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32nd CIRP Design Conference

# For an upscaling assessment integration in product design

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## Abstract

Reaching 2015 Paris Agreements means targeting zero-carbon emission worldwide societies by the second half of this century. It implies a wide-ranging transformation of all industries, supported by the deployment of numerous technologies at unprecedented industrial and time scales. This paper questions the definition of the concept of “upscaling”, often related to transitioning, used in different scientific communities without explicit definition shared across disciplines. A literature study is therefore carried out to investigate the characterizing factors defining “upscaling” as a transforming function applied to a studied system or a study boundary, and taking it from one state to another. The proposed analyzing framework enables us to establish five archetypes of upscaling. In addition, we itemize for each archetype, design methods used to consider and/or anticipate a “change of scale”, relying on techno-economic models or dealing with environmental aspects supported by partial or a system approach. Finally, the paper concludes on the current options helping product designers assess the environmental impact generated by its design choices in the context of upscaling.

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*Keywords:* Upscaling, Integrated design, Design to Environment, Planetary Boundaries, Sustainability

## 1. Introduction

Rockström et al., (2009) [1] complemented by Steffen et al., (2015) [2] defined the planetary boundaries, in which all mankind activities should be contained. Their work results in the definition of a *safe operating space* at a global scale based on the latest environmental science outcomes (including climate change). Thus, transitioning is a means to target tomorrow's activities into this space, including mitigate global warming below two degrees Celsius. As Geels et al., (2017) [3] note, “low-carbon transitions are goal-oriented or “purposive” in the sense of addressing the problem of climate change”. This dynamic has to be included into a systemic vision considering the interdependency between planetary boundaries. This implies a wide-ranging transformation of industrial processes and infrastructure, supported by the deployment of various technologies at unprecedented industrial space and time scales. Therefore, any designer working on such promising

technologies or processes should investigate the technology capacity in reinforcing the transition phenomenon or restricting it. To do so, designers have to assess the sustainable potential of a given technology or process. More precisely they have to question the relevance of the development of a product based on its early stage performances. Questioning this relevance with accuracy would then guarantee the sustainable targets to be reached with precision [4]. In that context, the term “upscaling” is increasingly used in the literature, but seems to cover several phenomena, methods or approaches more or less related to transitioning. In response, this article proposes (in section 2) a framework to explicitly characterize an upscaling in design discipline. Five recurrent archetypes of upscaling have been found in the literature study. Each case is documented, characterized, and associated with existing tools, preferably in design. Finally, section 8 discusses the accuracy of the theoretical framework to illustrate cumulative effects coming with upscaling, and the design methods to assess sustainability.

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## 2. Upscaling characterization

In this article, we define the upscaling as a transforming function applied to a studied system or a study boundary, and taking it from one state to another. According to the literature review, several characteristics are needed to fully distinguish one type of upscaling from another. As a consequence, we propose a theoretical framework to characterize an upscaling based on three interactive components, a subject, a scope and a goal (see Figure 1);

- The subject on which the upscaling is applied, can be a physical system as well as a service provided by a group of technology. It can also be virtual as the boundary of an analysis or a theoretical limit as discussed in section 5, 6 and 7.
- The scope includes two characteristics: the type and the boundary of the analysis used to carry an upscaling.
  - The type of scope can be techno-economic, environmental, social or of multiple kinds. It defines the “Domain(s)/Dimension(s)” on which the upscaling takes place, is represented and is studied. For instance, in the case of a technology upscaling, the scope is usually a techno-economic type and the domain in which the upscaling takes place is the technology Readiness level (TRL), productivity, and/or size of the system. The domain is thus a space linked to a performance or a design indicator.
  - The focus of the scope, or boundary, can be centered on the subject of the upscaling but not necessarily. It characterizes the interest core of the upscaling and can be seen as its perimeter. It can also be associated with a time specification by including one or several steps of the life of the subject, such as production or use.
- The goal of the upscaling sets the adequacy and relevance between the scope and the subject of the upscaling. It is based on performance indicators, for instance, increasing the maturity of a process, which is a techno-economic goal. Finally, the goal can be future-oriented (i.e prospective), retrospective or neither of those.

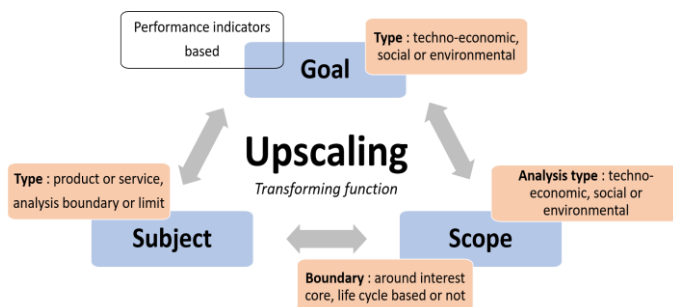


Figure 1. Scheme of the three components characterizing an “upscaling”

We define five types of upscaling, each one corresponding to a recurrent set of the triplet (subject, scope, goal) seen in the literature. These types are proper to one activity sector, or on the contrary common to different disciplines and professions.

To each definition corresponds several analysis methods and tools. Some are generic, effective and well developed, others are more discipline specific and/or in development. Moreover, according to the activity sector, the term “upscaling” is replaced by “scaling-up”, “scaling”, “sizing”, or related to “massification”, “deployment” and/or vocabulary about “level” in the system engineering science.

From now on, we will use the term “upscaling” and propose one or several synonymous in the titles of the sections dedicated to each of the five identified archetypes.

## 3. Upscaling – Upsizing or from laboratory to industrial scale – (a) type

The problematic of designing a process on an industrial scale in a laboratory context is well known in chemical industry and explicitly called “scale-up a process or a technology” [5, 6].

The usual goal is then to improve the maturity of a technology/process from the laboratory to industrial scale by increasing the quantity produced per unit of machine and time while minimizing cost. The related upscaling domain is associated with a production capacity indicator. This type of upscaling is assimilated to a design process, applied on a technology, based on an empirical step-by-step method. This process corresponds to successively validate the level 4,5,6 and 7 of the TRL scale. The upscaled system obtained confers larger performances than the initial laboratory system ones (i.e. the subject) as represented in Figure 2. The D plane refers to the domain of performance of one system unit. The boundary of the scope is represented by a red dashed box and the upscaling function by a blue arrow, from the subject until the result of the upscaling—so-called the system at an industrial scale. The diameter of a circle in domain D is correlated to the intensity of the technology’s performance.

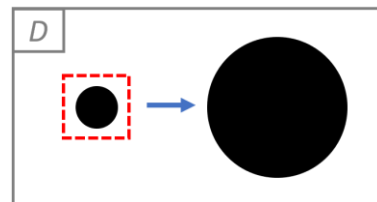


Figure 2. Scheme of the upscaling transformation (blue arrow) applied on a technology (left dot) in a domain of performance D (larger grey square), with a focus on the subject (red dashed square).

In Chemical Engineering and for processes, size is usually correlated to maturity/productivity [6] as represented in the upper part of the Figure 3. But this definition is also relevant for miniaturization phenomenon in electronic microchip industry or yield maximization in PV cells designing. In these cases, the aim is to increase performance per unit of system or surface. Thus, this first definition can be generalized as follows: upscaling a system corresponds to applying design methods to improve performance per unit of system. Note that this upscaling is observed even after reaching the industrialization state (TRL 9 scale). Some technologies, such as wind power systems, have an upsizing trend since they were first commercialized in the 1980s (cf. the lower part of the Figure 3 as an illustration of the type (a) upscaling). Finally, “giga-

factory” could also be seen as a result of an upscaling applied on a classic size plant.

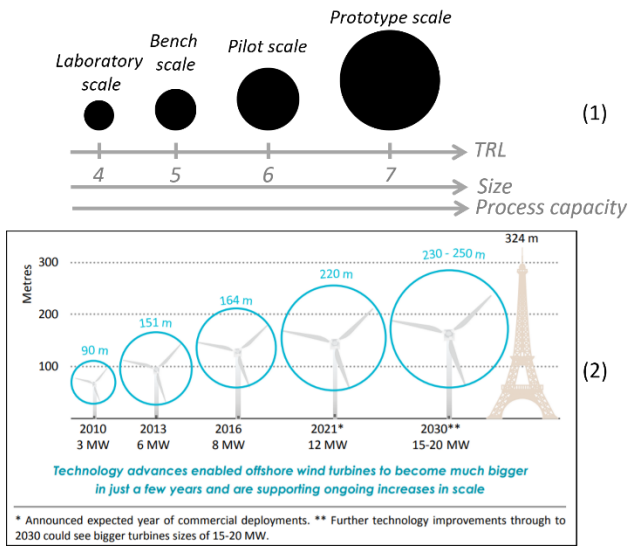


Figure 3. Examples in literature of upscaling/upsizing: (1) scheme inspired from Lopez Vizcaino et al., 2019 [6], (2) picture extracted from IEA report [7]

**Analysis tools and methods**

The type (a) upscaling is usually managed with models such as empirical power laws (so-called *scale laws*) [8] and guidelines. These guidelines are based on Design of Experiments (DoE) methods, implying the collaboration between designers of the early-stage technology, engineers, and manufacturers to ensure an operating space of the upscaling, and to guarantee the validity of the models’ domain [7,8,9]. Therefore, upscaling is limited by physical or techno-economic limits: heat evacuation, mechanical strength (e.g.: chemical vessel size) or specific limits, for instance the Shockley-Queisser limit for yield of a P-N cell in photovoltaic science. These limits can be expressed through a maximum diameter of the right circle in Figure 2.

Balgobin and Evrard (2020) [10] propose a method to implement Life Cycle Assessment at the early design stage to anticipate the potential environmental impacts of a (a) type upscaled system. The main issue being, for the chemical industry, the nonexistence of thermodynamic models to forecast characteristics of the industrial system such as its chemical yield. This uncertainty complexity the prospective analysis and prevent designers from using linear extrapolation of environmental impacts related to the upscaled technology.

**4. Upscaling – Industrialization, massification – (b) type**

In this section, upscaling relates to design methods application aiming to manage and anticipate the massive production of technology. With the (a) type, this type of upscaling is the most common meaning of the term. Its goal can be equated by aiming for the level 9 of the TRL scale. The scope is usually techno-economic, and the focus is made on the performance’s subject. This archetype of upscaling refers to the massive production of the study object (i.e the initial technology) as illustrated in Figure 4 with similar convention as for Figure 2.

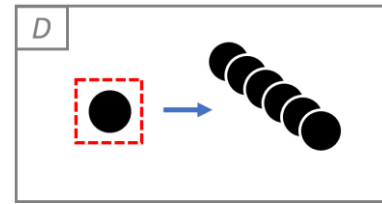


Figure 4. Scheme of the upscaling transformation (blue arrow) applied on a technology (left dot) in a domain of performance D (larger grey square) with a specific focus on the initial technology (red dashed square).

This type of upscaling expresses the different design methods applied to produce massive amounts with the same technology, constrained with techno-economic considerations; any industrialized product may contribute in its illustration.

**Analysis tools and methods**

The (b) type of upscaling is managed by classic Life Cycle Engineering design methods: Design for Manufacturing, as well as any additional methods enabling designers to integrate all life cycle steps of a product during the design phase. We will refer to these methods as the Design for X methods. For an exhaustive review, refer to Hauschild et al., (2020) [11]. In addition, the economy of scale models and empirical laws (so-called learning curves) are also tools to observe and possibly anticipate a (b) type upscaling. Such models and laws are commonly used in PV industry for instance to estimate future midterm trends of performances per system unit [9,12]. This category of techno-economic tools could be applied on environmental issues as implemented by Gwehenberger et al., (2007) [13] with the terms “ecology of scale”. This approach does not, however, hinge on systemic and multicriteria analysis in contrast to Life Cycle Engineering methods. This is a serious limit preventing systemic environmental considerations.

LCE methods argued by Hauschild et al. [11] are particularly adapted to this upscaling archetype. Life Cycle Assessments conducted attribute the environmental impacts of a product, from the extraction of its raw materials to its end-of-life treatments (from cradle to grave). These assessments are mainly retrospective but outcomes have been raised in recent years about the prospective LCA method, also called anticipative or ex-ante LCA [14,15].

Finally, the (a) and (b) archetypes of upscaling implicitly use a boundary analysis focused on the product (cf. red dashed line in Figure 2 and Figure 4).

**5. Upscaling – Deploying, reaching a level – (c) type**

In contrast to the two previous definitions, the upscaling presented in this section is not a design method, and is not explicitly called an upscaling. However, it is carried by researchers in the energy sector and echoes with transition definition by its goal-oriented characteristic. This third type of upscaling seems similar to a classic industrialization, but its difference relies on the boundary of the analysis, as represented in Figure 5. It illustrates that, in (c) type of upscaling, focus is made on the cumulated performance provided by the

multiplicity of the industrialized technology (cf. similar black dots, boxed with red dashed square in the left part of the figure) or variations of technology (cf. variable size dots in the right part of the figure). The explicit goal of this upscaling also differs from the (b) type. As this upscaling targets the sustainability of the entire activity sector considered, or at least mitigating its contribution to climate change. For instance, photovoltaic and generally renewable energy sectors intend to reach an installed power capacity to respond to a national or global demand (e.g. Verlinden (2020) [16] or IRENA reports [17]). In that context, contrary to the (b) archetype of upscaling, the industrialization is not an aim, but a means to be intensified, and market equilibrium is not reached until sustainability, if existing, happen.

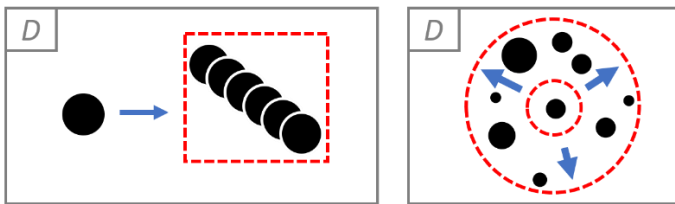


Figure 5. Scheme of the upscaling transformation (blue arrows) applied on a technology in a domain of performance D. (c) upscaling definition referring to the deployment of a technology to reach a level of cumulated performance.

### Analysis tools and methods

This type of upscaling is usually illustrated in technology deployment strategies linked with decarbonization, such as IRENA and IEA publications for photovoltaic or wind power deployments [17,7]. These reports intend to document the feasibility of such future deployments considering for instance raw materials requirements or surface consumption in addition to financial means. In that respect, Material Flow Analysis (MFA) methods are coupled with scenarios and Sankey diagrams can be used to illustrate cumulative effects as raw material criticality [18]. These approaches are sometimes associated with learning curves and systemic modeling of the value chain of the technology.

It should be noted that this upscaling transformation relies, more than others, on the foresight approach. This particularity bears on the fact that so far, there are no examples of successful country-wide transitions. It therefore requires some strong developments in sustainability prospective methods. A point for reflection could be guidelines to merge MFA with LCA to adapt to the goal and scope of the upscaling.

### 6. Upscaling – Up and down zooming – (d) type

For the present type of upscaling, it is necessary to introduce the concept of complex systems, defined by F. Cluzel [19], as a large geographical scale system including several interacting subsystems. One of the main difficulties to study a complex system is to justify the boundary analysis of the assessment. The building and energy sectors are dealing, with different vocabulary, with the common concept of up and down zooming on a studied system that is part of a larger one. In system engineering, the term “Multi-level analysis” is frequently used

to appoint this design thinking. Figure 6 presents a complex system as a group of different technologies with different functions (dots with different colors), interacting (lines between dots). The goal of this upscaling is usually to design or study the entire system or one of its subsystems from a techno-economic and sometimes from the social and environmental point of view. The focus is consequently made on both a subsystem and the system as a whole. The analysis boundary, or the field of study, is considered as the subject of the upscaling (cf. blue two-way arrows). In the Figure 6 upscaling is two-way conducted, from a subsystem to the whole and inversely. There is no starting “state” neither a temporal evolution in this type of upscaling. This archetype rather addresses a change of paradigm in the design method used. In that context, design should be based on systemic approaches considering any system as part of a macro-system, called complex system.

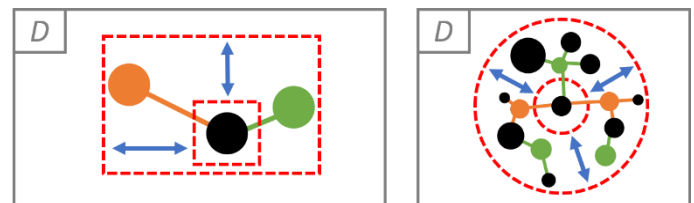


Figure 6. Scheme of the upscaling transformation (blue arrow) applied on the analysis boundary in a domain of performance D. Focus is made on interactions (coloured lines) between different technologies (represented in different colours).

In building and urbanism sectors, following the “urban metabolism” theory of Dijkstra et al., 2017 [20], complex systems can be cities, districts as well as interacting industries. In the energy sector, power plants, transporting and distributive systems and storage systems interact and form an energy system, sometimes named *hybrid energy system* [21].

### Analysis tools and methods

This type of upscaling requires network system modeling approaches to deal with complex system issues. Concerning the building sector, methodological developments are promoted by Beloin-Saint-Pierre et al., (2017) [22]. For the moment, however, no methodological consensus has been reached. In the energy and water distribution contexts, mathematical optimization is more and more implemented for dimensioning systems [23,24]. These methodologies require a specific mathematical expertise but software solutions are developed or under development in support to integrate them in design.

Kim et al., (2020) [25] present perspectives for eco-design based on a retrospective literature review adapted to multi-level analysis and environmental assessment. The main stake being that LCA applied to complex systems requires large-scale modeling and consequently a huge amount of data. In parallel, a consequential LCA approach has been developed on a national scale to consider techno-economic interactions between systems and resulting environmental impacts [26]. This latest example should be, however, adapted to design practice.

### 7. Downscaling – Down-limiting – (e) type

This type of transforming function comes from the idea of applying absolute environmental limits (global or local) such as planetary boundaries to define a safe operating space. Implementing this space in the design process would lead, as a goal, to an “absolute” sustainability as mentioned by Hauschild et al., (2020) [11]. Figure 7 illustrates this concept. The absolute limit is represented by the edges of the domain D. The upscaling is expressed through the transfer of this limit (cf. blue arrows) at the scale of a complex system (1) such as the energy sector; in a subsystem scale (2) or at a unit technology scale (3). Focus is made on the studied system or service provided by a macro or subsystem (cf. red dashed squares). This change of scale archetype can be interpreted as a local expression (black squares) of a limit that should not be crossed to stay in absolute terms and at macro/global scale in a safe operating space.

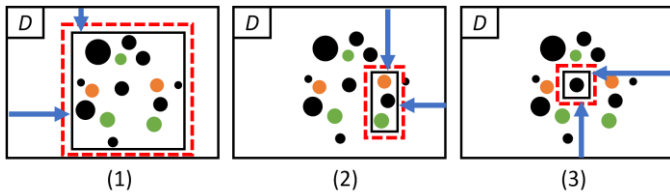


Figure 7. Scheme of the downscaling/upscaling transformation (blue arrows) applied to the limit of a domain of performance D (larger black square) and a complex system (case 1), a subsystem (case 2) or a specific technology/service (case 3).

### Analysis tools and methods

Ryberg et al., (2020) [27] present a review of applied methods to “downscaling the planetary boundaries” in the literature. These methods follow distributive justice theories and express ways to share (or not) limited resources, including CO2 emissions as carbon budgets.

Complementary to these methods, Bjorn et al., (2020) [28] set out a methodological framework to apply environmental boundaries in Life Cycle Assessment and to the process level.

### 8. Discussion

The provided framework has the following added value for product designers: first, it allows to assimilate a phenomenon to one of the five archetypes identified in this article, or to create a new one by characterizing a set of the triplet (subject, scope, goal). Second, it is possible to combine archetypes as elementary functions to describe multiple dynamic phenomena that compose a transition. For instance, where (a) type is focused on the initial subject, (c) type happens later in the process of industrialization, and deals with its macro effects. Therefore, the combination of both, represented in **Figure 8**, may help to study cumulative effects such as criticality of raw materials or rebound effect [29]. In our case, the rebound effect refers to the discrepancy between two effects: on the one hand the increase of technology’s efficiency results in the reduction of resource’s consumption per system. On the other hand, total consumption is still rising because of massification and

deployment of the technology. This second dynamic is sometimes driven by unpredicted usages. These two dynamics happen successively and are usually studied separately with different tools, by different professions. Thus, representing them as a whole could facilitate the identification of rebound effect phenomena during the design process.

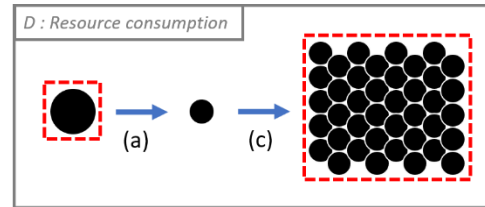


Figure 8. Illustration of composition of two types of upscaling, (a) type and (c) type, resulting in a rebound effect in resource consumption domain, aiming to an integrative design with a focus on cumulated effects.

Finally, this framework enables us to represent what could be a design method in the absolute sustainability paradigm [11] [30]: on the one hand, by analyzing an upscaling (for instance (a) type) from several perspectives illustrated by economic, social and environmental domains in the left part of Figure 9. Note that this upsizing can be assimilated to a downsizing in another domain than the techno-economic one usually chosen.

On the other hand, this framework promotes a design by constraints of different natures (i.e. economic, social and environmental). This supports the creation of a sustainable “solution space” for designers. An illustration of this design by constraint method is proposed in the right part of Figure 9: a techno-environmental limit is built in the productivity domain (cf. green square) to lessen the result of an upsizing transformation (1). To do so, a carbon budget (cf. black square in GHG emissions domain) would be produced by a down-limiting (2), as a local expression of the absolute limit in the GHG emissions domain. Then this local limit would be transferred to the productivity domain as a techno-environmental limit.

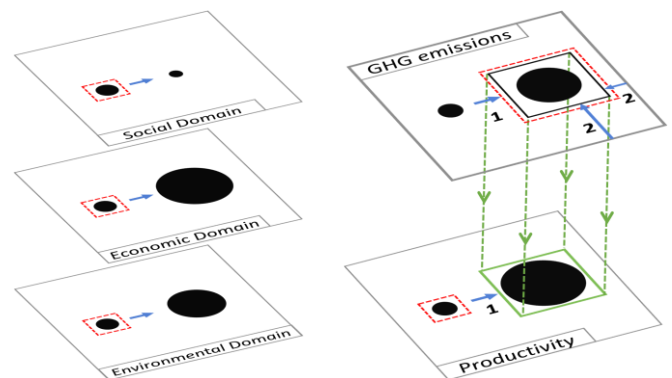


Figure 9. Scheme of a multi-domain representation of an upsizing in several domains (left) and use of a down-limiting transformation (2) to define a productivity operating space (green square) for an upsizing (1), limited by environmental absolute limits transfer (right).

Lastly, and concerning the limits, this framework does not enable the clarification of the scope in terms of life cycle phase. In other words, a picture for studying a system in its

manufacturing phase or in its whole life seems identical. There is also no distinction of time amplitude associated to each upscaling archetype.

## 9. Conclusion

This article proposes a theoretical framework characterizing the upscaling as a transforming function. Five archetypes of upscaling have been identified in the conducted literature review. Type (a) and (b) could be defined as current integrative design methods, type (c) and (d) as systemic analysis methods and type (e) as a method in progress to deal with absolute sustainability in design. This study shows the diversity of disciplines and sectors communications in current years, historically techno-economic oriented, that intend to integrate environmental aspects in the design process. It has been noted that Life Cycle Assessment is implemented in each archetype. These application cases open methodological development opportunities, particularly for prospective and consequential LCA. The proposed framework can be used to combine archetypes together helping designers to identify potential rebound effects that would result from their solutions after being upscaled. Finally, this framework offers a way to illustrate a solution space during the design process in an absolute sustainability thinking.

## Acknowledgements

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