous yearly pressure of human activities on the biochemical fluxes of the planetary boundaries and therefore requires a dynamic LCI or at least a date-dependent LCI (Ryberg et al., 2018a). As a maturing LCA mode, several theoretical and practical challenges remain to be overcome (*e.g.* temporal mismatch, boundary system, reference flows) to achieve an absolute assessment of sustainability (Guinee et al., 2022).

Transition LCA is close to the consequential framework as it attempts to assess a change in the current socio-technical system, however, it proceeds from a territorial approach, the aim being to study the transition of a given territory (Ventura, 2022a). This is a recent approach that takes LCA even further outside the product system framework (including functional unit definition), close to the "product" vision in engineering. Instead, it focuses on cumulative and interactive services provided in a given geographic area, implying a significant amount of data and a large boundary system.

Finally, it is important to understand that the category "Hybrid and combined" approaches (see Appendix 1), even more than the others, is not frozen in time and evolves accordingly to theoretical contributions, methodological and operational means, as well as academic and industrial practices. New combinations might appear in this category and then turned into a stand-alone "LCA mode". With regard to combinations, *attributional/consequential, regionalized/non-regionalized prospective/retrospective, and absolute/relative* can be seen as well-established continuums, and possibly as orthogonal properties. As such, these four continuums are, *a priori*, combinable. For instance, a *prospective*, *regionalized, consequential* LCA could therefore be adopted (*e.g.* assessment of the environmental consequences of rooftop photovoltaic deployment in the UK, Jones and Gilbert (2018)), as well as a *prospective attributional absolute* LCA (*e.g.* assessment of the environmental impacts of the photovoltaic electricity production in France in 2050 considering the Paris Agreement, Riondet et al. (2023)) or a non-*regionalized, retrospective, attributional* LCA (*e.g.* assessment of the average environmental aspects of a bottle, Marathe et al. (2019)). Such combinations therefore depend on the objective and scope of the assessment. In contrast and as evoked with *consequential* LCA and time consideration, *dynamic* and *prospective* modes are associated in the literature. They explicitly focus on the time-sensitivity of LCA results in the modelling.

Appendix 1 gathers the previous definitions and presents LCA modes and their characteristics for the upscaling assessment. Column 1 and 2 presents the usual names of LCA modes and their associated definitions extracted from the literature. Column 3 proposes a generic formulation of the question addressed by the LCA modes (main challenges, associated goal). These identified LCA modes are associated with the goal of the upscaling or the studied upscaling archetype (see Table 1). Columns 4 and 5 characterize the LCA modes with two elements of the scope: the usual studied object or the foreground system, and the temporal dimension. This second characteristic must be reconciled with the approaches to assess or anticipate the upscaling of a product. It sets the question "*Is it dedicated to anticipating (future-oriented) environmental impacts, taking stock of environmental aspects from an existing object (past-oriented), or both?*" This characteristic is crucial for LCA practitioners to select a LCA approach: it implies data availability conditions and/or scenario management requirements. Column 6 questions the existence of a standard for the LCA mode standard. This is congruent to the definition of the proposed category "historical/classic" of our LCA mode categorization. Being covered by the ISO standard 14040:2006 facilitates the application of the corresponding LCA modes into "classic" LCA practices (*e.g.* in a company or for labelling purposes). Column 7 details the required expertise and number of actors involved in the LCA mode application. This can provide an idea of the type of stakeholders and therefore can help guide LCA practitioners towards a specific upscaling archetype. Columns 8 and 9 propose additional resources, either to deepen concepts and definitions (column 8) or to apply the LCA mode (column 9).

3.2. *LCA practices suitable for upscaling archetype assessment*

Based on the review of LCA modes presented in the previous section, this section presents the outcomes of the literature review, related to the (RQ2) "*How should design teams be equipped to carry out or anticipate the upscaling of an emerging technology with regard to environmental sustainability?*". Thus, one of the difficulties faced by LCA practitioners in design teams is to choose the more adequate method(s) among the available ones (*cf.* Appendix 1). As a result, this section associates each upscaling archetype (*cf.* Table 1) with environmental methods, mainly multi-criteria and systemic, compatible based on shared analysis characteristics. This intends to guide LCA practitioners and their associated design teams in assessing and anticipating the environmental implication of an upscaling, depending on the analysis goal and the typology of upscaling studied (*i.e.* archetype). This association of upscaling archetypes and LCA modes is illustrated with multiple case studies from varying engineering fields.

3.2.1. *Archetype 1 – scaling-up, from laboratory to industrial scale*

The upscaling archetype 1 sets the question "*How to manage the prototype maturation process?*". The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented and focused on a technological product level. The environmental assessment of the scaling-up of a prototype can be supported by three complementary approaches:

- Environmental Technology Verification (ETV)
- Simplified LCA
- Ex-ante LCA (including parametrized LCA)

The ETV aims at testing and providing a certification that claims the environmental performance of an emerging technology as a competitive advantage to reach a market. The ISO 14034:2016 standard establishes the framework for this assessment, suitable for a large panel of products and sectors (*e.g.* water treatment, waste and resources, energy and agriculture) (European Commission, 2022; "ISO14034 (2016) - Environmental Management - Environmental Technology Verification (ETV)," 2016). It is, however, not explicitly based on LCA methodology and *a priori* rather retrospective, meaning that the analysis is applied at the end of the design process and does not support the design choices (*i.e.* post-ante assessment).

By contrast, ex-ante LCAs, are precisely dedicated to integrate environmental analysis during the design development process. Simplified and parametrized LCAs allow, to a limited extent, to consider the incremental improvement of a technology, often relative to a technology reference. The lower cost in time and the pre-selection of the scope, the background data, and sometimes parameters, imply that it can be used by non-LCA-expert designers (Arzoumanidis et al., 2017; Eleftheriou et al., 2022). Nevertheless, in case of a pre-constrained framework, designers are less able to deviate from the design architecture of the reference product, hindering disruptive innovations. Moreover, this partitioned organization of the design process also implies the need for an external LCA expert to apply regular updates of the database used and a monitoring of deviations from the initial hypothesis of the method (Arzoumanidis et al., 2017; Gazbour et al., 2018).

As mentioned at the beginning of the section, the definition we use here for ex-ante LCA is the one associated with the study of an emerging technology that does not exist on an industrial/commercial scale. Buyle et al. (2019) propose a generic theoretical framework for such assessments and detail the set of methods to apply in that case (*e.g.* proxies, scaling laws and extrapolations). The authors also described when these methods can be mobilized to build the data inventory, according to the level of maturity of the technology to be studied (*i.e.* TRL) (Buyle et al., 2019). Among them, participatory methods are defined as the collection of multiple points of view and opinions from experts and more generally from stakeholders. These methods are spread out over the maturation process of a technology (*i.e.* from TR3 to the diffusion of the technology, after TRL9) (Buyle et al., 2019; de Souza et al., 2023). This implicitly requires LCA practitioners to interact with researchers, or engineers and actively participate in the design process. Arvidsson et al. (2018) recommend generating prospective scenarios for design parameters from a current value: predictive scenarios are then combined with an exploratory approach to identify the "scenario range" for the set parameter value.

To deepen the LCA-expert integration into the design process, procedures and organizations of interactions between a technology expert (usually the designer) and a LCA practitioner, based on existing practice in chemical engineering are published. For instance, Tan et al. (2018) developed a hybridization of LCA with Environmental, health and safety (EHS) screening promoting multi-disciplinary designer teams (Tan et al.,

Table 2
Modelling recommendations for Archetype 1: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

Upscaling archetype	Methodological requirements to model the archetype profiles	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype	
		Geographical and temporality scopes	LCA specificities
Archetype 1 Scaling-up, upsizing from a lab. to an industrial scale	• Define the domain-technical expertise required to model the processes(Buyle et al., 2019), • Ensure strong interactions between researchers and engineers (e.g. technologist, chemist) (Tsoy et al., 2020), • Implement a future-oriented design (Arvidsson et al., 2024, 2018).	• Mainly use phase-focused scopes units integrated in a life cycle scope, • Object studied: a product. • Expertise's timescale: over months, • Geographical scale: from laboratory scale to an industrial site.	• Foreground system caution and clear scenario of use phase in the comparative framework: "to which incumbent technology the prototype is compared?" (Cucurachi et al., 2018; Thonemann et al., 2020), • Data production and collection challenges (Erakca et al., 2024), Parametrization of the LCI with design parameters (Kamalakkannan and Kulatunga, 2021; Tan et al., 2018; Tsoy et al., 2020).

2018), while Tsoy et al. (2020) reviewed 18 case studies to characterize analysis invariants for different engineering sectors and create a generic decision tree for the upscaling of emerging technologies with scenarios and constraints defined collaboratively (Tsoy et al., 2020). Except for design projects with a very identified location of the use phase (mainly in urban design or energy sector), a few ex-ante LCA are regionalized (Douziech et al., 2021), and even consequential (Buyle et al., 2019). However, some of the methods and tools presented (*e.g.* learning curves) introduce a consideration of dynamic phenomena in the LCA practice.

Finally, the converging point of the literature is the clarification of the targeted service that the emerging technology is supposed to fulfil. Cucurachi et al. (2018) insist on the comparison of the studied emerging technology with an incumbent technology, *i.e.* a commercialized technology that already fulfils the targeted service. Thonemann et al. (2020), based on a literature review, develop on LCA modelling consistency depending on the nature of the data collection. Authors specify for ex-ante LCA the matrix pedigree provided by Ciroth et al. (2016) for classic LCA data management challenges. Some indicators correspond to classic LCA practices (*e.g.* 'Reliability' and 'completeness' of data) and others require particular consideration (*e.g.* 'temporal' and 'geographical correlation') and may impose to be handled together. Additionally, the fifth criterion called 'further technological correlation' helps designers to question the accuracy of extrapolating data from other contexts in the studied scenarios when there is a lack of data concerning the emerging technology under study. Therefore, comparing the studied emerging technology to the best available technology (BAT) as the future incumbent technology is a common way to deal with midterm anticipation and functional unit consistency. However, comparison with one or more incumbent technologies should prompt specific reflection on an accurate functional unit, that may also evolve over the design process. Based on these elements, the authors provide a methodological framework to deal with the specificities of the ex-ante LCA concerning the four steps of LCA (goal and scope definition, LCI, LCIA and interpretation of results).

To conclude, the modelling requirements and LCA specificities to carry the environmental assessment of the scaling-up of a technology could be summarized in Table 2, as follows:

3.2.2. Archetype 2 – mass-producing, industrializing

The upscaling archetype 2 sets the question "*How to manage the mass-production of a technology?*". The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented and focused on a technological product level and its lifecycle. The environmental assessment of the mass-production of a technology can be supported by three complementary approaches:

- ISO Standards-based LCA (attributional, consequential)
- Prospective dynamic LCA
- Regionalized and dynamic LCA

Mass-producing a product deals with a value chain perspective and industrial engineering, compliant with an attributional approach. Consequently, many of the LCA performed in this upscaling archetype are carried out within the ISO 14040 standard ("ISO 14040," 2006; "ISO 14044," 2006).

In addition, in Europe, the Product Environmental Footprint (PEF) reports give product-specific instructions to apply LCA. For instance, Wade et al. (2018) give details about the process of PEF elaboration concerning Photovoltaic devices. It provides advice on functional unit and perimeter selection and cut-off rules. It also informs LCA practitioners about the modelling of end-of-life treatments and pinpoints emerging rules for new use of the studied product, including Building Integrated Photovoltaics (BiPV), *i.e.* PV devices used to replace material for the structure of a building while producing energy (Task12, 2019; Wade et al., 2018). Both standards are usually read as an ex-post (or retrospective) attributional framework, used to validate a design structure and the associated value chain (van der Giesen et al., 2020). However, PEFs are not deployed for every type of product. Critical reviews in the literature specific to the production of a product can thus make up for this shortcoming. (*e.g.* Martin et al. (2023) for vertical farming).

Regarding scale effects integration, Gwehenberger et al. (2007) give an example of the ecology of scale assessment, by considering the effect of scale on price and environmental impacts generated. It can be considered as a retrospective LCA, but such methodology could be applied prospectively, by using methods identified by Buyle et al. (2019) and suitable after or during TRL 9, such as learning curves. Since the environmental impacts are, in many cases, mostly related to material consumption, reduction phenomena per unit produced lead to the reduction of the LCA inventory (in amount) and thus ultimately to the reduction of its resulting impacts generated.

In the context of anticipating the implementation of an incremental change on a technology that already meets an existing market (*e.g.* new product design based on a previous form), and if the question is about choosing a material supplier, for instance, to increase production capacity, the consequential approach of LCA seems accurate. In that case, the levers for eco-design of a product, meaning to alleviate its environmental impact responsibility, can be relied on supplier choices or strategies outside the value chain of the designed system (*e.g.* to improve the production of the marginal supplier of a resource or invest to increase the capacity of its recycling process) (Weidema et al., 2018). Thus, this broadens the scope of possible levers for eco-design in return for an increase in the number of stakeholders involved in the analysis of the LCA results.

To conclude, the modelling requirements and LCA specificities to carry out the environmental assessment of a technology mass-producing are synthesized in Table 3, as follows:

3.2.3. Archetype 3 - reaching a level, deploying a technology

The upscaling archetype 3 sets the question "*How to reach a*

Table 3
Modelling recommendations for Archetype 2: confronting methodological requirements to model the archetype to the modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

Upscaling archetype	Methodological requirements to model the archetype profiles	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype	
		Geographical and temporality scopes	LCA specificities
Archetype 2 Mass-producing, industrializing	• Follow an integrative and normative approach (Hauschild et al., 2020; "ISO 14040," 2006), • Refer to techno-economic expertise (Buyle et al., 2019), • Identify the stakeholders of the value chain (life cycle engineering) ("ISO 14040," 2006).	• Life cycle-based, regionalized approach over the value chain (Weidema et al., 2018), • Studied system: a product system included in an industrial context (Hauschild et al., 2020), • Expertise's timescale: over years. • Geographical scope: adjusted to the mass production and worldwide industrialized system.	• Industrial trend focus (*e.g.* favour dynamic LCI), • End-of-life modelling challenges, • data collection/extrapolation challenges (Zargar et al., 2022).

cumulated service provided by a group of technology at a targeted time horizon?". The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented, time-dependent and focused on an upper level than the technological product level (*e.g.* regional or national level). Conducting an environmental assessment of the deployment of a technology can be supported by multiple complementary approaches depending on the system boundary and the targeted time horizon:

- Prospective, attributional and dynamic LCA
- Integrated LCA - dynamic modelling
- Attributional, consequential LCA
- Regionalized LCA
- Transition LCA

Similarly to the techno-economic methods, the environmental assessment of a technology used in a transition is based on prospective scenarios. Consequently, the attributional mode of LCA is accurate for the assessment of this upscaling archetype, because suitable for studying a technology that would have become an incumbent technology in a transformed system. For instance, Hung et al. (2022) propose a generic life cycle model, named ECOPT^2, to optimize the deployment of a technology, considering life cycle impact minimization. It integrates stock flow minimization and cumulative consumption of raw materials. It is illustrated in a case study on electrical vehicles (EVs) but authors assure that it could be suitable for technology deployment assessment in other activity sectors (*e.g.* energy production, waste management, multimodal passenger transport). In the topic of EVs, Tang et al. (2023) tend to assess a "European electric-mobility transition" on environmental criteria. They provide technology mixes over the period 2015–2040, following three deployment scenarios developed relatively to GHG reduction targets at the scale of the European Union. It also uses, to build their LCI, a model of dynamic material flow analysis and mathematical optimization. With regard to the energy sector, Cassoret et al. (2022) apply a prospective attributional LCA on the electricity production of France based on four institutional scenarios of energy transition. The authors present different material consumptions per unit of installed capacity according to power technologies and then aggregate them to finally compare the overall impacts of the power generation systems following the four transition scenarios. The results of this kind of work, as for any prospective LCA, must be analysed in light of the assumptions made (*e.g.* fixed lifespan, technological improvements neglected). Another example of this prospective and cumulative approach is given by a similar case study applied in the Netherlands building sector (Yang et al., 2022). A systematic prospective LCA framework is developed by Steubing and de Koning (2021). They provide an interfacing tool (so-called superstructure) between future scenarios concerning the background system and the corresponding LCI database supporting the results of an attributional prospective LCA. Its implementation in an open-access software (*i.e.* Activity Browser) asserts the author's willingness to facilitate LCA practicing. From then on, new methodologies are expected to attest to the robustness of the results, mainly related to the assumptions made in scenarios. Once again, this requires the involvement of various stakeholders to ensure the consistency of many hypotheses that may not be within the competence of a technical expert, an LCA practitioner, or even of the product company itself.

In addition, in a cumulated perspective, MFA can be applied simultaneously with the usual "per unit" impact assessment.

In contrast, if no market exists yet for the studied technology, or if the market is in a fast expansion (*e.g.* the lithium market), it becomes difficult to apply a prospective consequential LCA, due to the limits of underlying models (*e.g.* equilibrium models) will become an issue. However, it is possible, with strong assumptions on energy regulations, to identify a marginal electricity mix for instance (*cf.* demonstration for Denmark on the website consequential-lca.org (Muñoz and Weidema, 2021)).

To conclude, the modelling requirements and LCA specificities to

Table 4
Modelling recommendations for Archetype 3: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

Upscaling archetype	Methodological requirements to model the archetype profiles	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype	
		Geographical and temporality scopes	LCA specificities
Archetype 3 Reaching a level of cumulated service, deploying a technology	• Develop a market maturity and sectorial long-term expertise (Muñoz and Weidema, 2021), • characterize a cumulative technology's performance (Hung et al., 2022; Laratte et al., 2014; Menten et al., 2015), • Set up scenario expertise and specific data uncertainty management (Langkau et al., 2023).	• Large spatial/social scale (regional, national - sectorial or group of technology), • Scope studied: the industry sector where the products are deployed, • The phenomenon's timescale is over decades. Expertise's timescale is over months or years.	• Background system accuracy challenges: rigorous scenario hypothesis is required (Langkau et al., 2023), • Avoidance of temporal mismatch (*i.e.* favour dynamic LCA) (Mendoza Beltran et al., 2020), • Natural resources focus, and more broadly cumulative properties of the environmental impacts (Charpentier Poncelet et al., 2022).

carry out the environmental assessment of the deployment of a technology are summarized in Table 4, as follows:

3.2.4. Archetype 4 – integrating a complex system

The upscaling archetype 4 sets the question "*How to manage the integration of a technology into a complex (socio-technical) system?*". The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore focused on the complex system modelling with a boundary system accordingly designed (*e.g.* electricity network, industrial or urban metabolism). The environmental assessment of the integration of a technology into a complex system can be based on multiple complementary approaches depending on the type of interaction and the type of complex system to be studied:

- Regionalized/spatialized LCA
- Consequential LCA
- Transition LCA
- Integrated LCA - Optimization modelling

Broadening the perimeter of the studied object is accessible with an attributional approach, given the concept of Product-Service System (PSS). This approach focuses on the service provided by one or more products instead of one unit of product. Kjaer et al. (2018) developed in that case guidelines to deal with associated challenges (scope, functional unit, perimeter). It is consistent with a normative approach based on the ISO 14040:2006. This framework is, however, applicable to relatively small systems (*e.g.* fleet of bicycle sharing, leasing of soil compactor). Assessing the environmental implications of the integration of a technology in an existing complex system seems for the least congruent with the consequential approach. The consequential perspective focuses indeed on the technical and economic consequences of a decision on the techno-economic structure of human societies (Ventura, 2022a). In that regard, and given the common way that consequential LCA is implemented, the economic system can be considered as the complex system under study in which a technology is inserted. As such, Almeida et al. (2020) reviewed 25 studies of consequential LCA in the building sector and characterized the underlying economic models in terms of the scale of the studied economic consequences (small, medium, large) and their time horizon (short-term, mid-term, long-term). Authors state that Agent-based models (ABM), "bottom-up, nonlinear and dynamic socio-economic models" are increasingly used to study interaction between economic agents. This type of model combined with multi-regional input-output table (*i.e.* EXIOBASE) and stock-flow consistent model can be used to investigate the economic rebound effect associated with income redistribution (Almeida et al., 2022). These valuable insights for designers (and companies) to assess the introduction of a technology to a specific audience can only be produced with the assistance of an economist expert, in addition to an LCA practitioner.

Other authors, through case studies, investigate the technical consequences of the integration of a specific technology on a technical complex system.

Menten et al. (2015) developed a case study of prospective consequential LCA on the production of synthetic diesel from biomass in France. The analysis is supported by a bottom-up long-term energy model (TIME-MIRET). The authors decided to consider time-dependent characterization factors for GHG on the Global warming potential (GWP) between 2007 and 2030. This study aimed to help policymakers to identify how the economy could be impacted at a national level while focusing on a specific technology. Despite the limits of this analysis (*e.g.* mono-indicator), several accurate methodological recommendations for upscaling assessment can be retained, including taking into account non-linearity in the functional unit and system boundary definition. Menten et al. stress the importance of defining the system boundary in relation to the functional unit and magnitudes of expected consequences and warn about the representation of the results to avoid a linear reading of the results (*e.g.* X emissions per unit of product means X emissions times 2 for 2 products).

Note that this case study could be characterized as a (dynamic) prospective consequential LCA and as a hybrid LCA due to the use of a pre-existing model of the national energy system (*i.e.* the TIME MIRET model, as a bottom-up model).

Concurrently, Jones and Gilbert (2018) provide a consequential LCA example on a rooftop photovoltaic deployment, with a network perspective by considering aggregated installed PV capacity. Up and down zooming is thus implemented with network management trade-offs required to respond to PV network penetration, following three strategies (Reinforcing network, PV management and Voltage Control) resulting in varying greenhouse gas (GHG) emissions.

This case study also covers archetype 3 (reaching a level) as it considers PV devices with an aggregate/comprehensive approach. However, while archetype 3 focuses only on the technology, this paper explores interactions between fleets of PV panels and the electricity network made up of sub-systems (*e.g.* transformers, wires or on-load tap chargers).

Another example of up-and-down zooming is given by Baltazar et al. (2022) environmentally assessing the technical requirements of implementing EVs in a highway. Based on data collection, optimization modelling and an attributional framework, the study demonstrates that to fulfil the same service as a thermic vehicle, the electrical battery properties and the charging design are strongly related. These design parameters offer trade-off strategies for reducing the environmental impacts of the whole service system.

In practice, adopting (or even discussing) these strategies would require bringing together designers and decision-makers, usually not collaborating and dealing with different natures of constraints. (*e.g.* a designer of Battery of EV and municipal officials in charge of implementing charging stations). At least, such models support the cause-to-consequence link with design constraints and the potential environmental impact generated.

Lastly, with regard to technical system examples, Quisbert-Trujillo et al. (2020) reviewed LCA on the Internet of Things (IoT) to develop a sectorial eco-design framework. The method developed involves the interaction of three layers (sensing layers, edge layers and cloud layer), necessary to satisfy a given functional unit.

Interactions with the environment can also be considered with a spatialized approach, as in the study of the integration of a floating wind power farm on a particular site (Perez-Lopez et al., 2020; Poujol et al., 2020). In that study, the wind resource map is combined with the implemented technology location, deducing the environmental impacts generated. More broadly, territorial approaches are dedicated to identifying the interactions with the life cycle of a product and geographical regions (Loiseau et al., 2018).

These examples show that modelling choices are very dependent on what kind of complex system is studied and if a prospective approach is needed.

Addressing several complex systems modelling issues in LCA, Ventura (2022a) proposes the *transition LCA* framework, suitable for assessing ecological transition in a territory (*i.e.* a complex system) enabling to anticipate changes that would occur due to the implementation. The study provides several illustrations: concrete recycling at a regional scale, low-tech building materials in building work or shared electric scooters in a city. Additional case studies should emerge in the coming years based on this emerging framework to support its operability.

Thus, the modelling requirements and LCA specificities to carry out the environmental assessment of the integration of a technology into a complex system are compiled in Table 5, as follows:

3.2.5. Archetype 5 – down-limiting, downscaling the planetary boundaries to the technology level

The upscaling archetype 5 sets the question "*Are the environmental impacts of the studied object lower than environmental limits/sustainability*

Table 5
Modelling recommendations for Archetype 4: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

Upscaling archetype	Methodological requirements to model the archetype profiles	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype	
		Geographical and temporality scopes	LCA specificities
Archetype 4 Integrating a complex (socio-technical) system	• Mobilize system dynamic engineering and systems thinking with an interoperability focus as tools to model the complex system to be integrated (Ceschin and Gaziulusoy, 2019; Jones and Gilbert, 2018; Onat et al., 2017), • adopt a culture of trade-offs from optimization modelling or socio-economic expertise on a territorial scale (Baltazar et al., 2022; Ventura, 2022a), • more broadly, develop a multidisciplinary approach (Riondet et al., 2024).	• Large geographical scales (the one of the complex system). Usually includes a worldwide perspective(Sacchi et al., 2022b; Stadler et al., 2018), • Scope studied: the socio-technical complex system where the product or system developed is deployed (*e.g.* economic market, grid and network, urban metabolism), • Spatial and geographical properties focus. Phenomenon's timescale is varying from real-time to decades.	• Analysis perimeter challenges (*i.e.* which territory to consider?) (Ventura, 2022a), • Causal model to choose (if consequential approach) and more broadly interaction modelling challenges (Weidema et al., 2018), • Data collection and management challenges (Cluzel, 2012; Cluzel et al., 2010; Salehy et al., 2020).

levels normatively defined?". The AESA is therefore the suitable LCA approach for dealing with the environmental aspects of this archetype. In addition, depending on the time and region where the sustainability of the technology is studied, prospective and regionalized approach are recommended. The environmental assessment of the (absolute) sustainability of a technology can be based on:

- Absolute (attributional) LCA (or AESA)
- Prospective LCA
- Regionalized LCA

Absolute LCA or AESA intends to support the down-limiting of science-based global limits to a regional scale. As mentioned in the introduction, this approach relies on *sharing principles* applied to the SOS from the planetary boundary framework to build an *environmental space* (or limit) on the object's scale under study. Hjalsted et al. (2021) structure the process of building the environmental space (also called *SoSOS*) by going through two stages: The first step consists of reporting the SOS at an individual level, based on *allocation principles*. These allocation principles can follow an egalitarian line, or consider compensations (for example depending on the historicity of the environmental impacts or the supposed capacity to reduce them over time). The second step consists of "upscaling" the individual environmental space to the scale of the object under study, such as an industry, a country or a product. To do so, the authors develop two *upscaling methods* titled *Final Consumption Expenditure* (FCE) and *Green Incentive-Based* (GIB). FCE follows an allocation principle based on the current consumer preference for existing companies and products, while the GIB allocation tends to reward initiatives aimed at sustainability. These two methods are mainly intended for the industrial sector level. Hjalsted et al. (2021) applied both of them to a non-regionalized case study for the dairy sector. Ryberg et al. (2020) in the article titled "*downscaling the planetary boundaries in absolute environmental sustainability assessments*" reviewed the case studies in the literature applying AESA and clarified seven associated distributive justice theories (*e.g.* egalitarianism, utilitarianism, prioritarianism). The authors then proposed recommendations to build an environmental space (or SoSOS) according to the study objective and following a distributive justice theory.

In addition to methodological developments, Bjørn et al. (2020a,b) and Ryberg et al. (2018a,b) offer practical case studies of such an approach. Authors shape a SOS at the scale of a product (washing machine) respectively with (Bjørn et al., 2020b; Ryberg et al., 2018a) and without (Bjørn et al., 2020b; Ryberg et al., 2018a) a regionalized attributional LCA. The regionalization developed by Bjørn et al. (2020b) enables LCA practitioners to attribute to each region covering a life cycle step of the studied product takes place, the corresponding use of the SoSOS (*i.e.* environmental impacts). It is a retrospective case study because the washing machine already exists in the case study nevertheless the method could *a priori* be implemented for a prospective or ex-ante perspective (*i.e.* integrated in design), provided sufficient and accurate data and an implementation following this framework (Bjørn et al., 2020a; Ryberg et al., 2020).

In the building sector, Bendahmane et al. (2022) provide an example of a territorialisation approach in conjunction with AESA to define a carrying capacity specifically for abiotic material circularity concerning a specific territory. This method, untitled MIMOSA, defines normative thresholds for material circularity and therefore helps consider the sustainability of a building project.

Finally, as evoked in subsection 1, the AESA relies on allocation principles to be justified (and subject to discussion with the actors/population of a territory), as they are not imposed by physical laws or product operation. Therefore, AESA is today spontaneously used in connection with attributional LCA. Thus, for each attributional LCA applied (in each archetype), it could be possible to apply an AESA to compare the environmental impacts of a product or a service with a set SoSOS embodying absolute environmental sustainability objectives.

To conclude, the modelling requirements and LCA specificities to carry out the sustainability assessment of a technology are synthesized in Table 6, as follows:

3.3. Guidelines for LCA practices adapted to upscaling archetype assessment

The available LCA modes in the literature have been presented in section 3.1 and the LCA practices associated with each upscaling archetype in subsections 3.2.1 to 3.2.5. In this subsection, we propose synthetic guidelines for LCA practitioners and design teams to deal with the environmental aspects of the upscaling of a product. Table 7 compiles in column 2 LCA methodological requirements depending on each upscaling archetype to assess or anticipate an upscaling. It refers to the identified necessary expertise (*e.g.* techno-economic) and management strategies that design teams must apply during the upscaling assessment. Column 3 suggests relevant or regularly used LCA modes in the literature with regard to an upscaling archetype, and illustrated on study cases reviewed in previous subsections. Thus, as each of the first four archetypes has a different temporality, scope and purpose, one or more LCA "modes" appear to be suitable to environmentally assess an upscaling. The specificity of the upscaling archetype 5 (down-limiting) is that it does not have a predefined temporality and can therefore be applied at the same time as the others. We propose in column 4 "Additional LCA modes" that have to be considered as a possible enrichment of the recommended or current LCA practices. It might lead to further research into the interoperability of LCA modes and new guidelines for design teams including LCA practitioners. Columns 5 and 6 present recommendations and constraints to which LCA practitioners must pay attention. "Geographical/Temporality" (column 5) stands for aspects of

Table 6

Modelling recommendations for Archetype 5: confronting methodological requirements to model the archetype to the modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

Upscaling archetype	Methodological requirements to model the archetype profiles	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype	
		Geographical and temporality scopes	LCA specificities
Archetype 5 down-limiting, downscaling the planetary boundaries to the technology level	• Observe fair allocation methods (*i.e.* argue justice principles) and strictly define the service being studied. Multiple allocation methods are recommended (Hjalsted et al., 2021; Ryberg et al., 2020), • Manage the data collection associated with the service (usually techno-economically based) (Hjalsted et al., 2021; Kara et al., 2023), • Monitor methodological development (for product) from (AESA: impact indicators, weighting, allocation rules/justice principle).	• The pollution space is based on an attributional LCA of the product or system lifecycle, • Studied system scope: AESA implies adapting environmental phenomenon scale considerations to the scale of the functional system studied (Bendahmane et al., 2022; Bjørn et al., 2020b), • Temporal and geographical scopes focus on the services provided to humans through the artefact developed. The lifecycle inventory should describe best the local or regional focus (national/sectorial) and time variability (Kara et al., 2023; Ryberg et al., 2018b).	• Scope and analysis perimeter challenges (*i.e.* which human service/system to consider?), • The functional unit is measured per unit of time (as an annual pressure on the environment) (Ryberg et al., 2018b), • Use multi-criteria assessment and specify characterization factors of the impact assessment (Bjørn et al., 2020a; Sala et al., 2020).

the LCA scope related to spatial and time characteristics of the studied product or system and the implementation of its assessment (*e.g.* time-scale of the assessment). “LCA specificities” (column 6) provide particular features to be conserved by LCA practitioners. It concerns challenges for the modelling approach (*e.g.* foreground and background systems considerations, choices of impact categories, model selection) and result interpretations (comparative analysis or not). Column 7 gives additional methodological content or operational resources relevant for a specific upscaling archetype identified in the literature. This column aims to guide LCA practitioners towards available resources to facilitate or improve their practice of the upscaling assessment. Table 7 is intended to be completed and revised in the coming years by the interested communities, according to new methods, and case studies, demonstrating feasibility or incompatibility.

3.3.1. *From generic recommendations to specific guidelines; an illustration of the literature review of engineering fields*

In this research paper, and based on multiple examples and case studies from the LCA literature, the compatibility between LCA modes and upscaling archetypes has been illustrated. It clearly appears that “LCA modes” are not immovable and depend on the practices and identified needs for environmental assessments. Transition LCA is the best example of this trend. Many developments are coming concerning new interfaces or hybridizations between them, facilitated for instance by new practices. For instance, the Python-based LCA with open-source approaches supports new computational means and methodologies (Cardellini and Mutel, 2018; Mutel, 2017; Steubing et al., 2020) dedicated to dynamic, regionalized and prospective LCA, respectively. Thus, new practices and then LCA modes could therefore arise supported by new resources, expertise, habits, laws and standards to meet the crucial stakes of environmental assessment for technology upscaling. To complete the generic guidelines of Table 7, a cartography of our accessed literature is proposed in Fig. 1. This matrix, called UA-EF for *Upscaling Archetypes (UA) by Engineering Fields (EF),* has been designed to relate the upscaling archetypes (horizontally) to the engineering sectors in which LCA content and practices were identified during the literature review. It represents the references used to identify methodological invariants and structure the guidelines (large dots) and case studies to illustrate the LCA practices (small squares). The objective of this illustration is to present a snapshot at a given moment of an identified literature related to LCA practices to assess or anticipate the upscaling of a technology. It is not intended to be exhaustive but could be supplemented by further research with, for instance, a focus on a specific engineering field.

A few remarks can be made about this illustration:

- Archetype 1 (upsizing) is developed in multiple engineering fields and therefore benefits from a well-structured LCA approach, mainly based on ex-ante LCA.
- Archetype 2 (mass-producing) is evolving to a standard approach, not exhaustive in terms of case studies. Specific Product Environmental Footprint (PEF) could also enrich this column. As it stands, many examples may exist but are not specifically tagged as an assessment of “mass-produced” products.
- Archetype 3 (reaching a level) is mentioned in the energy and transport sectors, both related to energy transition scenarios (see large dots in column 3). As it is a relatively new topic of research in LCA, more case studies and structuring guidelines are forthcoming.
- Archetype 4 (integrating a complex system) presents many case studies. As there are no generic models for all possible interactions between a technology and the complex systems it integrates, there are few generic guidelines for LCA. The only identified generic framework is the description of the Transition LCA provided by (Ventura, 2022a) which is relatively recent and presents few associated case studies.
- Archetype 5 (down-limiting) hinges on two approaches structured in a few references (Bjørn et al., 2016; Ryberg et al., 2020) and applies theoretically to any engineering field. Like archetype 3, it is a relatively new topic of research in the LCA community, implying upcoming case studies and developments to solve methodological dilemmas (Guinee et al., 2022). Currently, methodological results and case studies in various engineering fields are regularly arising (*cf.* researches of Center for Absolute Sustainability team, DTU).

Finally, The matrix UA-EF (*i.e.* Fig. 1) could help members of design teams, including LCA practitioners, to identify which engineering field is proactive on a certain vision of the upscaling (*i.e.* upscaling archetype). It also points to which groups of authors have been identified as contributing to the development and/or operationalization of methodologies through case studies.

3.4. *Discussion: LCA, upscaling archetypes and ecodesign*

To be clear, the upscaling archetypes must be understood as five analysis grids to study specific aspects of a technology upscaling. These aspects rely on each other, and their predominance and interactions depend on the industrial sector as evoked in subsection 3.3.1 and illustrated by Fig. 1. Moreover, each archetype hinges on a particular vision (supported by its goal, scope and subject), making an upscaling assessment ideally merging component vision, product vision, value chain or market vision, holistic vision, *etc.* The integration in the design

Table 7

Synthesis of environmental methods and guidelines for LCA practitioners according to upscaling archetypes.

Upscaling archetype	Methodological requirements to model the archetype profiles	Main used environmental assessment modes adapted to the archetype (from literature study)	Additional compatible LCA modes	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype		Additional resources for further development
				Geographical and temporality scopes	LCA specificities	
Archetype 1 Scaling-up, from laboratory to industrial scale	• Define the domain-technical expertise required to model the processes(Buyle et al., 2019). • Ensure strong interactions between researchers and engineers (*e.g.* technologist, chemist) (Tsoy et al., 2020). • Implement a future-oriented design (Arvidsson et al., 2024, 2018)	• Ex-ante LCA • Simplified (attributional) LCA • ETV	• Regionalized • Parametrized	• Mainly use phase-focused scopes units integrated in a life cycle scope. • Object studied: a product. • Expertise's timescale: over months. • Geographical scale: from laboratory scale to an industrial site.	• Foreground system caution and clear scenario of use phase in the comparative framework: "to which incumbent technology the prototype is compared?" (Cucurachi et al., 2018; Thonemann et al., 2020), • Data production and collection challenges (Erakca et al., 2024), • Parametrization of the LCI with design parameters(Kamalakkannan and Kulatunga, 2021; Tan et al., 2018; Tsoy et al., 2020).	Available means in literature for data collection: (Zargar et al., 2022)
Archetype 2 Mass-producing, industrializing	• Follow an integrative and normative approach. • Refer to techno-economic expertise. • Identify the stakeholders of the value chain (life cycle engineering).	• ISO Standards-based LCA (attributional, consequential) • Prospective dynamic LCA	• Regionalized • Dynamic	• Life cycle-based, regionalized approach over the value chain (Weidema et al., 2018), • Studied system: a product system included in an industrial context (Hauschild et al., 2020), • Expertise's timescale: over years, • Geographical scope: adjusted to the mass production and worldwide industrialized system.	• Industrial trend focus (*e.g.* favour dynamic LCI), • End-of-life modelling challenges, • data collection/extrapolation challenges (Zargar et al., 2022).	Design for X (Manufacturing) LCA standards and European commission ("European Platform on LCA | EPLCA," 2011)
Archetype 3 Reaching a level of cumulated service, deploying a technology	• Develop a market maturity and sectorial long-term expertise (Muñoz and Weidema, 2021), • characterize a cumulative technology's performance (Hung et al., 2022; Laratte et al., 2014; Menten et al., 2015), • Set up scenario expertise and specific data uncertainty management (Langkau et al., 2023).	• Prospective, attributional and dynamic LCA • Integrated LCA - dynamic modelling	• Attributional, consequential • Regionalized • Transition	• Large spatial/social scale (regional, national - sectorial or group of technology), • Scope studied: the industry sector where the products are deployed, • The phenomenon's timescale is over decades.	• Background system accuracy challenges: rigorous scenario hypothesis is required (Langkau et al., 2023), • Avoidance of temporal mismatch (*i.e.* favour dynamic LCA) (Mendoza Beltran et al., 2020), • Natural resources focus, and more broadly cumulative properties of the environmental impacts (Charpentier Poncelet et al., 2022).	Material indicator: mineral resource dissipation (Charpentier Poncelet et al., 2022) Prospective scenario management: (Langkau et al., 2023) Uncertainties and prospective (Maier et al., 2016)
Archetype 4 Integrating a complex (socio-technical) system	• Mobilize system dynamic engineering and systems thinking with an interoperability focus as tools to model the complex system to be integrated (Ceschin and Gaziulusoy, 2019; Jones and Gilbert, 2018; Onat et al., 2017), • adopt a culture of trade-offs from optimization modelling or socio-economic expertise on a territorial scale (Baltazar et al., 2022; Ventura, 2022a),	• Regionalized/spatialized LCA • Consequential LCA • Transition LCA • Integrated LCA - Optimization modelling	• Attributional • Consequential • Hybrid • Dynamic • Prospective	• Large geographical scales (the one of the complex system). Usually includes a worldwide perspective(Sacchi et al., 2022b; Stadler et al., 2018), • Scope studied: the socio-technical complex system where the product or system developed is deployed (*e.g.* economic market, grid and network, urban metabolism), • Spatial and geographical properties focus. Phenomenon's timescale is varying from real-time to decades.	• Analysis perimeter challenges (*i.e.* which territory to consider?) (Ventura, 2022a), • Causal model to choose (if consequential approach) and more broadly interaction modelling challenges (Weidema et al., 2018), • Data collection and management challenges (Cluzel, 2012; Salehy et al., 2020).	Design for Sustainability (Ceschin and Gaziulusoy, 2019)

(*continued on next page*)

Table 7 (*continued*)

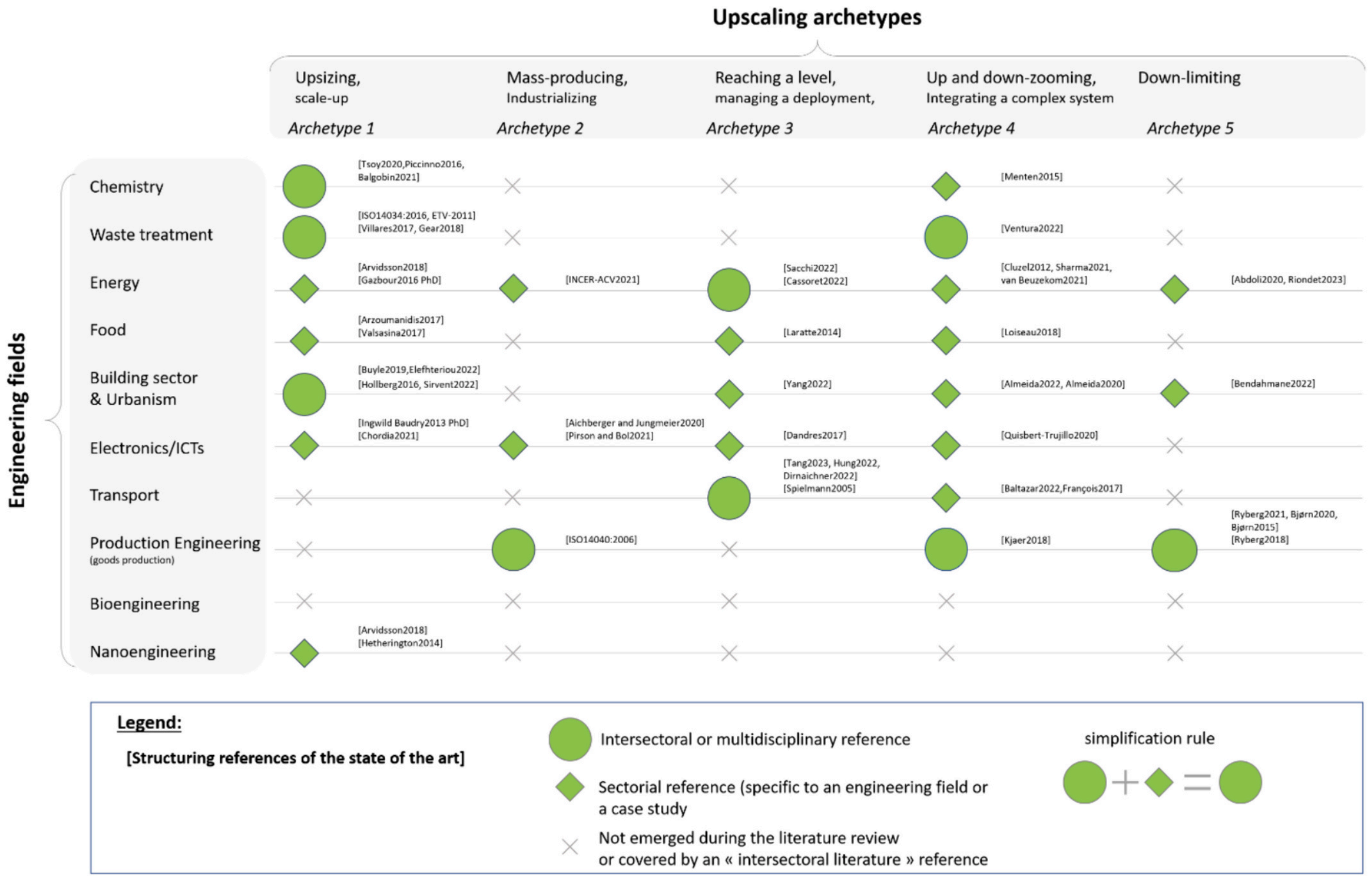
Upscaling archetype	Methodological requirements to model the archetype profiles	Main used environmental assessment modes adapted to the archetype (from literature study)	Additional compatible LCA modes	Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype		Additional resources for further development
				Geographical and temporality scopes	LCA specificities	
	• more broadly, develop a multidisciplinary approach (Riondet et al., 2024).					
Archetype 5 down-limiting, downscaling the planetary boundaries to the technology level	• Observe fair allocation methods (*i.e.* argue justice principles) and strictly define the service being studied. Multiple allocation methods are recommended (Hjalsted et al., 2021; Ryberg et al., 2020). • Manage the data collection associated with the service (usually techno-economically based) (Hjalsted et al., 2021; Kara et al., 2023). • Monitor methodological development (for product) from (AESA: impact indicators, weighting, allocation rules/justice principle).	• Absolute (attributional) LCA	• Prospective • Regionalized • Dynamic • Spatialized	• The pollution space is based on an attributional LCA of the product or system lifecycle. • Studied system scope: AESA implies adapting environmental phenomenon scale considerations to the scale of the functional system studied (Bendahmane et al., 2022; Bjørn et al., 2020b). Temporal and geographical scopes focus on the services provided to humans through the artefact developed. The lifecycle inventory should describe best the local or regional focus (national/sectorial) and time variability (Kara et al., 2023; Ryberg et al., 2018b).	• Scope and analysis perimeter challenges (*i.e.* which human service/system to consider?); • The functional unit is measured per unit of time (as an annual pressure on the environment) (Ryberg et al., 2018b); • Use multi-criteria assessment and specify characterization factors of the impact assessment (Bjørn et al., 2020a; Sala et al., 2020).	Specific characterization factors (PB-LCA): (Ryberg et al., 2020; Sala et al., 2020; Winther, 2023; Ryberg et al., 2018b)

process of these “visions” is variable. Those related to engineering are more integrated, while others are not yet (*e.g.* vision of long-term energy transition management or absolute sustainability). Consequently, our research work strives to be aligned to integrate environmental aspects of a technology upscaling in the design process. This objective can be included in the *Design for Sustainability* (DfS) framework of Ceschin and Gaziulusoy (2019). In this future-oriented paradigm, the integration of knowledge is a crucial stake which, on the one hand, may add a possible new designer's levers by considering phenomena that are currently considered at best as externalities. In contrast, it could drastically modify the organization and design process, which is never an easy point. Each upscaling archetype has a specific timescale, from several months or years for the laboratory to industrial scale (archetypes 1 and 2), to decades for transitioning (archetype 3), through spatial varying focus (archetype 4), oscillating between real-time up to several decades. The efforts to environmentally assess them must be strengthened, especially as the time horizon is distant. The duration and precise steps in the process design to apply methods for each archetype are not covered by this paper, partly due to the specificities of engineering sectors and technology development timescales. Further research could be held to answer the question, “*What is the necessary maturity to carry out a specific archetype of upscaling?*”, in the wake of the work of Buyle et al. (2019) for the first archetype and to complete the present guidelines (*cf.* Table 7).

More broadly, the issue of integration in design is part of the consideration of the consequences of choices that are increasingly outside the traditional scope of designers. Rae et al. (2020) for instance define researchers, planners, designers and consumers as stakeholders of an upscaling. All of these actors take part in the upscaling process. Indeed, the literature reviewed usually involves only a few of them, *e.g.* technology experts and engineers, joined recently by LCA practitioners (Tsoy et al., 2020). In that perspective, the upscaling archetypes could be mobilized throughout other types of literature to reflect the management of a technology upscaling in disciplines other than environmental assessment (*e.g.* engineering design, risk assessment, management or governance, *etc.*). Thus, a review process similar to that presented in this article could be conducted in further research to complete the UA-EF matrix with complementary assessment methodologies. Hackenhaar et al. (2024) provide a comprehensive framework, grouping environmental, social and economic indicators. This approach, mentioned as Life Cycle Sustainability Assessment (LCSA) could also be applied to the phenomenon of emerging technology upscaling. The present article would then only support the environmental part of a LCSA of the upscaling.

3.4.1. Literature review exhaustivity for LCA modes and perspectives for LCA practices

This article is not intended to be exhaustive regarding LCA approaches and their specificities. For instance, matrix UA-EF (see Fig. 1) presents some lack of structuring references for the fields of Chemistry or Bioengineering. With a view to completeness, these engineering fields could be completed with additional literature review, and new engineering fields could be integrated into the UA-EF matrix. More broadly, this paper focuses on currently available approaches in LCA literature for environmentally assessing a technology upscaling. In that regard, it presents a partial picture of the LCA literature between 2022 and 2024 on this topic. The accessibility of methodologies, their nominations and associated practices will require updating as they evolve rapidly (see prospective LCA tools and practices). In addition, LCA modes have different levels of maturity and new approaches could emerge, challenging the LCA practices. However, a characterization process similar to the one presented in this paper could be applied to these future LCA modes to delve into their operability to assess a technology upscaling. A cross-disciplinary vision would then be crucial to identify the technical upscaling models and databases available from engineering fields.



Engineering fields	Upsizing, scale-up *Archetype 1*	Mass-producing, Industrializing *Archetype 2*	Reaching a level, managing a deployment, *Archetype 3*	Up and down-zooming, Integrating a complex system *Archetype 4*	Down-limiting *Archetype 5*
Chemistry	● [Tsoy2020,Piccinno2016, Balgobin2021]	✕	✕	◆ [Menten2015]	✕
Waste treatment	● [ISO14034:2016, ETV-2011] [Villares2017, Gear2018]	✕	✕	● [Ventura2022]	✕
Energy	◆ [Arvidsson2018] [Gazbour2016 PhD]	◆ [INCER-ACV2021]	● [Sacchi2022] [Cassoret2022]	◆ [Cluzel2012, Sharma2021, van Beuzekom2021]	◆ [Abdoli2020, Riondet2023]
Food	◆ [Arzoumanidis2017] [Valsasina2017]	✕	◆ [Laratte2014]	◆ [Loiseau2018]	✕
Building sector & Urbanism	● [Buyle2019,Elefhteriou2022] [Hollberg2016, Sirvent2022]	✕	◆ [Yang2022]	◆ [Almeida2022, Almeida2020]	◆ [Bendahmane2022]
Electronics/ICTs	◆ [Ingwild Baudry2013 PhD] [Chordia2021]	◆ [Aichberger and Jungmeier2020] [Pirson and Bol2021]	◆ [Dandres2017]	◆ [Quisbert-Trujillo2020]	✕
Transport	✕	✕	● [Tang2023, Hung2022, Dirnaichner2022] [Spielmann2005]	◆ [Baltazar2022,François2017]	✕
Production Engineering (goods production)	✕	● [ISO14040:2006]	✕	● [Kjaer2018]	● [Ryberg2021, Bjørn2020, Bjørn2015] [Ryberg2018]
Bioengineering	✕	✕	✕	✕	✕
Nanoengineering	◆ [Arvidsson2018] [Hetherington2014]	✕	✕	✕	✕

Legend:
[Structuring references of the state of the art]
● Intersectoral or multidisciplinary reference
◆ Sectorial reference (specific to an engineering field or a case study
✕ Not emerged during the literature review or covered by an « intersectoral literature » reference
simplification rule
● + ◆ = ●

Fig. 1. The Matrix UA-EF, presenting the selected LCA literature depending on the archetype of upscaling and the engineering field.

3.4.2. *Towards environmental assessment practices encompassing the five upscaling archetypes*

As mentioned in section 2 "Formalism of upscaling archetypes", ideally, as many of the five upscaling archetypes should be assessed during the development of a product or technology. However, very few engineers or LCA practitioners can fully master the five upscaling archetypes or all the LCA modes presented with associated databases and models. Moreover, as shown in this paper, the degree of maturity for LCA methods and practices varies depending on the upscaling archetype.

Nevertheless, following an integrative posture, the cogitation should rather focus on the level of detail that engineers and designers (including LCA practitioners) need to target, to properly model a product and the related potential upscaling. Thus, the interpretation of the results must be made in light of sustainability goals and, therefore, document "go/no-go" strategies regarding the upscaling of an emerging technology. To an extent, documenting an existing or underdevelopment upscaling process could be a requirement to clarify the designer's decisions taken during the evolution process steps transparently, and justified by socio-technical and environmentally scientific-based assessment methods.

Finally, no structured methodology yet exists to aggregate several facets of the upscaling and help LCA practitioners in product design teams to orchestrate a LCA-based assessment concerning archetypes and identified prior upscaling goals. However, this research paper paves the way for such methodological outcomes, as well as tests of operational conditions to consolidate the development of emerging technology strategies from the environmental perspective.

4. Conclusions

In response to a *lack of clarity of available LCA modes for design team members* including LCA practitioners, this paper defines and characterises fifteen LCA "modes", including attributional, consequential, prospective, spatialized, dynamic, and absolute LCA. These LCA "modes" are categorised into classic or historical modes, temporal or geographical-focused approaches and hybrid or combined approaches depending on the diversity of case studies over different engineering fields, the availability of practical tools, software and guidelines and the age of the structuring references. The analysis points out the lack of adoption by design teams of some of these available LCA modes that would best fit to model a technology upscaling.

Then a critical review has been carried out to investigate which LCA modes best fit the technology upscaling aspects design teams are confronted with. This review matched the modelling requirements of the fifteen LCA modes to the objectives of the five technology upscaling archetypes commonly faced by designers: *scaling-up*, *from laboratory to industrial scale* (archetype 1), *mass-producing* or *industrializing* (archetype 2), *reaching a level of cumulated service* or *deploying a technology* (archetype 3), *integrating a complex system* (archetype 4), and *down-limiting* or *downscaling the planetary boundaries to the technology level* (archetype 5).

Multiple examples and case studies from various engineering fields (*e.g.* mobility, chemistry, energy, urbanism) are provided to illustrate the LCA practices associated with each archetype, together with synthetic guidelines for design team members about methodological requirements to model the archetype profiles, the main used LCA modes in literature and additional compatible ones, and LCA modelling recommendations. Available resources for specific LCA modes to go further on theoretical aspects, or for applications, are also provided.

This paper also reveals that LCA modes are not time-frozen categories. New frameworks and practices emerge depending on the needs for environmental assessments, that are particularly challenging in the case of the technology upscaling phenomenon (*e.g.* transition LCA or

AESA). To extend the applicability conditions of the given recommendations, the paper proposes LCA practitioners a graphical tool, to support them in finding the best available method to assess their upscaling case, *i.e.* regarding their respective engineering field (EF) and the targeted upscaling archetype (UA). This tool, called matrix (UA-EF) is intended to be updated to follow the evolutions of LCA mode categorization.

This paper finally addresses several challenges to extend the present methodological recommendations and move towards a systematic eco-design practice integration when dealing with technological system upscaling in the coming years.

CRediT authorship contribution statement

Lucas Riondet: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maud Rio:** Writing – review & editing, Supervision, Formal analysis. **Véronique Perrot-Bernardet:** Writing – review & editing, Visualization, Formal analysis. **Peggy Zwolinski:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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