THE ROLE OF THE BUILT ENVIRONMENT IN THE REGENERATIVE TRANSITION

Implementation of the exergy analysis and ecosystem services through the design according to the Life's Principles

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Date: 06/12/23

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Abstract

This research focuses on the environmental impact of cities, proposing a biomimetic approach for urban development. Cities can be redesigned to have a positive impact on the environment if their identity is challenged. For that, deeper understanding of ecosystems is needed. This study advocates for recognizing the real value of ecosystem services (ES), often overlooked in urban planning, by introducing the concept of exergy in the ES framework. Besides, it also highlights the need of applying regenerative design in urban structures, drawing inspiration from the Wheel of Life's Principles. Lastly, it concludes that cities must become autopoietic, fostering connectivity and relying on regenerative design principles. The integration of ecosystems in the built environment, mirroring life system processes, is proposed to efficiently distribute exergy in urban metabolism and address climate change.

Layman's summary

Growth of cities generate both challenges and opportunities. Despite their advancements, they operate in ways that harm the environment and, in turn, affect the people who live in them. In this research, we take a closer look at how cities function from a biomimetic perspective, identifying what changes are needed to make cities thrive while having a positive contribution to the world around them.

Firstly, acknowledging the real value of ecosystem services (ES) is key to integrate ecosystems in the built environment. ES are the benefits derived from nature, like clean air and water. Surprisingly, these services are often overlooked or misunderstood. The value of ES can be better recognized by applying the concept of exergy in the ES framework. Exergy is defined as the maximum useful work that can be extracted from a system, practical to identify inefficiencies in energy converting processes. Through exergy analysis, we can better understand the impact of ES and how they connect to the flows in our cities.

Secondly, our buildings and urban structures are not designed to target regeneration. While sustainable design only aims for neutrality, regenerative design creates spaces that have a positive impact to the environment. The Wheel of Life's Principles helps to look in nature for inspiration. In this way, we proposed how the urban environment should mimic life systems to create a more sustainable and harmonious space.

The main outcomes of this research are based on the application of exergy and biomimicry to challenge the current identity of cities. It was concluded that cities must become autopoietic and shaped to connect. Buildings must rely on regenerative design and, like living beings, work as thermodynamically open systems while being operationally closed. Besides, cycling of resources and energy must mimic the processes observed in life systems, integrating ecosystems in the built environment to interconnect their flows. As a result, exergy is more efficiently distributed in the urban metabolism and climate change is properly addressed.

While our study doesn't dive into the exemplification of these ideas, it provides a foundation for future discussions and actions. Making cities more regenerative requires a combination of effective governance, smart design, and societal changes. By embracing these regenerative principles, we can pave the way for cities that not only meet our needs but also actively contribute to a healthier and more resilient planet.

Contents

1. Introduction

1.1 Challenges in the built environment

Cities cover approximately 3% of the earth's surface and still consume 78% of the energy available on the planet, being responsible for 38% of the global GHG emissions (Pedersen Zari et al., 2022; Ulgiati & Zucaro, 2019). Cities are also the heart of technological development and economic growth of many nations, among other benefits, but they also serve as a breeding ground for inequality, poverty, environmental hazards and communicable diseases (Kuddus et al., 2020). Considering the continuous growth in human population and urbanization trends, countries will face big challenges when meeting the housing demand while keeping up with the 2030 Sustainable Development Agenda (Haan, 2022).

Urbanization has been largely associated with human development and progress (Kuddus et al., 2020). Still, cities are the source of many global issues due to the local and global environmental stresses they exert, result of the unsustainable consumption of resources and depletion of the surrounding natural habitats (Ulgiati & Zucaro, 2019; Vegt, 2022a). What is more, cities are vulnerable places suffering the consequences of their rapid growth, making them extremely exposed to the risks of climate change (sea-level rise, higher mean temperature, water scarcity, increased frequency and magnitude of extreme events, spread of diseases, etc.) (Hobbie & Grimm, 2020; Kuddus et al., 2020; Pedersen Zari et al., 2022).

Understanding how the inflows and outflows of cities relate to population, resource availability and environmental carrying capacity is a crucial task to the correct management of cities. This is performed by the study of urban metabolism, science that finds a parallelism between cities and living organisms: the internal processes by which they continuously exchange matter, energy and information with the environment to enable operation, growth and reproduction (Ulgiati & Zucaro, 2019). In this way, achieving a holistic administration of resources that considers the well-being of human and ecosystems is possible, shifting the future of cities and their dwellers.

1.2 Strategies to overcome urban challenges and their downsides

Devising strategies to manage and adapt cities to the impacts of climate change is an urgent task, as the global population is becoming more and more concentrated in urban areas (Hobbie & Grimm, 2020). Nevertheless, these strategies must conceal the crucial link among growth, natural resources exploitation and consequences of the state of the environment (Ulgiati & Zucaro, 2019).

The Ecosystem Services framework (from now on, ES) highlights the importance of investing in ecosystem management, as it categorizes and describes the many benefits that healthy ecosystems derive (Millennium Ecosystem Assessment (Program), 2005). Unfortunately, the value of ES is not acknowledged by many, failing to integrate ecosystems well-being in governance and decision making. On the other hand, when acknowledged under a capitalistic perspective, they can also be handled like another production chain: a link of goods that can be exploded to the interest of people. This is clearly represented in the cascade model of CICES (**Figure 1**) (Potschin & Haines-Young, 2011), which categorizes ES in a linear model. The CICES cascade model focuses only on the human benefits that can be extracted from ES, ignoring the underlying (but important) mechanisms in natural systems that we cannot comprehend at this point (Czúcz et al., 2018; Vegt, 2022a). If the value of ES was properly understood, the integration of natural spaces in the urban area would be one of the first targets to alleviate the internal and external stresses that cities suffer and exert.

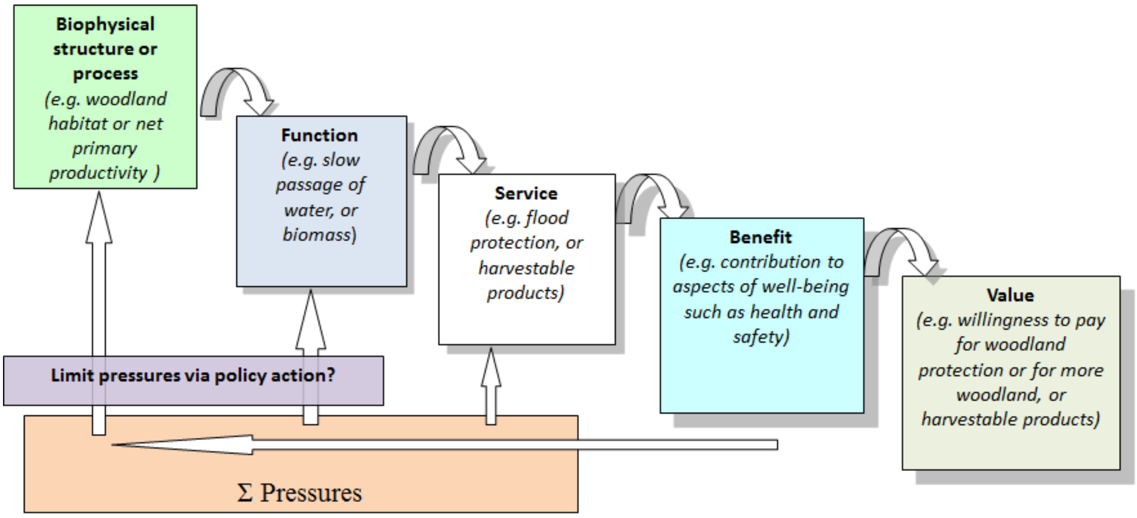

Figure 1. CICES cascade model. Biophysical structures or processes provide a function, which is linked to a service. These services derive benefits to humans, translated into economic value (Czúcz et al., 2018).

Besides, the study of organisms and the ecosystems they create can help to mitigate and adapt cities to climate change, serving as inspiration for new techniques and technologies. This is the basic principle of biomimicry and biological engineering (Pedersen Zari, 2010; Pedersen Zari & Hecht, 2020). Nevertheless, the application of biomimicry does not always reach its full potential. Sometimes, it is only used to represent single aspects of an organism in products or materials rather than the study of complex systems; or its results might lead to unsustainable outcomes (Pedersen Zari, 2007). A clear example are initiatives that mimic the processes of sharing, sequestering or / and recycling carbon in nature (Hobbie & Grimm, 2020). In this case, carbon sequestration might help to adapt and retrofit existing infrastructure, but it is still an intermediate step: it does not question the idea of excessive burning of fossil fuels in our system. Translation can always remain at a shallow level, without addressing the real root of the problem (Pedersen Zari, 2010).

Nature-based solutions (NBS) merge the integration of ecosystems and the use of the biomimicry design approach to reduce climate hazards. They are gaining popularity in cities because they are more flexible, multi-functional and adaptable to uncertain and non-stationary climate conditions than traditional approaches. Still, NBS by themselves are not automatically enough for conserving biodiversity and facilitating the ecological adaptation to climate change (Hobbie & Grimm, 2020). If the root of the problem is not questioned, these initiatives might be perceived as patches in a deep wound that calls for a more groundbreaking, systematically complex solution.

1.3 Integration of a paradigm shift in the built environment

Moving away from conventional practices into a regenerative approach requires a paradigm shift (**Figure 2A**), characterized by a less anthropocentric vision of our role in nature and wider trust on ES to satisfy most of our needs (Reed, 2007). To achieve this goal, the focus of our system must change, so as our perception of nature. In fact, nature is not only the main radix of assets, but also a source of knowledge. Inspired in the natural mechanisms ubiquitously present in our environment, the wheel of Life's Principles (**Figure 2B**) comes as an indispensable tool to adapt our system to the ways of nature. Regenerative design is the activity of depicting systems or solutions mimicking the Life's Principles. As clearly stated in the work of Pedersen Zari, 2010, change will not come from the application of new technologies, but by the adoption of new mindsets and goals.

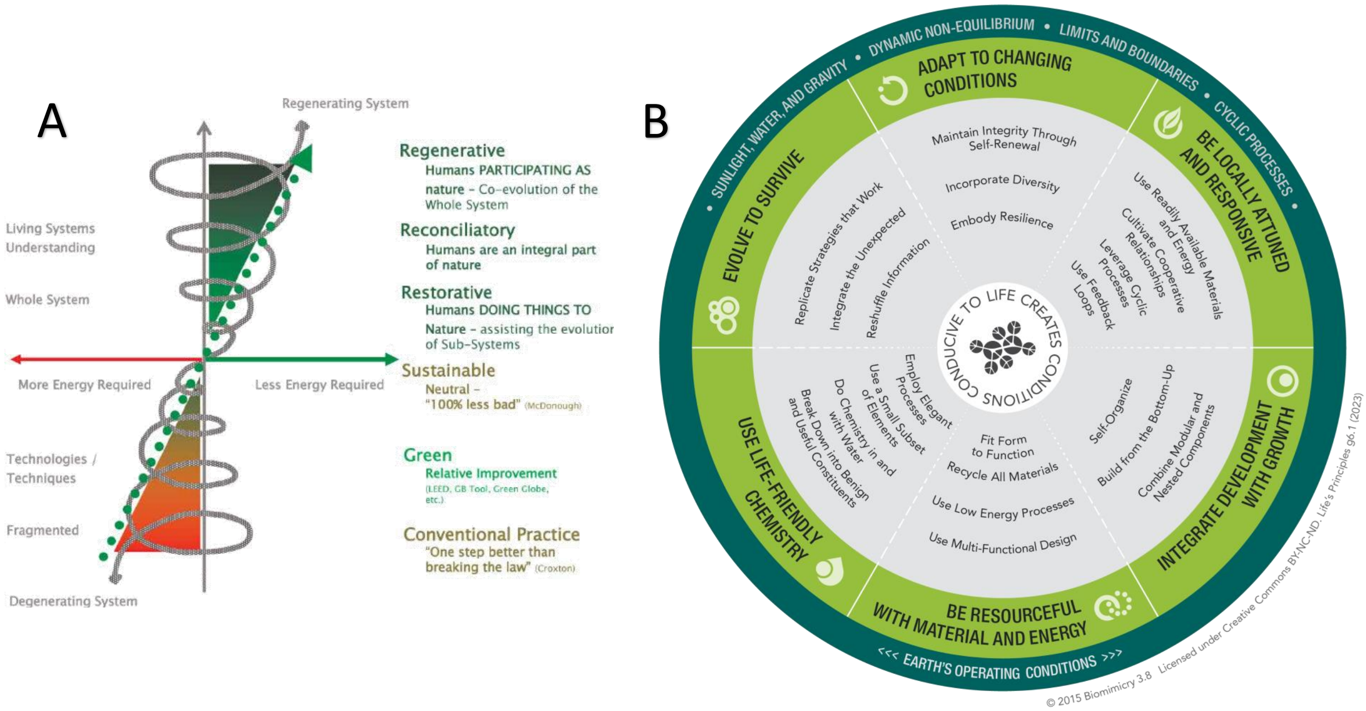

Figure 2. (**A**) Graph representing the transitioning steps from a degenerating system, which is based on conventional practices, towards a regenerative system (Reed, 2007). (**B**) Wheel of the Life's Principles used in biomimicry (Biomimicry 3.8).

The paradigm shift in the urban environment must start by challenging ground conceptions of cities and the way they are organized. Redesigning cities through the Life's Principles is the solution to route its development into more environmentally sound, safer and integrative urban spaces (Hobbie & Grimm, 2020).

Understanding the relations between societies, environment, mass and energy flows and population growth is a complicated, but essential task to integrate ecosystems in cities (Ulgiati & Zucaro, 2019). An exhaustive study and classification of the building metabolism flows was performed in Haan, 2022. They identified that 83.2% of the urban metabolism flows relate to the flows of a single building, while 37.9% of the building metabolism flows related to ES. This portion of the flows could be supplied or managed by the implementation of ecosystems in the built environment. Progressive understanding of natural processes might increase the ratio of links to the built environment, connecting more ES through the development of new ES designs. Still, the fact of relating more than a third of the manmade flows in buildings to natural systems shows their applicability and importance. Even if not all ES can be yet provided or mimicked by the built environment (Pedersen Zari, 2010), regenerative design can provide, integrate, or supports ES in the creation of regenerative nodes (Pedersen Zari, 2012; Pedersen Zari et al., 2022).

1.4 Exergy and ecosystems in regenerative design

Introducing the concept of exergy and emergy in the regenerative design process serves as a tool to visualize relationships between ES, untangling their complex interconnections (Vegt, 2022a). Exergy is described as 'the maximum theoretical work that can be done by a system when it comes to thermodynamic equilibrium with the reference system (or the environment)', while emergy is 'the available solar energy used up directly and indirectly to make a service or product' (Salehi et al., 2018; Vihervaara et al., 2019). They both can be used to trace energy flows, showing the energetic interaction and conversion processes in complex systems (Vegt, 2022a).

Exergy unifies the units of generation and expenditures in a system, as it is the sum of the potential, physical, kinetic, and chemical exergy presented in its flows (Salehi et al., 2018). Besides, exergy is not necessarily subjected to a conservation law: exergy can be destroyed in irreversible processes to create entropy (Rosen, 2021). The analysis of exergy is applicable throughout a whole process chain, both ecosystem flows or urban flows, quantifying the amount and quality of the circulating energy and providing a universal method for the rational use of resources (Salehi et al., 2018; Vihervaara et al., 2019). This will help to give concrete value to the ES provided by an ecosystem without the human benefit bias; perform trade-offs under a living system perspective; and evaluate the amount of wealth generated by regenerative design, considering the amount of organizational exergy stored in the generated system (Vegt, 2022b; Vihervaara et al., 2019).

During the following sections, the organization of cities is analyzed from a biomimetic perspective, integrating the concept of exergy in the ES framework and urban flows. This is expected to facilitate the application of regenerative design in the built environment, helping to visualize and understand its impact.

2. Problem statement and research questions

Recapping from the introduction, cities keep on growing, being sinks of external resources that act beyond planetary boundaries. At the same time, consequences of climate change make them vulnerable places uncapable of satisfying human needs. In this research, we point out what could be the possible reasons of this outcome, followed by the research question that will be addressed:

a. Cities consume resources without taking care of the ecosystems where they are originated. Cities must learn from the organization of ecosystems to manage their challenges in a more life-friendly strategy. ***RQ1. What are the differences in organization between cities and ecosystems?*** (Chapter 4.1)
b. The ES value's lack of acknowledgement hampers its integration in the urban metabolism. Explaining its richness using exergy analysis could inspire links between natural and urban flows. ***RQ2. How is it possible to reformulate the perception of the ES framework?*** (Chapter 4.2)
c. The built environment is not based on regenerative design. Cities leading the paradigm shift must adapt their structure based on the inspiration of living beings. ***RQ3. What is the scheme that regenerative buildings and cities of the future should follow?*** (Chapter 4.3 and 4.4)

3. Research approach

To systematically address the research questions in the problem statement, a comprehensive literature review was conducted, focusing on the current state of cities, the application of exergy from an ecological perspective, and the potential landmarks for regenerative design. The methodology employed in this review is outlined below.

Three main databases were searched to identify relevant articles to answer the research questions: Google Scholar, PubMed, and the repository of the biology department of the Utrecht University. Used keywords were variations of terms related to cities, ecosystems, regenerative design, ecological services and exergy analysis.

Articles were included if they directly addressed the research questions and contributed insights into the current situation of cities and regenerative design, prioritizing those published in the last 5 years. Articles lacking relevance to the specific themes or having solely a social approach were excluded to the scope of this research.

The Wheel of Life's Principles served as a guide throughout this report, facilitating the integration of diverse perspectives for designing and ideation of cities of the future. Besides, the classification of ES framework by MAE, 2005, was used as a reference for the ecological aspect.

Nevertheless, two main limitations were identified in this work: (1) the theoretical sustain of its findings, which lacks practical exemplification; and (2) the exclusion of the social perspective, which is essential in the ideation of a paradigm shift. Future research should focus on these two gaps.

4. **Results**

4. 1 Learning from nature. Turning cities into ecosystems (RQ1)

The extended life and slow rate of renewal of buildings make them necessary to be part of a long-term solution. It is a matter of fact that buildings that will inhabit cities of the near future are already present (Pedersen Zari, 2010), but it is still possible to reorganize their structure so they link biophysical aspects with social, environmental and well-being community aspects (Ulgiati & Zucaro, 2019). The life's principles (**Figure 2B**) can be a used as a guideline to reorganize the built environment. In the context of this research, two main differences between the way nature functions and the way humans design need to be considered:

(1) Nature mostly relies on open, thermodynamically dissipative systems. In these, the system's identity is given by its pattern of organization: the configuration of the network of processes among the components and its intrinsic relations, given by context (Pelorosso et al., 2017; Vegt, 2022b). The system's identity is physically embodied in the structure of the system, and its pattern of organization gives new capabilities to the system itself. This latter fact is defined as emergence, and it is one of the key principles conducive to life (Capra & Luisi, 2017). Currently, buildings function like closed systems. They are focused on minimal dissipative and irreversible processes and are composed of isomorphic structures, as each element performs a specific function (Vegt, 2022a).

(2) Ecosystems maintain and grow their habitat through community, capturing solar energy (high exergy of high quality) that the elements of the system will transform and reuse to produce their own structure. This structure, at the same time, maintains the systems dynamic and keeps the community running together (Gibson, 2012; Pelorosso et al., 2017; Vegt, 2022b). In general, cities are not autopoietic either, a principle conducive to life which refers to the capacity of a system to produce and maintain by itself (Capra & Luisi, 2017; Vegt, 2022a). Cities are built with technology that consumes high exergy (oil and gas) and natural resources. Their internal organization is ruled through the logics of competition and the cost-benefit analysis, dividing its own space for individual aims (Vegt, 2022b). At the same time, they consume most of the resources available on the planet without investing in the growth of these ecosystems. These ecosystems are uncapable of producing resources at the rate they are consumed, going beyond planetary boundaries (Ulgiati & Zucaro, 2019).

For these reasons, cities must become autopoietic and shaped to connect, where buildings function like thermodynamically open systems and rely on biological engineering to satisfy their needs. To achieve this goal, there must be a change in the way ES are perceived and a transformation in the way buildings are designed.

4. 2 Reconciling cities and ecosystems through the CICES circular model (RQ2)

The topic of sustainability in cities is mostly linked to optimization of energy, material reduction potential, increasing efficiency and recycling of resources (Vegt, 2022b). Nevertheless, environmentally responsible design must move forward conventional practices, aiming for a regenerative approach in which we co-evolve hand in hand with nature (Reed, 2007). The negative impact of human societies on ecosystems could be reduced if the economic value of ES is acknowledged (Vihervaara et al., 2019), but focusing only on the human benefit hampers real, effective decision making for regenerative design. For this reason, a redefined CICES cascade model is needed to highlight ecosystem's interconnectedness, where its dynamic balance and web of relations (known or unknown to us) is not ignored (Vegt, 2022a).

Living systems maintain their equilibrium through circular processes, while human processes mostly ignore this need and follow linear dynamics (Capra & Luisi, 2017). In **Figure 3**, the CICES cascade model is turned into a circular model, where the 'Benefit' produced by the 'Service' is relinked again to sustain the 'Biophysical structure or process', eliminating the anthropocentric connotation of the ES' benefits. This continuous loop enhances, as an outcome, the well-being of ecosystems and humans (which are not separated elements), placed in the center of the scheme. As stated in Jiménez Hernández, 2016, healthy ecosystems provide many benefits to local communities but also services for the ecosystem itself. Thus, decision making under this new circular model will shift design focus to the correct functioning of ecosystems, their progressive integration in human spaces, and the respectful use of their resources.

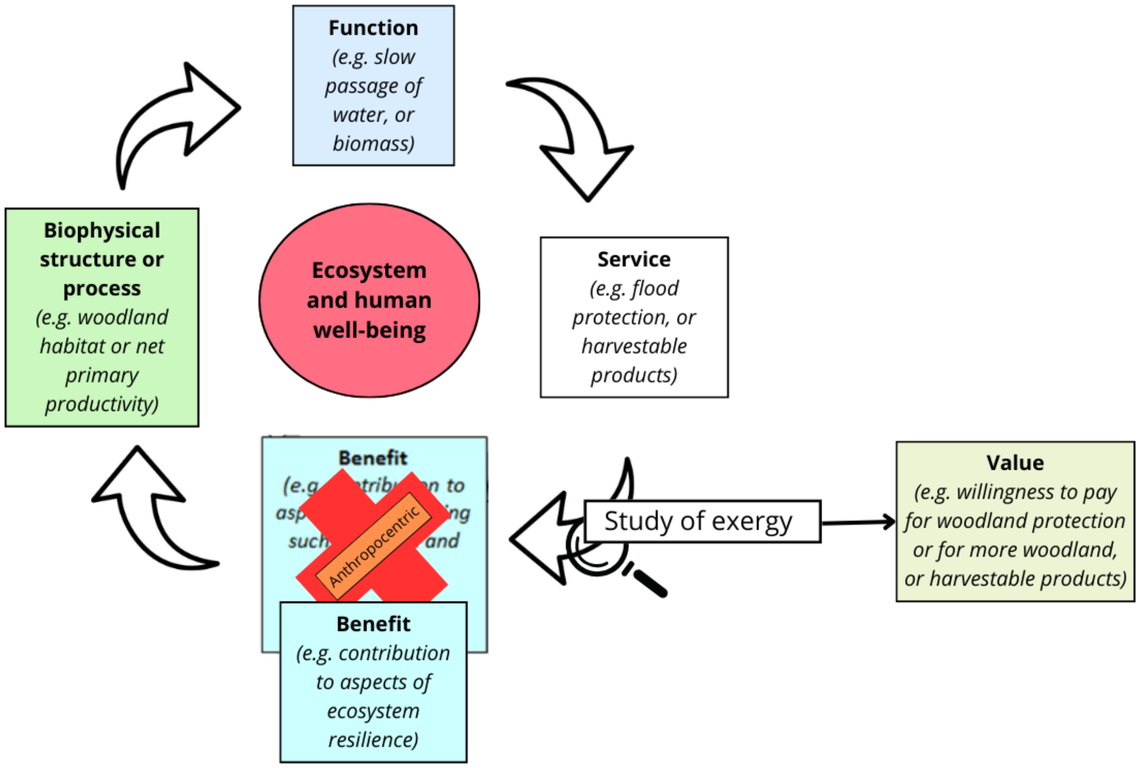

Figure 3. A redefined CICES circular model. The benefit (light blue) of services (white) is not only considered from an anthropocentric perspective, as it happens in the CICES cascade model. To represent underlying mechanisms within ecosystems that are essential for their sustain, 'benefit' is linked back again to 'biophysical structure or process' (light green). The correct functioning of this loop enhances ecosystem well-being, which also includes human well-being (in reed). Through the exergy analysis, it is possible to visualize the actual value of these ES.

The role of exergy in **Figure 3** is quantifying the value of the services provided, properly acknowledging its importance. As previously stated, exergy unifies the units of measure of the energy flows, thermodynamically tracing the different energy / exergy generation and expenditures in a system. Thus, not only the environmental capacity of ecosystems can be properly controlled, but also the organizational exergy stored in them. Decision making that targets the increase of exergy efficiency leads to a reduction in the environmental impact, resulting in higher sustainability (Salehi et al., 2018). Regenerative design will experience a turning point within the urban environment because, from this moment onwards, the exergy accumulated in a system (that can be a building, for example) can be used to assess how much 'regeneration' has been performed, which can be ultimately linked to economic value (Vegt, 2022a).

4.3 The scheme of the buildings of the future (RQ3)

As explained in the introduction, cities mostly nurture human activity and technology for its growth, obtaining most of its resources from external ecosystems to which they exert enormous environmental stresses. This latter fact makes cities incapable of creating safe, healthy, sustainable, equal spaces for the development of human and non-human life (Hobbie & Grimm, 2020; Kuddus et al., 2020; Pedersen Zari et al., 2022; Ulgiati & Zucaro, 2019). Rooted in the imbalance between human activity, technology and nature, progression of societies exceeds planetary boundaries. Despite this trend, many studies suggest that the achievement of a regenerative built environment comes from (A) the integration of ecosystems and (B) application of biomimicry, not through the development of new technologies in a conventional system (Hobbie & Grimm, 2020; Pedersen Zari, 2010; Reed, 2007).

A. Integration of ecosystems

Urban metabolism must be based on the services that can be locally generated. For that, ecosystems should be integrated in the built environment, but this requires a change in governance and design processes (Ulgiati & Zucaro, 2019). Introducing exergy analysis in the urban metabolisms provides a bridge of knowledge between the ES framework and the building flows. With it, it will be possible to quantify and match the energy flows that a building requires / generates with the energy flows present in an ecosystem, identifying which ES should be applied during the design process.

Figure 4 models the potential inner interactions of a building that integrates ecosystems through regenerative design strategies. Its flows are interconnected through the network metabolism, which refers to building and ecosystem metabolism. More extensive research on the link between metabolism of buildings and ES is given in Haan, 2022, exemplified with case studies. Thermodynamically comparing the scheme of regenerative buildings to living beings, the overall activity produced by both have the same outputs: (1) decrease of entropy; (2) increase of the organizational exergy, reflected in the structural order (system information; energy input; amount, size and nº of elements; and the metabolic pathways within); and (3) increase of entropy in its surroundings, which is the natural tendency of the universe (Vegt, 2022a).

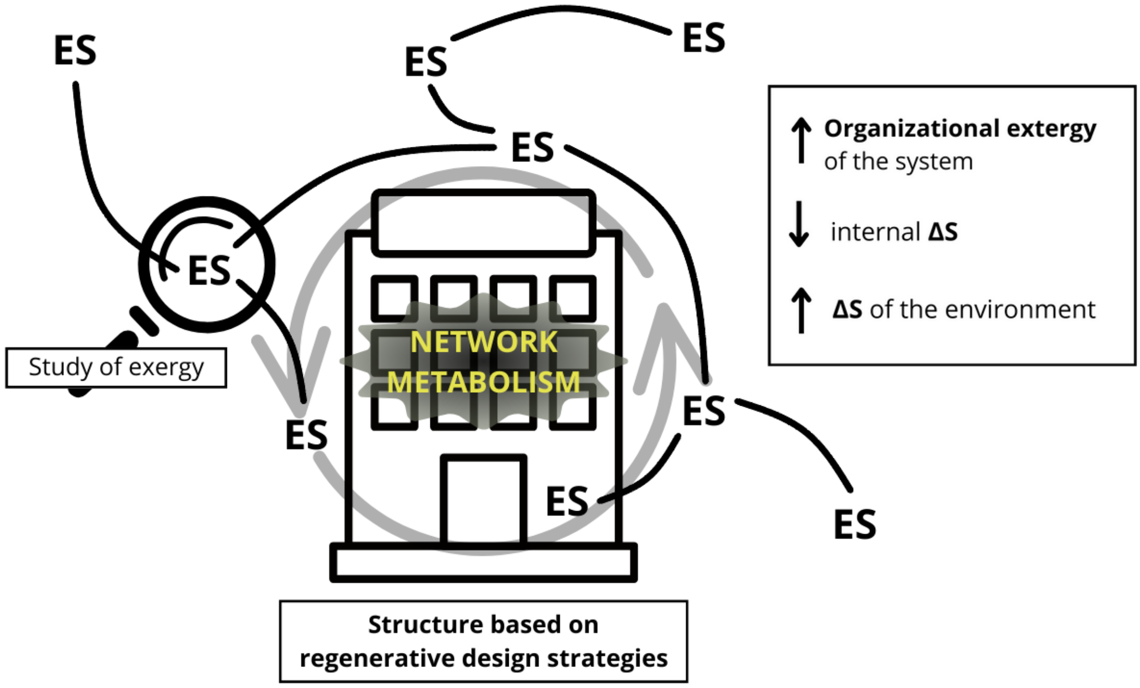

Figure 4. Scheme of the integration of ecosystems in buildings of the future. Through regenerative design strategies, ES are provided in the built environment. Building and ecosystem flows are combined in the network metabolism, maintaining a local flux of energy and resources. In the process, buildings are capable of increasing their organizational exergy, decreasing their inner entropy and increasing the surrounding entropy as living beings do (Vegt, 2022a).

B. Application of biomimicry

Redesigning cities under the inspiration of living beings and ecosystems is the pathway to develop them into resilient places where life can thrive. For instance, ecosystems create a nature-positive environment taking high-quality energy and transforming it into intermediate-quality energy to increase their structural order (Vegt, 2022a). To also create a nature-positive environment in cities, their metabolisms should follow the same conditions, as described in the next section.

4. 4 The scheme of cities of the future (RQ3)

To give insight on how future regenerative cities should function, a scheme of the regenerative building was designed in this study, using the Life's Principles (**Figure 2B**). An open that is operationally closed system is represented, with a flow of energy, matter and information. This flow is not a linear, but circular, as every output participates in another process within the building or its surroundings: the internal metabolism of the building is interactive, integrative and full of loops (**Figure 5**). Moreover, the boundaries of the system are flexible and permeable, arbitrary to the point of view of the observer (Vegt, 2022a). It is possible to explain the flows of these buildings through the Life's Principles:

(1) Energy from the sun is the power cell of the system, characterized by its high exergy and low entropy (high quality). After it passes through the network metabolism, it is

transformed into low quality and high entropy, increasing its organizational exergy. This process is efficient, connecting exergy flows of human activity that ecosystems can transform into higher quality exergy.

(2) Matter is the physical input of the system and takes shape in its structure and inner processes. It must come from local precedence and rely on water chemistry. Nothing is considered waste in nature (Capra & Luisi, 2017), everything leaving the system is useful as an input for another cycle.

(3) Information is held by genetic diversity and knowledge. Humans can organize their own habitat to integrate into environmental processes like cells in an organism or ants in a colony. Their activity depends on the synergy with technology and nature, and the interaction of all these components drives the flow of energy and matter in the building (emergence). In the same way nature integrates strategies that work, buildings are also affected by some natural laws: Lotka's maximum power principle; Darwin's evolution; and natural selection (Ulgiati & Zucaro, 2019). This means that they are in constant adaptation, communication with their surroundings, and evolution (autopoiesis).

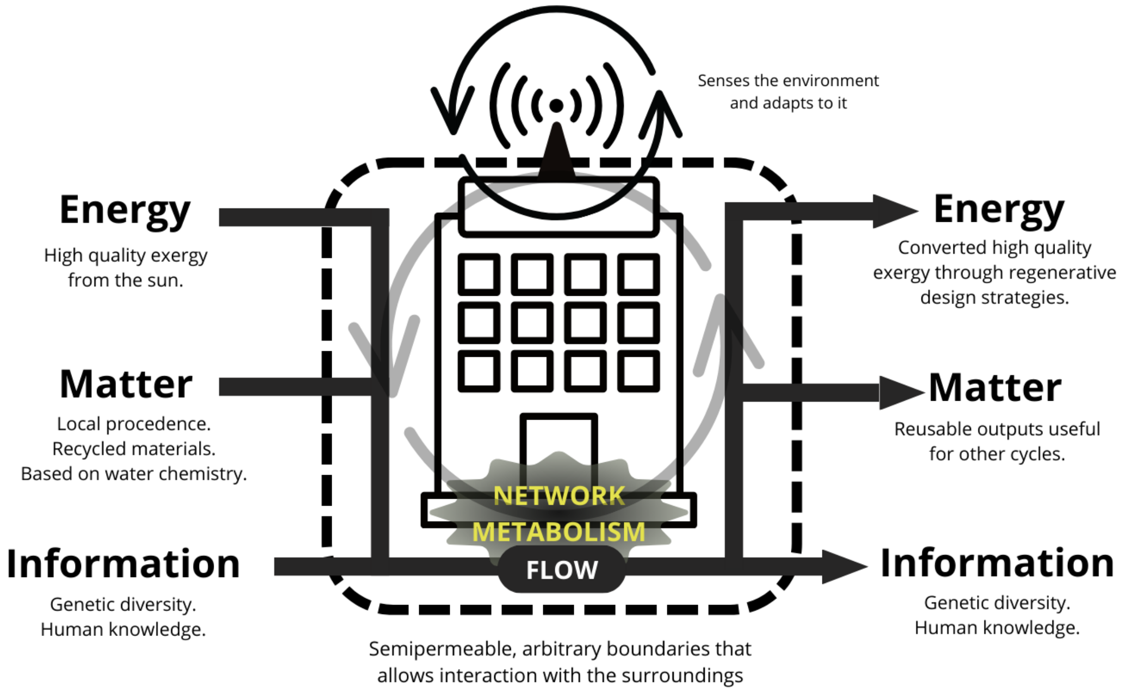

Figure 5. Scheme of the inner flows of buildings of the future.

As mentioned before, flow is created in these systems as a result of the right equilibrium between human activity, technology and nature, composing urban metabolism. Coupling regenerative buildings in the same area have emergence properties, as it happens in nature: an open system with a flow of energy, matter and information between them progressively collaborate in their own growth and complexity. This is achieved through the creation of synergies, instead of solving conflicts via trade-offs (**Figure 6**).

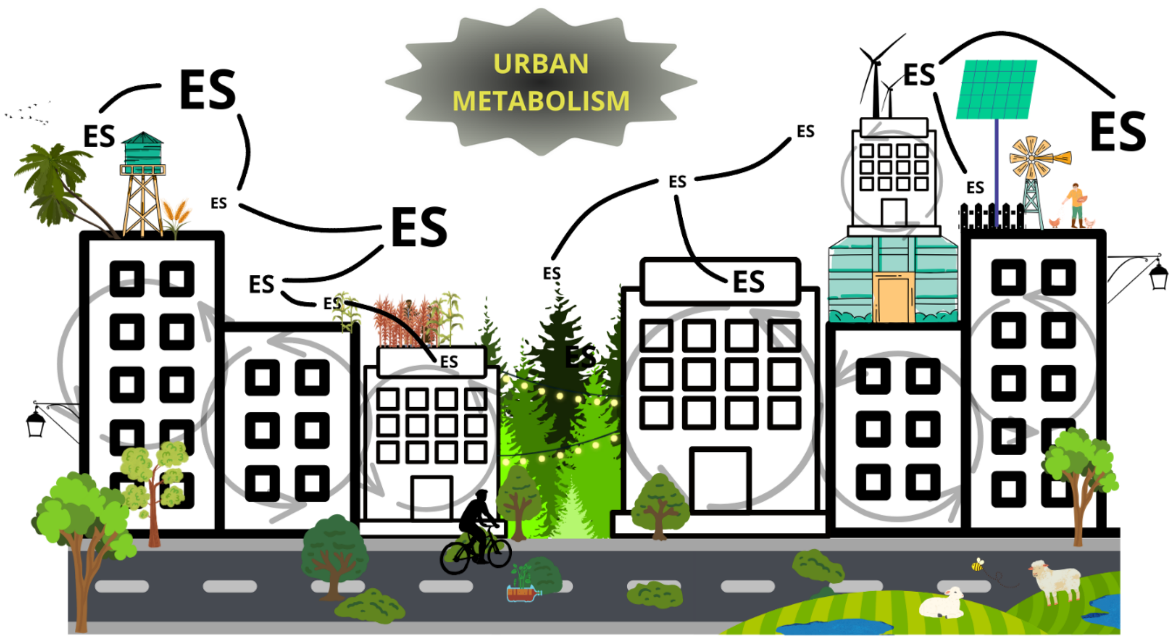

Figure 6. Scheme of the cities of the future. Ecosystems are integrated in the urban landscape. The global combination of the network metabolism in buildings configures urban metabolism, maintaining a local flux of energy and resources.

5. Discussion

5. 1 The role of cities in the regenerative transition

Cities are the source of many global issues due to the local and global environmental stresses they exert, but they also suffer the consequences of their rapid growth (Ulgiati & Zucaro, 2019; Vegt, 2022a). Their high population density is extremely exposed to the risks of climate change (Hobbie & Grimm, 2020; Kuddus et al., 2020). Moreover, they suffer from inequality, poverty and other social and economic imbalances that lay beyond the scope of this research (Hobbie & Grimm, 2020; Kuddus et al., 2020; Pedersen Zari et al., 2022; Ulgiati & Zucaro, 2019). Analyzing cities through the lens of the Life's Principles (**Figure 2B**) shows the large differences between how nature and how humans design functions. Challenging the identity of the built environment is the first step to bring down this gap, reorganizing their structure and functioning so cities can be part of a long-term solution (Pedersen Zari, 2010; Ulgiati & Zucaro, 2019).

Currently, the urban environment is built through technology that consumes high exergy (oil and gas) and extracts natural resources beyond planetary boundaries (Ulgiati & Zucaro, 2019; Vegt, 2022a). Buildings are composed of isomorphic structures that function like closed systems, characterized by minimal dissipative and irreversible processes (Vegt, 2022a). Their internal organization is ruled through the logics of competition and the cost-benefit analysis, dividing its own space for individual aims (Vegt, 2022b). Thus, cities of the future must change these characteristics to become autopoietic and naturally shaped to connect, consuming solar energy (high exergy of high quality) and integrating local ecosystems for their sustainable management and extraction, growing through synergies and community labor. The identity of buildings inhabiting regenerative cities must change as well, functioning like living systems: thermodynamically open systems relying on biological engineering to perform its processes.

5. 2 The role of ecosystems in the regenerative transition

Ecosystems receive most of the energy from the sun and rely on this source of low entropy and high exergy for their processes. Human activity, on the other hand, is mostly powered by exergy from fossil fuels, which is of a lower quality. The process of converting chemical energy into work is not completely efficient and releases large amounts of exergy into the environment. Some of the exergy is irreversibly transformed into entropy and delivers a number of high entropy byproducts, like pollutants (Rosen, 2021; Salehi et al., 2018; Vegt, 2022b, 2022a).

Performing energy analysis can help to improve efficiency in our systems and reduce our footprint, but the input given by energy analysis can be misleading and confusing. For that reason, exergy analysis is preferred to identify inefficiencies in energy converting systems, as they quantify the potential work that a system can perform. Applying the study of exergy in the urban metabolism could enhance the efficiency of human activity, reducing fuel use and, consequently, lowering greenhouse gas emissions (Rosen, 2021).

Nevertheless, improving our energy and exergy efficiency is not enough to combat climate change. We need to move beyond conventional practices to achieve a regenerative built environment. One of the changes leading this paradigm shift is the integration of ecosystems in cities (Hobbie & Grimm, 2020; Pedersen Zari, 2010; Reed, 2007).

Latest advances in the ES framework make it possible to interconnect the flows of the urban metabolism with the flows of natural processes (Haan, 2022), consequently improving the well-being of the inhabitants and enhancing resilience against climate change (Hobbie & Grimm, 2020; Kuddus et al., 2020; Ulgiati & Zucaro, 2019). The importance of ES is not acknowledged by many still, being ignored during urban management or, on the opposite extreme, exploited for resources like a production chain. This anthropocentric perspective, represented in the CICES cascade model (**Figure 1**), leads to the imbalance of consumption and management of ecosystems, that mostly ends up in their destruction (Potschin & Haines-Young, 2011; Reed, 2007).

The CICES cascade model puts value in the economical profitability of services provided by natural spaces. Thus, the value of ES is subjected to market trends and personal human interest, ignoring the underlying mechanisms essential to ecosystems (Vegt, 2022a). This research proposes the CICES circular model (**Figure 3**), which puts the value to the amount of exergy a service provides to an ecosystem. Exergy analysis helps to quantify the potential work ecosystems can provide and its environmental capacity, contributing to a more comprehensive understanding of their underlying mechanisms and energy flows (Vihervaara et al., 2019). In this way, the focus shifts back to the health and resilience of ecosystems, without being influenced by the market value.

Incorporating exergy analysis in the CICES model also has a big impact in the regenerative design: the exergy accumulated in a system can be used as an indicator of how much ‘regeneration’ has been performed. This exergy is described as ‘organizational exergy’ and can be linked to economic value, known as ‘eco-exergy’ (Salehi et al., 2018; Vegt, 2022a). This could also open a door for its introduction in the carbon credit market.

However, global application of exergy analysis will encounter economic and engineering limitations. Hence, engineering and economic considerations should be combined during the exergy analysis to find cost-effective and realistic improvement options (Salehi et al., 2018). Even though exergy is not yet fully applied when assessing the environmental performance and sustainability of socioecological systems (Vihervaara et al., 2019), this papers shows that they can provide valuable information about the development and complexity of ecosystems.

5. 3 The role of buildings in the regenerative transition.

Nature is a pandora box. Currently, we do not fully understand what is happening inside, but biomimicry allows us to imitate their structures with the hope to experience the same functions as natural systems. This process of trial-and-error gives deeper insight of the underlying mechanisms beyond our current comprehension. By using the Life Principles (**Figure 2B**), it is possible to challenge the identity of buildings and redesign their structures and functions from scratch, out of the inspiration of natural process.

This is needed to find an equilibrium in buildings between human activity, technology and nature, since we have long gone beyond planetary boundaries. Better relationships, health improvement, cultural equity, and economic improvements are not necessarily linked to increased per-capita resource consumption (Ulgiati & Zucaro, 2019). Aiming for a regenerative built environment is possible through the integration of ecosystems and the application of ecosystem biomimicry, not by the development of new technologies in a conventional system (Hobbie & Grimm, 2020; Pedersen Zari, 2010; Reed, 2007). In Pedersen Zari & Hecht, 2020, there are given examples of integrating ES in the built environment through design strategies, concepts, technologies, and case studies.

Ecosystems consume exergy to increase their complexity, reducing entropy (Vegt, 2022a). Exergy inefficiently processed by the built environment could be coupled to the growth and maintenance of urban ecosystems or building integrated ecosystems (**Figure 4**), whose ES can be linked again to the energy flows of the building. Matching urban metabolism with the local environmental capacity of the area is a challenge that regenerative design must address, and this requires a change in governance and design processes (Ulgiati & Zucaro, 2019).

Figure 5 shows the flows of a potential future building relying on the Life Principles, where humans play an organizational role like cells in an organism. In a nutshell, using the exergy from the sun, buildings increase their organizational exergy (complexity) decreasing their internal entropy, leading to an increase of entropy in its surroundings. At the same time, the building can sense the environment and adapt to it, sharing its information by genetic diversity and knowledge transfer. Coupling regenerative buildings together will result into emerging properties, as synergies will be forming between their internal circular flows (**Figure 6**).

Nowadays, it would be impossible to achieve the presented ideas in this report without going off-grid. This is why it is important to remember what the concept of regeneration entails: not a less negative or neutral effect, but progressively positive. Designing having these schemes in mind will help creating spaces that boost the implementation of regenerative practices, increasing their positive impact along time. We should not be overwhelmed about the challenge, or dismissive because we cannot have the perfect conditions in the current time.

In the end, buildings should act as buffers of the human activities by recycling low entropy and regenerating high exergy. In the same way organisms create their unique system, humans must find their unique offering to the world in symbiosis to the rest of the living beings. This change of paradigm depends much as well on the social aspect, which was not mentioned before due to the scope of this research. Future research should focus on how to integrate the social aspect into this scheme.

6. Conclusion

In this study, we delved into the transformative potential of regenerative principles in addressing the multifaceted challenges within the urban environment. Cities, being both sources and victims of environmental stresses, require a paradigm shift in their design and functioning. Analyzing urban structures through the lens of Life's Principles highlights the disparities between human-designed systems and natural processes, emphasizing the need to challenge the identity of the built environment.

The current urban landscape, characterized by high exergy consumption and resource extraction beyond planetary boundaries, requires a radical reorganization. Future cities must evolve into autopoietic entities that harness solar energy, integrate local ecosystems, and operate as thermodynamically open systems. Buildings need to transition from isomorphic structures to living entities, relying on biological engineering and embodying the principles of biomimicry.

Ecosystems, as exemplars of efficiency in utilizing solar energy, play a pivotal role in the regenerative transition. The integration of the ES frameworks, especially through the proposed CICES circular model, aligns the value of services with the exergy they contribute to ecosystems. This shift from anthropocentric perspectives to a focus on the health and resilience of ecosystems is crucial for sustainable urban management.

The application of exergy analysis within the CICES model not only enhances our understanding of ecosystem dynamics but also provides a metric for assessing regeneration. This introduces the prospect of incorporating regenerative efforts into economic mechanisms, such as the carbon credit market, marking a step toward a more sustainable future.

Considering the role of buildings, ecosystems biomimicry emerges as a key strategy for redesigning structures to operate within ecological boundaries. Aligning buildings with Life Principles and coupling their exergy flows with ecosystem growth presents a tangible path toward a regenerative built environment. While current limitations may restrict the full realization of these ideas, the concept of regeneration calls for a progressive shift rather than immediate perfection.

In essence, the journey toward regenerative cities requires concerted efforts in governance, design processes, and social integration. By embracing the regenerative paradigm, we have the potential to create urban spaces that not only mitigate negative impacts but actively contribute positively to the environment over time. This shift demands a holistic approach, acknowledging the interplay between human activities, technology, and nature. As we envision regenerative cities, we must remain mindful of the ongoing societal transformation needed to fully realize this regenerative future.

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