REGENERATIVE PRODUCT DESIGN: A LITERATURE REVIEW IN AN EMERGING FIELD

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ABSTRACT
Regenerative practices have evolved over time from the paradigms of sustainability and regenerative sustainability. This literature review focus on guides and methods in the emerging field of regenerative product design and regenerative materials. The study identified a knowledge gap and a need for methodologies to bridge the higher system levels of socio-ecological processes and regenerative architecture with the product and material levels. The study presents 10 common denominators for regenerative design processes found in architecture and socio-ecological introduces a first attempt at classifying regenerative materials. The study's findings indicate a clear need to develop strategies and methods that product designers can implement in their future professional practices and design educations.

Keywords: Regenerative development, bio-based materials, regenerative materials, regenerative sustainable behaviour, product design

1 INTRODUCTION
Regenerative practices have evolved over time from the paradigms of sustainability and regenerative sustainability. Central to circular and regenerative economies and cultures are the prevention of the depletion of raw materials and the continued undermining of ecosystems [1]. The key difference between sustainable and regenerative design is the holistic worldview fundamental to regenerative practices and going from "recycle, reduce and reuse" to "restore, renew and replenish." The term regenerative refers to a process that repairs, recreates, or revitalises its own sources of energy, air, water, or any other matter [2], [3]. Regenerative design sets an ecological benchmark that is pre-industrial and net positive in impact [4], [5], [6]. Mang & Reed [6], supported by du Plessis [7], suggest a transition towards a new worldview as necessary, from a mechanical view towards an ecological one. Accommodating a transition towards a regenerative future entails understanding regenerative practices, not only on a higher system level but also the materials in a product and how they affect the user's behaviour and interaction with the product. Regenerative systems can be defined in different scales depending on the temporal and spatial framing; the most common are global, regional and local. Architects have been working with regenerative buildings for the last decade and have developed theoretical framing, methods and assessment tools. This literature review aims to map out existing definitions and methods on an emerging level, the product and material level.

Our world is in transition. We no longer live in an era of change but are witnessing the change of an era [8].

2 METHOD
The initial literature study was conducted using backwards and forward snowballing [9] as a systematic search strategy. Snowballing was applied as it dramatically reduces the amount of noise in database searches, mainly when the keywords for searching include general terms (e.g. design and material). Searches were conducted through Google Scholar, Science Direct, Lib Search and ResearchGate. The primary keywords used were regenerative material, regenerative design, regenerative sustainability, regenerative systems and the second set of searches combined with manufacturing, framework, methods, sustainable behaviour, design for behavioural change, and sustainable future. This reduced the initial search result of 40 601 papers to 182 papers; of these, 94 papers were selected as primary sources.
A comparative study [11] of the literature and electronic sources was conducted. In the first step, the commonalities and distinct differences of the collected definitions and methods were noted. The material

was then coded top-down and bottom-up, resulting in 10 main categories (see Table 1). Each category was summarised in short descriptions.

3 REGENERATIVE GUIDES & METHODS

In the initial review, no guides or methods for regenerative product design were found, so the review was expanded to architecture and social-ecological systems. Regenerative development as a scientifically grounded approach acknowledges the principles of interdisciplinarity and methodologies within systems thinking, which recognises the interdependencies and feedback loops among ecological, social, and economic systems [12]. Working within a field of high complexity, in the cross-section between disciplines and with different expertise and skillsets required in a regenerative development process, requires a strategy that breaks down the complexity into manageable parts. Most of the reviewed guides and methods offered around 10 guiding principles or steps, and Table 1 lists the most common denominators with short descriptions.

Table 1. Common denominators identified in reviewed regenerative guides and methods

Biomaterials	Defined as materials made of 100% organic raw material from a renewable resource and 100% compostable.
Renewable resources	Must derive from regenerative non-polluting feedstocks that do not compete with food or feed production.
Utilising waste streams as resources	Organic waste streams from food industry, agriculture, and forestry. (Can also in the future be non-organic waste processed with biotechnology e.g. mycelium and bacteria into nutrients.)
Renewable energy	Non fossil fuelled derived energy with net-zero impact.
Active & passive Energy	Low energy consumption in manufacturing, use face and end of life/ new life. In some cases, contributes to lower energy use in its application during use face.
Regenerative impact	Actively restore and revitalise ecosystems and communities for positive and lasting change.
Ecological Footprint	The extraction and harvesting of the raw materials do not negatively impact the region's habitats and ecosystems or contribute to deforestation.
Support thriving communities	Stakeholders are acting in an ethical way and contributing to regenerative systemic change in local and global communities.
Promote wellness	Designing ecosystems that integrate natural and human living systems that contribute to and sustain health and wellness for both.
Sequestration, neutralisation, & elimination	Materials which directly contribute to the sequestration, neutralisation, and elimination of GHGs. Renewable materials that contain CO2 contribute to an increase in sequestered carbon. Low embodied carbon in the manufacturing process, transport, use face and embodied in the material itself.

In architecture, the Building Information Modelling (BIM) tool is a digital representation of physical and functional characteristics of a facility; it is often used in combination with Life Cycle Assessment (LCA), which is also commonly used in product design. When analysing the BIM tool combined with an LCA tool through integrated methods, it became clear that the limitation of this approach is that BIM-LCA tools require a wide range of input data that usually are not present in the early stages of development; thereby, the regenerative design process loses momentum, and do not provide a holistic overview. Supporting methods are needed to provide a richer understanding of the regenerative aspects during the design process. Several of the reviewed architectural guides and methods are challenged when it comes to combining quantitative measures, e.g. Regenerative Contribution Units, with qualitative ones, e.g. Sustainable Development Goals and calls for further development. Integrating data science and artificial intelligence (AI) as tools can contribute to accelerate the transition towards the regenerative approach [32]. Examples of regenerative design guides for system development are The Regenerative Lens and The Regenerative Evaluation tool, which try to break down complex systems into comprehensible parts for novices and communities. The Regenerative Lens [13] is a conceptual cross-disciplinary regenerative systems framework that can be used as a reflexive tool that can be applied as an orienting tool to guide practices for those unfamiliar with regenerative development and to conceptualise regenerative systems. It focuses mainly on regenerative social-ecological systems and identifies five key parameters to achieve regenerative outcomes (1) embodied ecological worldview (2) mutualistic interactions (3) high diversity (4) agency, and (5) reflexivity. The Regenerative Evaluation tool [14] provides general guidance for thinking and decision-making that identifies regenerative development principles and core characteristics of regenerative living systems. It is a qualitative evaluation tool for reflection and action, suitable for co-creation in a community. The review found clear dominance of assessment methods and identified a profound lack of generative design methods. The only method found that directly dealt with the design perspective was the framework *Designing from a place* [15]. It builds on theories and extensive practical experience from developing regenerative architecture and can be applied in product design projects with a few adjustments. The Regenerative Design and Development method identify four principles (1) co-evolving mutualism (2) place-sourced potential (3) regenerative capability, and (4) vocation of place (fig.1).

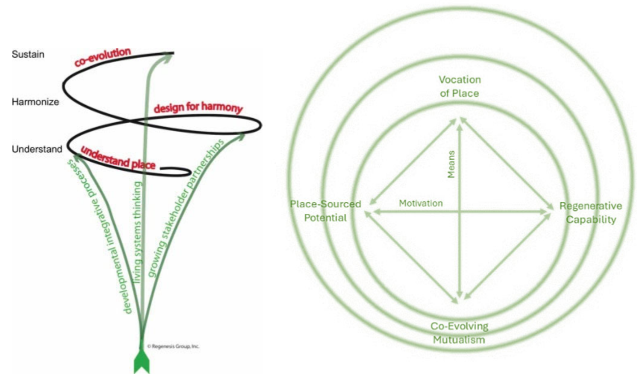

Figure 1. The overall framework guides and structures the approach to the Regenerative Design and Development method [15]

4 REGENERATIVE MATERIALS

Regenerative materials are materials that play an active role in restoring and regenerating natural resources, ecosystems, and biodiversity. A material cannot be regenerative in isolation; its potential to regenerate depends on the infrastructure, communities, and ecosystems within which it exists. Materials should preferably be built on circularity at three levels: raw materials, recyclability, and biodegradability to allow for cascading [16]. Building a regenerative materials system entails designing compostable materials that return biological nutrients to soils at the end of life. Biopolymers such as chitin, sodium alginate, carrageenan, keratin, gelatine, and whey protein have the potential to support crops' nutrient needs as compost in regenerative agriculture systems. They can also add beneficial carbon and organic matter needed by plants and soil microbes back into soils and enhance their ability to sequester carbon [17]. The U.K.-based company Biohm was one of the first companies to develop models for regenerative material development. They have divided the development into four categories (1) regenerative decarbonisation (2) organic waste streams as material resource (3) mycelium technology (4) bioremediation with mycelium and bacteria [18]. Another example of implementing regenerative practices is The Regenerative Cotton Standard (RCS) certification by The Aid by Trade Foundation that aims to help smallholder farmers be more resilient to the effects of climate change and offer companies a solution to future-proof the production of cotton as an essential raw material for their textiles [19]. RCS targets the entire production system to achieve these aims rather than only the cotton itself.

4.1 Agricultural resources as material resource

Agricultural resources for regenerative material development must derive from regenerative, non-polluting feedstocks that do not compete with food or feed production [16] [20] [21] [22]. Agricultural residues and by-products are a viable feedstock option for biomaterials production if the sustainability of underlying agricultural systems is considered sustainable. In regenerative farming the use of cover crops offers lignocellulose biomass as well as the residues from the main crop and buffer zone pruning [20] [22]. The other category of agricultural resources is biomaterial feedstocks such as cotton, nettles, hemp, natural latex, cork, and wool that can be sourced from polycultures or livestock-integrating regenerative agroecosystems. An overlooked regenerative outcome is using the biomaterials as soil nutrients when it is no longer possible to reuse the material [20]. An emerging category is ocean farming, which, besides providing 'ecosystem services,' regenerative ocean farms can also boost marine biodiversity. The farms' assemblies mimic the vertical structure of an ocean reef, providing layers of different habitats for a wide diversity of marine species [16]. Raw materials that are sourced from regenerative ocean farms are, e.g. seaweed, algae, eelgrass, and mussels (used for cleaning the water and not suitable for eating).

4.2 Organic waste streams as material resource

Using secondary biomass sources such as industrial byproducts and post-consumer food waste reduces the demand for primary crops, reducing stress on soils, land use, and biodiversity [21]. The food industry provides a constant flow of residues from processing food stock before reaching consumers. The residues can sometimes be processed in two steps, first for animal feedstock, and then the final residues become biomaterials. Biopolymers such as PHA can be derived by bacteria from food waste and qualify as regenerative biopolymers as it is compostable and a part of the biological cycle [17]. PLA, on the other hand, is only compostable in industrial compost in a controlled environment and only qualifies as sustainable, not regenerative, material, as it contributes to microplastics if it ends up in nature.

4.3 Forestry resources as a material resource

Regenerative agroforestry practices improve and increase ecosystem services at the local and landscape level, capturing carbon, improving biodiversity, controlling erosion, and improving water resource management [23]. Residues from regenerative forestry and wood biomass are important material resources and have been throughout our history. With new processing methods, both biochemically and mechanically, the wood biomass offers lignin, cellulose, hemicellulose, oils, bark extractives, and derivates combined into new materials having regenerative potential and replacing fossil-based materials.

4.4 Living materials

When living entities such as mycelium, algae, yeast, and bacteria were introduced to the intersection of biology and design, it created a new landscape, bio fabrication of materials, artefacts, and architectural systems. Co-designing with nature entails manufacturing under life-friendly conditions, in water, at room temperature, without harsh chemicals or high pressures. Bioremediation might offer great potential in the future with strains of mycelium that can consume plastics, e.g. PE, PU, PET, and PS, into sugars, benign hydrocarbons, and carbon dioxide. The sugars and hydrocarbons are consumed by the mycelium and the carbon dioxide is transformed into oxygen using photosynthesising organisms [18].

5 SUSTAINABLE BEHAVIOURS

In a regenerative future, good intentions must be transformed into responsible behaviour. The first step is recognising that a sustainable future needs to transform physical and social infrastructures [24]. If we do not address intangibles like motivation, will and behaviour, the tangible solutions that seem so obvious will continue to elude us. The users' behaviour becomes an essential part of the system by facilitating changed perceptions and behaviours from the current take-make-dispose culture towards environmental and circular user behaviours, e.g. care, maintenance and emotional bonds with a product as the first step towards regenerative practices. Design for behavioural change provides methods that identify the driver for users and strategies to encourage desirable environmental and circular behaviours. Increasing environmental awareness amongst users has shown to be an efficient strategy [25] [26].

6 DISCUSSIONS

According to Wahl [5], reconnecting with nature is a precondition to achieving a regenerative global and local system. The regenerative architectural framework *Designing from Place,* developed by Mang and Reed [15], states that it demands a radical change in the designer's mindset and stresses the importance of how designers interpret the user's role in a built environment. In literature, regenerative materials are, in general, defined as (1) can be sourced sustainably, (2) used efficiently, and (3) recycled or repurposed at the end of their life cycle [5]. This definition needs to be expanded to include the following parameters: energy, water, biodiversity, health, and equity to be able to provide a holistic view. In material design, there are emerging approaches, e.g. bio-fabrication [27], livingness in materials

[28], DIY materials [29], organic waste streams as material resources [30], and established methods like Material Driven Design [31], that could be useful in regenerative design practices as they interconnect the design of the material and the product in an early stage of the design process. Mang & Reed [15] state that each time design practitioners select a particular set of methods and techniques to address a design problem or measure and evaluate the solution, they implicitly or explicitly express what they believe is the ethically appropriate way to work based on their worldview. This literature review identified skills such as Eco literacy, facilitating participatory and co-creative processes, psychological literacy, and cultural sensitivity are needed when working with regenerative development processes as a designer.

7 CONCLUSION & FINAL REMARKS

This literature review in the emerging field of regenerative product design has identified a need to develop guides and methods supporting the design process of regenerative products made of regenerative materials. Literature provides rich theory, case studies and guidance for, e.g., the selection of construction systems, measurable performance indicators and thresholds when developing regenerative architecture. The identified common denominators for guidelines and methods in the regenerative development of architecture and social-ecological systems offer a foundation for further development of methods in the field of product design and design education. The study concludes that a product or material cannot be regenerative in isolation; its potential to regenerate depends on the infrastructure, communities, and ecosystems within which it exists. To be considered a regenerative material, the raw material must come from a regenerative source and be processed in a sustainable and circular manner. The study identified four categories of regenerative material resources: agricultural resources, organic waste streams, forestry resources, and living materials. A series of existing methods and frameworks from materials design have been suggested as inspiration or for integration in the future development of regenerative design processes. Further studies will be made to explore the dynamics and different elements of existing regenerative design methods from surrounding fields as a step towards developing a regenerative product design process. This paper has been written in collaboration between a doctoral student (main author), two BA design students and a product designer.

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