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Summary of “Emerging technologies upscaling: a framework for matching LCA practices with upscaling archetypes.”

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This summary presents the content of the paper entitled “**Emerging technologies upscaling: a framework for matching LCA practices with upscaling archetypes**”, soon to be submitted to the journal **Sustainable Production and Consumption**.

The content of this paper is summarized in the following abstract, extended with an overview of the results and the references cited in this research.

Abstract

Purpose: Society asks engineers and designers, though sustainability targets, to be highly concerned with socio-technical and environmental consequences generated by the technology they develop or use in products. Regarding technology upscaling, we proposed in previous research five related archetypes in engineering: *upsizing*, *mass-producing*, *deploying*, *integrating a complex system*, and *down-limiting* (Riondet et al., 2022). However, these five facets of the upscaling of technology are not explicitly associated with LCA practices. More precisely, usual upscaling technology LCA guidelines mainly focus only on the two first archetypes. Clarifying LCA approaches available in the literature is, therefore, necessary to match LCA practices with the five upscaling archetypes.

Methods: This research paper is based on the characterization framework for upscaling assessment presented in previous research, completed by an LCA practices literature review in terms of addressed questions, theoretical basement, required expertise, and applicability issues. Then, this characterization of available LCA approaches and their applicability is confronted concerning a given goal of upscaling environmental assessments. The sorted references have been characterized in terms of “engineering field” to identify whether any guidelines they provide are generic or attached to a specific discipline or a type of product.

Results: This literature review produced three main results: first, fifteen LCA modes are characterized in terms of 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.

Conclusions: The proposed synthesis, guidelines and representation provide practical recommendations for LCA practitioners considering the upscaling of emerging technologies. This overview can be completed with currently adopted LCA practices in literature and companies. 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 LCA practitioners to transfer ongoing and future LCA developments and bring comprehensiveness to the environmental assessment of upscaling.

Keywords: Upscaling, Life Cycle Assessment modes, Emerging technologies, Environmental Assessment for Upscaling, Absolute sustainability.

The upscaling of an emerging technology can be decomposed into five archetypes depending on the declared goal, the studied object, and the stated scope (Riondet et al., 2022). Table 1, based on a literature review in Life Cycle Assessment (LCA) and ecodesign, identified 15 LCA modes suitable for environmentally assessing each archetype. These LCA modes are characterized by a definition, an associated addressed question, and specificities related to their usual scope.

Then, Table 2 is an extract of the proposed framework for matching these LCA modes with the upscaling archetypes. It presents methodological requirements, LCA modes usually applied, and recommendations concerning the “goal and scope” step of LCA. The spotlight is on the common features (i.e. interdisciplinary invariants) shared by technology upscaling from different sectors such as energy and chemistry.

Finally, Figure 1 represents a matrix of LCA practices in literature to match upscaling archetype treatments and engineering fields. Complementary to Table 2, Figure 1 pinpoints the disparity of treatments of upscaling archetypes for ten industrial sectors (chemistry, waste treatment, energy, food, building, electronics, transport, production engineering, bioengineering, and nanoengineering). Figure 1 matrix is built on an extended literature review of environmental assessments (LCA-based) per archetype of upscaling conducted from March 2021 to January 2024. The matrix displays the main references found that best characterize one or more engineering field(s) archetype assessment. The engineering fields cited in the first column may be extended or detailed in the future. The intersectoral references have the potential to cover several fields. Those references may therefore support designers from different sectors in assessing the archetype of upscaling they are dealing with.

Archetype 1 main references: (Buyle et al., 2019; “ISO14034 (2016) - Environmental management - Environmental technology verification (ETV),” 2016; Tsoy et al., 2020, p. 14; van der Giesen et al., 2020)

Archetype 2 main references: (“ISO 14040,” 2006)

Archetype 3 main references: (Cassoret et al., 2022; Hung et al., 2022; Sacchi et al., 2022; Tang et al., 2023)

Archetype 4 main references: (Kjaer et al., 2018; Ventura, 2022a)

Archetype 5 main references: (Bjørn et al., 2020; Hjalsted et al., 2021; Kara et al., 2023; Ryberg et al., 2020)

This matrix is not exhaustive and is intended to be completed over time and additional research work.

Definitions of LCA modes

Table 1 – Synthesis of fifteen LCA modes definitions and extract of associated characterization.

| LCA mode | Definition | Scope | |
|---------------------------------|---|---|--|
| | | Reference flows/ object in the foreground system | Temporal |
| Attributional | <ul style="list-style-type: none"> “The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle).” (Sonnemann et al., 2011). “Describe actual and/or forecasted specific and/or average life cycle of a studied object relative to its functional unit into a static background system” (Ventura, 2022a). | A product system (including the product’s life-cycle), usually product and value-chain-focused. | Future or past-oriented. |
| Consequential | <ul style="list-style-type: none"> “The consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product).” (Sonnemann et al., 2011). “Describe expected changes in response to possible decisions or to changes in demand for the functional unit into a dynamic background system” (Ventura, 2022a). | Product systems as they change due to a decision. (Multiple value chains). | Future-oriented. |
| Prospective | “Prospective LCA deals with technologies in the future, whereas retrospective studies deal with products in the past, regardless of other modelling approaches.” It is a scenario-based approach and can be motivated by predictive, exploratory, or normative perspectives (Arvidsson et al., 2018). | A product system, already mature or not. | Future-oriented: predictive, exploratory, normative. |
| Ex-ante | <p>A particular case of prospective LCA.</p> <ul style="list-style-type: none"> Describe the “environmental profile of an emerging technology on an industrial scale and use this information to steer further research efforts or compare an emerging technology with an incumbent technology on an industrial scale”. (Buyle et al., 2019). “Ex-ante is defined as before a product or technology is commercially deployed at scale and information and insights on the topic under assessment are not (yet) readily available.” (Tecchio et al., 2016; van der Giesen et al., 2020). | An emerging/early-stage/prototype technology or product system. Rarely including EoL. | Future-oriented: predictive, exploratory. |
| Parametrized | <p>A particular case of ex-ante LCA.</p> <p>“The basic concept of the parametric life cycle assessment (PLCA) approach is combining the principles of parameterization with a general LCA method. [...] it helps to identify the eco-design as well as the effective parameters based on their effects on the entire life cycle through sensitivity analysis and scenario analysis.” (Kamalakkannan and Kulatunga, 2021)</p> | A future or current emerging/early-stage technology or product system. | Future-oriented: predictive, exploratory. |
| Anticipatory | <ul style="list-style-type: none"> Describe future developments and “states that stakeholders should be included in the process to obtain more valuable results”. (van der Giesen et al., 2020). Based on anticipatory governance, “takes a forward-looking (not retrospective assessment) and engages stakeholders to inform critical modelling decisions and increase the credibility and relevance of results. <p>Anticipatory LCA can be defined as “non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology”. The aim is to identify the most relevant uncertainties and engaging research and development decision-makers to guide research and development and innovation” (Wender et al., 2014).</p> | An early-stage technology/ product system. | Future-oriented: exploratory, normative. |
| Ex-post/retrospective | Describe the environmental profile of a product after it had been “Commercially in use for extended periods of time and information and data are available from empirical experience” (van der Giesen et al., 2020). | A commercially existing product system. | Past-oriented. |
| Dynamic (Static) | <p>Dynamic LCA “assess the environmental impacts at different time steps, according to both different moments of emissions and kinetics of their effects inside the ecosphere.”; “The dynamic approach is justified by the fact that the environmental impact of a pulsed emission is certainly different from that of the same quantity emitted but spread over time” (Ventura, 2022b).</p> <p>Static : “LCIA considers that all of the elementary flows in a product’s life cycle are emitted at the same time” (Ventura, 2022b).</p> | A group of systems (fleet of products). | Future or past-oriented. |
| Regionalized (non-regionalized) | <p>Regionalization:</p> <ul style="list-style-type: none"> Describe the environmental impacts with “assigned geographical location” (Frischknecht et al., 2019). A term used to describe the representativeness of the processes and phenomena of a given region (Patouillard et al., 2018). | A product system (including the product’s life-cycle). | Future or past-oriented. |

| | | | |
|---|---|--|--------------------------|
| | <p>Spatial differentiation = regionalization of characterizing factors : site generic, site dependent and site specific (Potting and Hauschild, 2006).</p> <p>Non-regionalized: use aggregated/generic environmental impacts without spatial differentiation.</p> | | |
| Territorialized | <p>A particular case of regionalized LCA. Territorial LCAs have been divided into two types: type A and type B (Loiseau et al., 2018). Type A study a technology anchored in a known territory of which functions may vary according to that territory, and type B study one territory with all its functions and related activities. In both methods, the foreground system is inside the considered territory. [...]</p> <p>Territorial LCAs (type A) assess environmental impacts relatively to a unitary functional unit, but it may include several actors if these are located inside the considered territory.</p> <p>Territorial LCAs (type B) assess environmental impacts relatively to the total numbers of products that are produced and consumed inside the considered territory and thus all concerned actors inside this territory.” (Loiseau et al., 2018; Ventura, 2022a)</p> | <p>Type A: One product system produced in a territory.</p> <p>Type B: A territory (“several products produced or consumed in a territory” (Ventura, 2022a)).</p> | Future or past-oriented. |
| Spatialized | <p>Spatialization: act of assigning a location to something, e.g. a flow (Patouillard et al., 2018). A term used to describe the variability of processes and phenomena depending on geography.</p> | A large area system. | Past-oriented. |
| Transition (Hybrid) | <p>A particular case of hybrid LCA, using consequential and spatialized attributional LCA frameworks. “Describe expected changes in response to possible decisions or to changes generated by transition solutions into a dynamic background system” (Ventura, 2022a).</p> <p>Hybrid: use methodological elements of LCA (e.g. environmental indicators, models, characterization factors).</p> | Territory, including the human activities | Future-oriented. |
| Input Output (IO) | <p>A particular case of hybrid LCA: “Describe macroscale changes in response to possible decisions or changes in a given economic sector“ (Ventura, 2022a).</p> | An economic sector (multiple product systems or economic sectors). | Future or past-oriented. |
| Absolute/ Planetary-Boundary-based / Environmental Sustainability Assessment (AESA) | <p>A particular case of hybrid LCA, using the attributional LCA framework and completes it by comparing resulting impacts with an external list of environmental carrying capacities. It implies that for a given functional unit, it is possible that no technical solution is environmentally sustainable (Bjørn et al., 2020).</p> | Product system, organization, industrial or economic sector, human activities. | Future or past-oriented. |
| Relative | <p>Also identified as “classic” attributional LCA, meaning a relative assessment comparing products’ impacts between each other, and enabling to determine the “best technology” from the environmental point of view. (Bjørn et al., 2020a). Use methodological elements of LCA (e.g. environmental indicators, models, characterization factors).</p> | Product system. | Future or past-oriented. |

LCA practices for the environmental assessment of upscaling archetypes

Table 2 - Extract of the generic guidelines to practice LCA by upscaling archetype

| Upscaling archetype | Methodological requirements | Main used environmental assessment modes | Recommendations / clauses and constraints | |
|---|---|--|--|---|
| | | | Geographical/ Temporality | LCA specificities |
| Archetype 1 Scaling-up, upscaling | <ul style="list-style-type: none"> Define the specific technical expertise; ensure strong interactions between researchers and engineers; implement a future-oriented design. | <ul style="list-style-type: none"> Ex-ante LCA Simplified (attributional) or parametrized LCA | <ul style="list-style-type: none"> Mainly use phase focused, integrative life cycle. Studied: the product. Expertise's timescale is over months. | <ul style="list-style-type: none"> Foreground systemcaution and clear scenario of use phase in the comparative framework: "to which incumbent technology the prototype is compared?" ; data production/collection challenges; parametrization of the LCI with design parameters useful. |
| Archetype 2 Mass producing, industrializing | <ul style="list-style-type: none"> Follow an integrative and normative approach; develop techno-economic expertise; Identify the stakeholders of the value chain. | <ul style="list-style-type: none"> ISO Standards based LCA (attributional, consequential) Prospective dynamic LCA | <ul style="list-style-type: none"> Life cycle based, regionalized approach if possible over the value chain. Studied: The product system. Expertise's timescale is over years. | <ul style="list-style-type: none"> Industrial trend focus (e.g. favor dynamic LCI); End-of-life modelling challenges; data collection/extrapolation challenges. |
| Archetype 3 Reaching a level, deploying | <ul style="list-style-type: none"> Develop a market maturity and sectorial long-term expertise; characterize a cumulative technology's performance; Set up scenario expertise and specific data uncertainty management. | <ul style="list-style-type: none"> Prospective, attributional and dynamic LCA Integrated LCA - dynamic modelling | <ul style="list-style-type: none"> Large spatial/social scale (regional, national - sectorial or group of technology). Studied: The industry sector associated with the product. Phenomenon's timescale is over decades. Expertise's timescale is over months/years. | <ul style="list-style-type: none"> Background system accuracy challenges: rigorous scenario hypothesis is required; avoidance of temporal mismatch (i.e. favor dynamic LCA); Natural resources focus, and more broadly cumulative properties of the environmental impacts. |
| Archetype 4 Up and down-zooming, integrating a complex system | <ul style="list-style-type: none"> Mobilize system dynamic engineering with interoperability focus: adopt a culture of trade-offs from optimization modelling or socio-economic expertise: more broadly, develop a multidisciplinary approach. | <ul style="list-style-type: none"> Regionalized/spatialized LCA Consequential LCA Transition LCA Integrated LCA - Optimization modelling | <ul style="list-style-type: none"> Large geographical scale (the one of the complex system). Studied: the complex system interacting with the product. Spatial/geographical properties focus. Phenomenon's timescale is varying from real time to decades. | <ul style="list-style-type: none"> Analysis perimeter challenges (i.e. which territory to consider?); causal model to choose (if consequential approach) and more broadly interaction modelling challenges; data collection and management challenges. |
| Archetype 5 Down-limiting | <ul style="list-style-type: none"> Observe fair allocation methods (i.e. justice principles) and strictly define the service being studied: manage the data collection associated with the service (usually techno-economically based): monitor methodological development (for product) from (AESA: Indicators, weighting). | <ul style="list-style-type: none"> Absolute (attributional) LCA | <ul style="list-style-type: none"> Focused on services provided to humans, life cycle based on possible regional focus (national/sectorial). | <ul style="list-style-type: none"> 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); Specific characterization factors of the impact assessment. <p>Refer to (Ryberg et al., 2020, 2018).</p> |

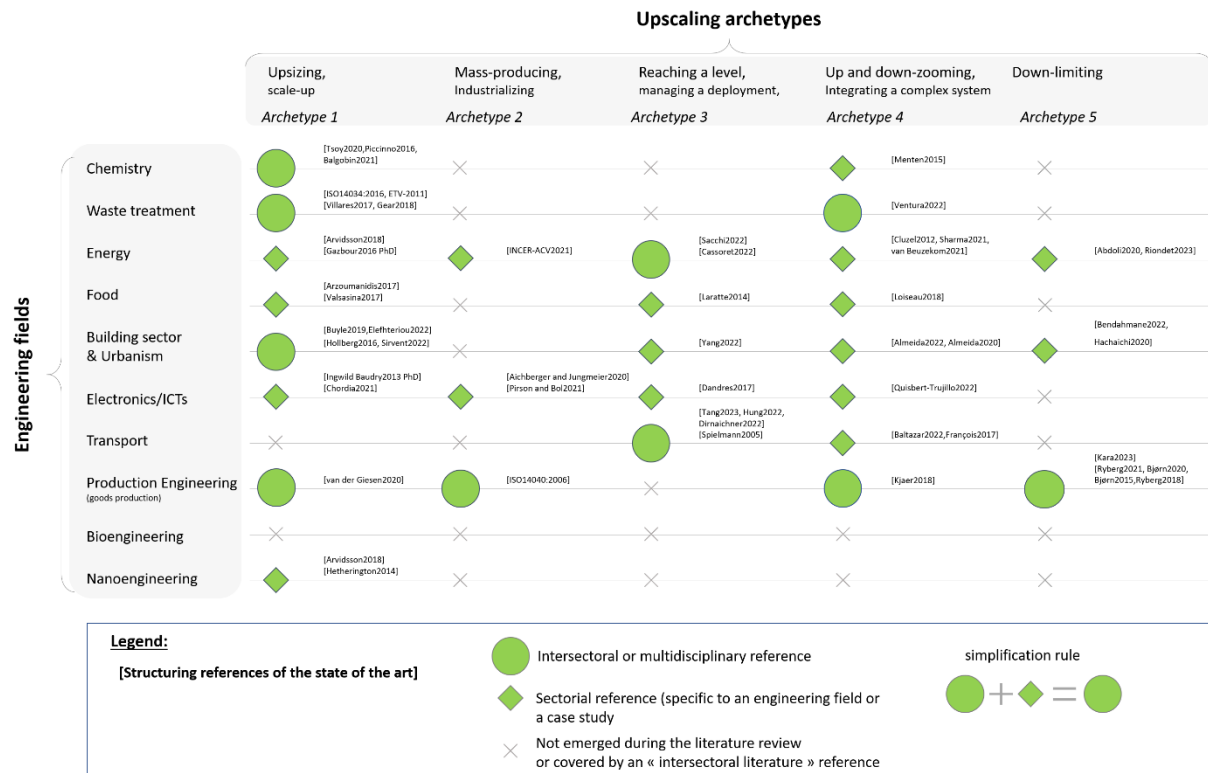


Figure 1- Visual summary of the disparity in treatment in the scientific literature for upscaling archetypes regarding the related engineering fields and for environmental assessment purposes.

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