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PRODUCING BENEFITS FOR NATURE AND SOCIETY: AN URBAN DESIGN FRAMEWORK BASED ON ECOSYSTEM-LEVEL BIOMIMICRY AND REGENERATIVE DESIGN

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Producing benefits for nature and society:

An urban design framework based on ecosystem-level biomimicry and regenerative design.

Aménager des bénéfices pour la nature et la société : Un cadre de conception urbaine basé sur le biomimétisme des écosystèmes et la conception régénérative.

Para meus pais, Antônio e Margarete.

Abstract

In the last decades, cities have progressively polarised human activities. As key nodes of our socio-economical systems, they increasingly concentrate human populations and economic activities, but they are also one leading cause of ecosystem and biodiversity degradation. Urban design organises and transforms the space by choosing and implementing urban interventions. Thus, it holds a significant opportunity to integrate and operationalise sustainable and ecological engagements presented in public policies. In this context, the neighbourhood scale is ideal for addressing such systemic questions and several sustainable design frameworks aimed at this objective. Nevertheless, the established frameworks present several lacks, such as their too prescriptive and non-holistic approaches.

However, innovative design approaches emerge to face these shortcomings. In this work, we are interested in regenerative design implemented through ecosystem-level biomimicry. This approach aims to design net-positive urban projects that promote benefits for society and nature, actively contributing to the production of ecosystems services. Despite the theoretical development and a few cases application, the approach remains perceived as not operational. Through literature review, case studies, surveys and interviews, this research aims to propose an urban design framework that could help design teams to apply these concepts to draw urban projects that are net positive in terms of ecosystem services and benefits society and nature.

The first chapter concentrates on theoretical regenerative design and ecosystem-level biomimicry approaches and their case applications. We understand the underpinnings of contemporary regenerative design, how ecological concepts of ecosystem and ecosystem services are used in real-world projects, and their limitations. Despite their interest, we highlight that the ecosystem services theories are still not fully acknowledged in regenerative and biomimetic urban project design.

Following, the second chapter focus on the urban design practice, relying on case studies that somehow find inspiration in ecosystems and promote positive impacts on local ecosystems. Here we identify the different strategies and solutions proposed to promote positive impacts. We note a focus on managing energy and material flows. The attention to the ecosystem's biophysical structures remains in the background. We also explore governance aspects of the project's design and implementation, defining potential governance success factors, such as the stability of the core stakeholders and a participative design approach.

Finally, the third chapter investigates the trends in selecting these strategies in a large sample of certified sustainable neighbourhoods and the barriers and needs to implement them successfully. We highlight the important role of diagnostics in informing decision-making and the lack of circular economy strategies on the projects. In this last chapter, we also identify an indicator set that can be used to design and assess regenerative neighbourhood projects, focusing on the French reality. Finally, in the discussions, we delineate an operational design framework for regenerative and bio-inspired neighbourhood design, relying on the different results and learnings acquired in this research.

Keywords: Regenerative design; ecosystem-level biomimicry; ecosystem services; sustainable urban design; neighbourhood sustainability assessment.

Resumé

Au cours des dernières décennies, les villes ont progressivement polarisé les activités humaines. Nœuds essentiels de nos systèmes socioéconomiques, elles concentrent de plus en plus les populations humaines et les activités économiques, mais elles sont aussi l'une des principales causes de la dégradation des écosystèmes et de la biodiversité. La conception des projets urbains organise et transforme l'espace en choisissant et en mettant en œuvre des interventions urbaines. La pratique du projet urbain offre donc une opportunité d'intégrer et de rendre opérationnels des engagements durables et écologiques présentés dans les politiques publiques. Dans ce contexte, l'échelle du quartier est idéale pour aborder ces questions systémiques et plusieurs cadres de conception durable visent cet objectif. Néanmoins, les cadres établis présentent plusieurs lacunes, telles que leurs approches trop prescriptives et non holistiques.

Cependant, des approches de conception innovantes émergent pour faire face à ces lacunes. Dans ce travail, nous nous intéressons au «regenerative design» mis en œuvre par le biomimétisme des écosystèmes. Cette approche vise à concevoir des projets urbains à impact positif qui favorisent les bénéfices pour la société et la nature, en contribuant activement à la production de services écosystémiques. Malgré le développement théorique et quelques cas d'application, l'approche n'est toujours pas opérationnelle. Par le biais d'une revue de la littérature, d'études de cas, d'enquêtes et d'entretiens, cette recherche vise à proposer un cadre de conception du projet urbain qui pourrait aider les équipes de conception à s'approprier de ce concepts pour dessiner et évaluer des projets à impact positif qui bénéficient la société et la nature.

Le premier chapitre se concentre sur les approches théoriques du «regenerative design» et du biomimétisme des écosystèmes, ainsi que sur leurs applications concrètes. Nous comprenons les fondements contemporains du «regenerative desing», la manière dont les concepts écologiques d'écosystème et de services écosystémiques sont utilisés dans les projets réels, ainsi que leurs limites. Nous soulignons que les théories des services écosystémiques ne sont pas pleinement reconnues dans la conception de projets urbains régénératifs et biomimétiques malgré leur intérêt.

Le deuxième chapitre se concentre sur la pratique du design urbain, en s'appuyant sur des études de cas qui, d'une manière ou d'une autre, trouvent leur inspiration dans les écosystèmes et promeuvent des impacts positifs sur les écosystèmes locaux. Nous identifions ici les différentes stratégies et solutions proposées pour promouvoir des impacts positifs. Nous constatons que l'accent est mis sur la gestion des flux d'énergie et de matières. L'attention portée aux structures biophysiques de l'écosystème reste encore en deuxième plan. Nous explorons également les aspects de gouvernance de la conception et de la mise en œuvre du projet, en définissant les facteurs potentiels de réussite liés à la gouvernance, tels que la stabilité des principales parties prenantes dans le temps et une approche de conception participative.

Finalement, le troisième chapitre porte sur les tendances en matière de sélection de ces stratégies dans un large échantillon de quartiers durables certifiés, ainsi que sur les obstacles et les besoins pour les mettre en œuvre avec succès. Nous soulignons le rôle important des diagnostics pour éclairer la prise de décision et le manque de stratégies d'économie circulaire dans les projets. Dans ce dernier chapitre, nous identifions également un ensemble d'indicateurs qui peuvent être utilisés pour concevoir et évaluer les projets de quartiers régénératifs, en nous concentrant sur la réalité française. Enfin, dans les discussions, nous délimitons un cadre de conception opérationnel pour la conception de quartiers régénératifs et bio-inspirés, en nous appuyant sur les différents résultats et apprentissages acquis dans cette recherche.

Keywords: *Desing régénératif; biomimétisme des écosystèmes; services écosystémiques; conception urbaine durable; évaluation de la durabilité des quartiers.*

Deliverables

Scientific conferences:

1) Ecosystem-level biomimicry and regenerative urban planning: Linking natural ecosystems functioning and urban projects. Eduardo Blanco. Oral presentation. Conférence GDR 2088 Biomim, 14/10/20, Nice, France;

Peer reviewed published articles:

1) Blanco, E., Raskin, K., & Clergeau, P. (2022). Towards regenerative neighbourhoods: an international survey on urban strategies promoting the production of ecosystem services. Sustainable Cities and Society, 80, 103784. https://doi.org/10.1016/j.scs.2022.103784;

2) Blanco, E., Raskin, K., & Clergeau, P. (2022). Reconnecting neighbourhoods with ecosystem functioning: Analysis of solutions from six international case studies. Sustainable Cities and Society, 77, 103558. https://doi.org/https://doi.org/10.1016/j.scs.2021.103558;

3) Blanco, E., Raskin, K., & Clergeau, P. (2021). Le projet urbain régénératif : un concept en émergence dans la pratique de l'urbanisme. Cahiers de La Recherche Architecturale, Urbaine et Paysagère, 0–20. https://doi.org/10.4000/craup.8973;

4) Blanco, E., Pedersen Zari, M., Raskin, K., & Clergeau, P. (2021). Urban Ecosystem-Level Biomimicry and Regenerative Design: Linking Ecosystem Functioning and Urban Built Environments. Sustainability, 13(1), 404. https://doi.org/10.3390/su13010404;

5) Blanco, E., Cruz, E., Lequette, C., Raskin, K., & Clergeau, P. (2021). Biomimicry in french urban projects: Trends and perspectives from the practice. Biomimetics, 6(2), 1–16. https://doi.org/10.3390/biomimetics6020027;

6) Uchiyama, Y., Blanco, E., & Kohsaka, R. (2020). Application of biomimetics to architectural and urban design: A review across scales. Sustainability (Switzerland), 12(23), 1–15. https://doi.org/10.3390/su12239813;

Peer reviewed articles under review:

1) Blanco, E., Raskin, K., & Clergeau, P. (under review). Designing sustainable neighbourhoods: governance success levers on the urban design process. Cities;

2) Blanco, E., Raskin, K., & Clergeau, P. (under review).Indicators for regenerative neighbourhood design: defining an operational indicator set;

3) Clergeau P., Blanco E. Des projets urbains régénératifs ? Métropolitiques;

Book and report chapters:

1) Chapter 5: From Regenerative Buildings to Regenerative Urban Projects. Design frameworks to scale up within the area of regenerative practice. Eduardo Blanco, Jonas Gremmelspacher, Cristina Jiménez-Pulido, Dorota Kamrowska-Załuska, Melinda Orova. In: Scale Jumping – Regenerative Systems Thinking within the Built Environment. COST Action CA16114 RESTORE (2021);

2) Chapter 2: Report on existing indicator frameworks for ecosystem services. Eduardo Blanco. In: Synthesis report on current datasets and their applicability of ecosystem services mapping and modelling. REGREEN Project. (2020);

3) Chapter «Biomimétisme : Inspirer nos villes des systèmes vivants». Eduardo Blanco. In: Urbanisme et biodiversité. Philippe Clergeau (2020);

Other diffusion activities :

1)TEDx Talk IMT Alès: Changer et innover avec le vivant. 2020. https://www.youtube.com/watch?v=skEidKEICZE&t=12s;

2) TEDx Talk Sanca: Temos que repensar a condição dos não humanos. 2021. https://www.youtube.com/watch?v=cOd60EFWXdE.

3) COST RESTORE Final Diffusion Conference: Biomimicry in French regenerative urban projects: trends and perspectives from the practice. 2021. https://www.youtube.com/watch?v=tR86vyozLN0&t=28s;

4) French American Innovation Day 2021 : Green&Blue: Energy - Water - Resilience - Biomimicry. Biomimicry in French sustainable urban projects: trends and perspectives from the practice. 2021.

5) Fête de la Science 2019 au MNHN: Bioinspiration urbaine. 2019.

6) Saison France-Portugal 2022: Biomimicry workshop. Urban design for people and nature: perspectives from ecosystem-level biomimicry and regenerative design. 2022.

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Obrigado.

Foreword

As this work stands between urbanism, ecology and environmental sciences, I believe it is essential to acknowledge my personal path and perspectives on these topics. They represent the starting point and a catalyst for this work.

I am a Brazilian white queer male. I grew up in the suburbs of a middle-sized city in the inner lands of Brazil in the state of São Paulo (São Carlos/SP, 257 thousand inhabitants). I lived on the edge of a popular and under development neighbourhood, by the side of a natural protected zone. From this perspective, I have started to experience and live the urban and natural spaces.

I am a walker. Walking created much of my other urban and nature experiences. Experiences that deeply influenced my professional path. Along with my brother, I explored the woods and unpaved streets around our house, looking for adventures. With my mother and father, I walked for leisure, as a moment to connect. With friends, we walked daily towards and back to the school. On these walks, my father slowly convinced me about the interest in environmental sciences and the need for transformative changes in our daily lives. During these walks, I learned to watch the city and how people and nature used and interacted with the space.

I graduated as an environmental engineer. Reducing human impacts and promoting sustainability has become core in who I am. In this path, I had my first international experience in the south of France, discovering new cities, new urban and social dynamics and new landscapes. When I went back to Brazil, I lived in São Paulo for my first job. It was my first immersive metropolitan experience. Living in the lovely and chaotic São Paulo in 2013, in the middle of the protests against the new public transportation fare, forged a solid desire to redirect my practice toward urban questions. In this movement, I came back to France to follow my studies. This time I was in the Metropolitan Parisian region, studying Sustainable Transportation, Mobility and Planning.

In my never-ending movements, I went back to Brazil and created a consulting company on sustainability. This company, Genos, was born from the idea to create the change that we desired to see in Brazilian sustainability practice. At this company I structured and led an offer for sustainable urban planning projects for small and medium-size Brazilian cities. It was a continuous process of learning and co-creation, trying to fight inequalities and externalities of our urbanisation process and urban lifestyles.

The present research was born from this challenge and my desire of transforming urban sustainability in Brazil. I wanted to move forward in my practice and knowledge. Just reducing damage was no longer enough for me. I was eager for new methods, new approaches that could be more disruptive than the incremental changes we were proposing.

From an informal discussion with my best friend, I learned about biomimicry. We wondered how bees organised their hives and how these principles could be used in urban planning. It was mind-blowing but straightforward for me at that time.

I started talking to people in Brazil and structuring this research project. I applied to a few PhD programs there, without much success - my subject was considered utopic for the Brazilian urban and ecological research reality. In the quest to make it happen, I met Ceebios, who helped me make this project mature and put me in touch with the CESCO research Lab and Philippe Clergeau, who were crucial in helping me organise and realise this research.

Ceebios is the french network of competencies and a centre of expertise in biomimicry, catalysing its development in France. Besides funding this research in partnership with ANRT, Ceebios contributed with the specialised knowledge and expertise on biomimicry. Ceebios aimed with this work to advance ecosystem-level biomimicry theories, making it operational for its stakeholders.

The CESCO (UMR 7204 « Centre d'Ecologie et des Sciences de la Conservation) is a French research lab in ecology and conservation sciences, associated with the French Natural History Museum. Philippe Clergeau, who supervised this work, led the Urban Ecology research group, contributing to this work's ecology perspectives and methods.

With this triple configuration, this research materialised in a CIFRE PhD from 2019 to 2022. The results of this work may be a little far from the first question on my mind (i.e. the hives). Maybe they are even more utopic and challenging than my first ideas. They address the inevitable question of how to design, create and inhabit urban spaces that are net positive for society and nature.

As human beings, we are not the single engineering species, others have changed the space to create their habitats before us, and others will still do once we are gone. Ants, beavers and woodpeckers are all ecosystem engineer species. They create, modify, and maintain their habitats, causing physical state changes on ecosystems' biotic and abiotic structures. In this process, they also module the availability of resources to other species.

But what are the differences from these species and their way of creating their habitat to our way? I would say that they are constrained by ecosystems and ecological limitations that we humans somehow succeed to deal with and to bypass. Nevertheless, their modifications usually create positive feedback loops, increasing the ecosystem complexity and structure, sharing the benefits, and thus creating more conditions for life. We, humans, opperate in extreme opposition from the previous example. We simplify ecosystems, destroy habitats, and concentrate benefits. It may be a sad statement, but our current life patterns and urbanisation create conditions for death. And here, death does not only refer to the biodiversity crisis and habitat destruction. It also relates to the death of fellow human beings marginalised, with lesser access to benefits from nature, suffering from natural disasters and pollution-related diseases.

Rethinking how we inhabit this planet and how we share benefits among ourselves and other living species is crucial in our time. I hope this work can mark a small step toward it.

Eduardo Blanco.

Table of contents

Table of figures

Introduction

In the last decades, cities have progressively polarised human activities. As key nodes of our socio-economical systems, they increasingly concentrate human populations and economic activities. For instance, in 2018, 55% of human society lived in urban areas, generating more than 80% of the global GDP. Furthermore, by 2050 it is expected that 66% of the human population will be urban (United Nations - Department of Economic and Social Affairs - Population Division, 2019; United Nations, 2018).

Important environmental impacts follow this urbanisation process. From 1992 to 2019, the total urban area around the globe doubled, characterizing an unprecedented land-use change and urban sprawl process (IPBES, 2019). Moreover, urban activities and the urban lifestyle are responsible for more than 70% of worldwide greenhouse gas emissions, playing a central role in climate change (United Nations, 2018) . These urban impacts profoundly affect ecosystems' functioning, destroying natural habitats, artificializing land and driving global biodiversity decline (Alberti, 2005; IPBES, 2019). Therefore, these impacts are also responsible for creating and exacerbating existing social inequalities (IPBES, 2019).

However, the complex functioning of ecosystems provides human society with a series of essential benefits for our well-being, such as food, climate regulation and potable water (Millenium Ecosystem Assessment, 2005). This interdependency, highlighted through the notions of Ecosystem Services and Nature Contributions to People (IPBES, 2019; Millenium Ecosystem Assessment, 2005), has become widely acknowledged in science.

In this context, urbanisation processes hold several action opportunities to revert actual unsustainable urban trajectories. In the political sphere, international engagements towards these objectives multiply. Examples are the Sustainable Development Goal 11 – Sustainable Cities and Communities, formalising the objective to enhance sustainable urbanisation around the globe by 2030 (United Nations, 2018), and the New Urban Agenda, presenting commitments on the preservation of urban ecosystems functions and sustainable urban development patterns (United Nations, 2017). In science, the IPBES report from 2019 highlighted the necessary transformative change in our urbanisation process to allow us to build sustainable cities that address societal needs while conserving and restoring nature and enhancing ecosystem services (IPBES, 2019). Finally, from a societal perspective, we also observe a raising awareness on the topic by city dwellers, which tends to request more green spaces and nature interaction opportunities in urban spaces (Clergeau, Jarjat, Raymond, & Ware, 2020).

Urban areas are a subject of human design, and hence, the way we design and redesign them is an important lever to tackle the previously discussed challenges (Barot et al., 2019). Using methods, resources, knowledge and creativity, we design, organise and transform the space, directing it towards a considered preferable situation from the design team's perspective (Arab, 2018). On this basis, different methods and tools have been proposed to assist in integrating sustainabilty in the urban design process (Fenker & Zetlaoui-Léger, 2017; Grazieschi, Asdrubali, & Guattari, 2020; Reith & Orova, 2015). Namely, the diverse market-based or public initiated green building and neighbourhood sustainable assessment tools, such as LEED and EcoQuartier labels.

Despite their advancements helping mainstream sustainable practices in architecture and urban design, recent research highlighted these frameworks gaps and limitations to promote sustainability (Subramanian, Chopra, Cakin, Liu, & Xu, 2021). This scientific and operational debate leads to the development and proposition of innovative tools and design approaches that could contribute to the transformative change necessary in urban design practice, the focus of this research.

i. Designing sustainable neighbourhoods

From an instrumental perspective, neighbourhoods are an urban component, a delimited part of urban space imbricated on the complex structure of a city, a part of a larger whole and a system itself. From a phenomenological perspective, neighbourhoods are also unique urban phenomena and cultural entities. They represent an urban unit with a certain degree of social and historic cohesion, a collective sense of place and an identity (Choguill, 2008; Kallus & Law-Yone, 2000).

Since modernism, the neighbourhood unit has become a recurrent design subject and an essential part of the urban production mechanisms. Based on an instrumental point of view, the neighbourhood scale offers a manageable environment to designers and planners, and it allows to address systemic questions that would be too complex at the city scale and limited at the building scale (Grazieschi et al., 2020; Kallus & Law-Yone, 2000). Moreover, the neighbourhood scale allows society to reorganise the city and manifest current societal ideals and goals in urban space. In this logic, small city patches are designed and redesigned, promoting expansion and incremental changes to the urban area and enhancing human well-being (Kallus & Law-Yone, 2000).

In a capitalist and market-based urban development context, neighbourhoods also became a marketable product, reinforcing their role as an urban production mechanism. They are not only residential units for sale but a whole urban system, associated with various benefits for the dwellers adding value to the final product (Fenker & Zetlaoui-Léger, 2017; Kallus & Law-Yone, 2000).

The design or redesign process of a neighbourhood is usually manifested as an urban project. In this process, a design team will elaborate and implement strategies and interventions into a site, to move it from an initial situation to a new desired one (Arab, 2018). Internal and external factors, such as the site reality, local governance, political agenda, financial resources, economic context, design team composition, project vision and societal goals, highly influence the design process and its outcomes (Arab, 2018; Carmona, 2014).

Within the context of climate change, ecological crises and the rising awareness of the role of urbanisation on these processes, sustainability and environmental topics have gained space in the neighbourhoods design practice (Chastenet et al., 2016; Grazieschi et al., 2020; Larrue, 2017; Subramanian et al., 2021). Thus, the notion of sustainable neighbourhoods emerged and consolidated, with sustainability topics affecting the neighbourhood's design process and outcomes.

The first sustainable neighbourhood examples worldwide can be traced back to the 1980s and 1990s, such as the Kranichstein bioclimatic district (1981–1983). The subject gained then momentum by the end of the 1990s and the 2000s, following the emergence of environmental topics marked by the Bruntland report in 1987 and the Rio summit in 1992, giving birth to iconic sustainable neighbourhoods, namely Malmo Boo1 (1998 – 2001) and BedZED (1998 – 2002) (Grazieschi et al., 2020).

Lately, between 2006 and 2012, we observed the introduction of several tools to assist the design process of sustainable neighbourhoods and assess their performances (Grazieschi et al., 2020). These tools aimed to foster the integration of sustainable practices at the neighbourhood's scale, evolving established green buildings tools and principles, focusing on reducing the project environmental impacts. Examples are BREEAM Communities, launched in 2008, LEED-Neigbourhoods, launched in 2010, DGNB Urban Districts, launched in 2011, the Green Star Communities, launched in 2012, the EcoQuartier framework ("*Référentiel EcoQuartier*") officially launched in 2012 in France and the CityLab Framework developed and proposed by the Sweden Green Building Council in 2010 (Figure 1) (Chastenet et al., 2016; Grazieschi et al., 2020; Reith & Brajković, 2021).

These sustainable neighbourhood frameworks have gained significant attention and internationalisation, helping mainstream sustainable practices and reducing neighbourhoods environmental impacts. Today, several frameworks are available (Sharifi & Murayama, 2013), and for instance, only LEED-ND counts with more than 230 certified projects worldwide. However, despite its development, they have been the target of critiques, primarily pointing to their incapacity to foster sustainability from a holistic and systemic perspective (Reith & Orova, 2015; Sharifi & Murayama, 2013; Subramanian et al., 2021).

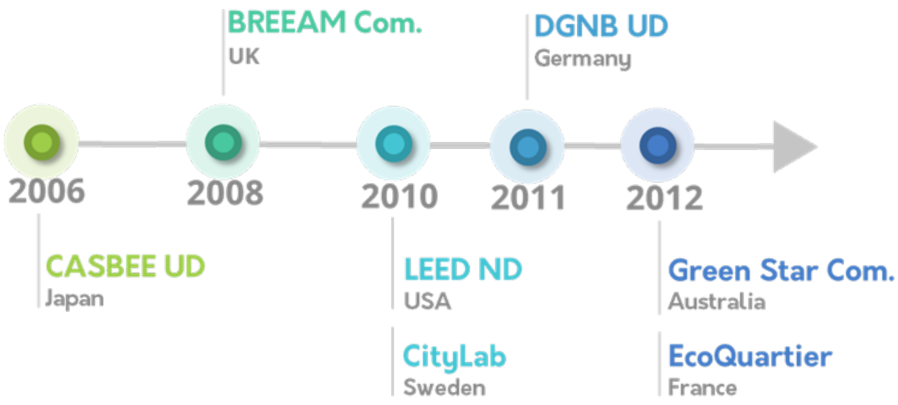

Figure 1: Timeline of the emergence of sustainable neighbourhood design tools.

Some of these sustainable neighbourhoods frameworks, such as LEED-ND, have a too prescriptive and top-down approach, relying on checklists and optional design principles (Grazieschi et al., 2020; Wangel, Wallhagen, Malmqvist, & Finnveden, 2016). This kind of approach can promote homogenisation of the project outcomes, projects that are not linked to the site context and do not necessarily have a better environmental performance than conventional projects (Cole, 2012; Sharifi, Dawodu, & Cheshmehzangi, 2021).

While some frameworks focus on projects environmental performance, such as Green Star Communities, relying on environmental performance indicators, they still hold a static and non-systemic perspective of the urban project (Boyle, Michell, & Viruly, 2018; Cole, 2012). They fail to integrate a life cycle perspective, to address future evolutions of the neighbourhood and its relation to its surroundings (Grazieschi et al., 2020; Wangel et al., 2016). Furthermore, topics such as energy, which presents more technical maturity and societal awareness, are privileged in relation to other more recent and emerging ones, such as biodiversity (Grazieschi et al., 2020; Reith & Orova, 2015). Regarding urban biodiversity, despite the growing number of studies on the topic, operational recommendations to favorize it still struggle to see the light and to be integrated in design frameworks (Flégeau, 2020).

These lacks and limitations created space for the conceptualisation of more systemic, sustainable urban design approaches. Among the emerging theories on the topic, one, in particular, has gained remarkable relevance in research and practice since the 2010s, it is called regenerative design (Brown et al., 2018).

ii. Regenerative design: theory and practice

Unlike the established sustainable neighbourhoods' frameworks, which aims primarily to limit environmental impacts, the regenerative design proposes to go beyond neutral environmental performance (Figure 2). To promote net-positive urban projects that benefit society and nature and promote a co-evolution of the two systems, it urges to rely on a systemic perspective and a territorialised approach (Attia, 2016; Brown et al., 2018; Cole, Oliver, & Robinson, 2013; Zhang, Skitmore, De Jong, Huisingh, & Gray, 2015).

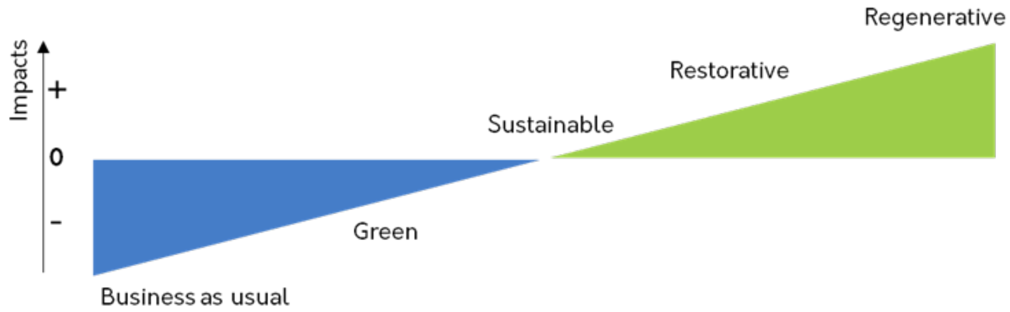

Figure 2: The regenerative design paradigm shift.

The theory dates from 1994, with the work of John Tillman Lyle, an American landscape architect. Lyle built upon the previous works from other researchers and practitioners on landscape architecture, such as Olmsted and MacHarg, to postulate that human-designed systems should replicate the performance and logic of natural systems. In his work, Lyle highlighted the need to improve the circularity of our urban systems, relying on their own functional process. For Lyle, landscape and urban projects should rely on the local ecosystems patterns and the site potentialities, leading to a new site reality that strengthens the existing natural and social systems process (Lyle, 1994).

In the last decade, the theory regained attention for its potential to bypass the limitations of green buildings and sustainable neighbourhoods frameworks. Hence, giving birth to a new generation of frameworks and experimentations to move from theory to practice. Examples are the architectural and urban design practices of companies such as Perkis+Will and Regenesis, which applied regenerative approaches to several projects, mainly in America, such as the Blatchford Redvelopment project that requilfied an airport site located in Edmonton, Canada (Figure 3). Besides, the Living Building Challenge (LBC) and the Lenses Framework are two regenerative design tools that reached maturity levels and have also been applied in architectural and urban design (Forsberg & de Souza, 2021; Hes & Du Plessis, 2014; Reith & Brajković, 2021).

While these experimentations have increased the number and reach of regenerative design (for instance, there are 134 certified LBC buildings worldwide), the approach is still seen as lacking operability and holding a too theoretical perspective (Clegg, 2012; Tainter, 2012). Regenerative design theories tend to reject reducionist approachs, like those using checklists and performance indicators. This fact, makes its translation on operational tools too complicated (Tainter, 2012). Moreover, assessing the desired positive impacts lack specific methods, reducing its credibility within operational stakeholders (Clegg, 2012). These difficulties led to an application that reached maturity in more manageable scales, such as at the building level, even if a larger scale offers more opportunities for systemic interventions (Pedersen Zari, 2018; Tainter, 2012).

The LBC and the LENSES framework are examples of such limitations. In the LBC, we note that the framework is only operational at the building level, with only a prototype for the neighbourhood scale. Moreover, it adopts a reductionist approach to translate regenerative design principles in design guidelines, presenting performance imperatives and checklists to guide design teams towards a regenerative project (International Living Future Institute, 2019). In contrast, the Lenses framework is more flexible in terms of scale but does not aim to assess the positive impacts, focusing on the design process and not on the outcome (Plaut, Dunbar, Wackerman, & Hodgin, 2012).

Facing such limitations, new fraemeworks to promote operational approaches of regenerative design are still necessary (Cole, 2012). Among the current developments, one based on ecosystem-level biomimicry has been highlighted as holding particular potential in guiding the design process and assessing the positive impacts of the regenerative approach (Pedersen Zari & Hecht, 2020).

a)

b)

c)

Figure 3: a) Edmonton City Center Airport. b) Blatchford Redevelopment project using Regenerative Design, by Perkins+Will. c) Blatchford land use map that is under implementation.

iii. Ecosystem-level biomimicry for regenerative design

Biomimicry is defined as "interdisciplinary philosophy and conceptual approaches that take nature as a model to address the challenges of sustainable development (social, environmental and economic)" (ISO, 2015). With a wide range of applications, such as on chemistry and material sciences (Rovalo, McCardle, Smith, & Hooker, 2019; Wanieck, Fayemi, Maranzana, Zollfrank, & Jacobs, 2017), recently it has also consolidated as an opportunity to promote sustainable innovations for urban areas, helping to tackle climatic and ecological challenges (Buck, 2017; Chayaamor-Heil, Guéna, & Hannachi-Belkadi, 2018; Pedersen Zari, 2018).

By taking inspiration from living systems, we can enhance the performances of our urban systems. For instance, it is possible to design new building materials, construct the buildings more efficiently, and optimise their water and energy consumption (Uchiyama, Blanco, & Kohsaka, 2020). While opportunities are at all scales, biomimicry has mainly been explored for architecture, at the building scale (Buck, 2017; Uchiyama et al., 2020). The development of biomimetic façades is a particular field of interest. On this topic, designers tend to find inspiration on individual organisms, aiming to design adaptative systems for building regulation (e.g. temperature, light, humidity regulation)(Cruz et al., 2021). Still, building thermal regulation is also a recurrent topic at this scale. Examples are the Eastgate Building in Harare (Zimbabwe),the Council House 2 (CH2) in Melbourne (Australia) and the Nianing Church in Senegal (Figure 4), which finds inspiration in termite mounds to propose passive thermal regulation systems (Chayaamor-Heil et al., 2018; Cruz et al., 2021; Pedersen Zari, 2018).


Figure 4: Nianing Chuch, Senegal. The project draw inspiration from termite mounds for passive thermal regulation (Regis L'Hostis/IN SITU ARCHITECTURE).

The opportunities at the urban scale just started to emerge later, with higher relevance from 2010 onwards (Uchiyama et al., 2020) (Figure 5). At this scale, where it is apparent, inspiration typically draws upon ecosystems rather than single organisms (Blanco, Cruz, Lequette, Raskin, & Clergeau, 2021; Buck, 2017). Ecosystems are also emerging as models at the architectural level, holding opportunities to address systemic questions, related to the project environmental performance (see Blanco et al., 2021 in Appendix C, page 219 in which the ecosystem model has been the more frequent model declared by 16 french bio-inspired urban projects).

Ecosystems are complex ecological systems that integrate biotic and abiotic components of an environment and their interrelationships, such as matter and energy flows (Odum, 1969). These systems are resilient, adaptable, self-regulating and function as semi-open systems (Kay, 2000; Odum, 1969). Cities, also complex systems and central to current environmental and climate issues, are a potentially fertile field for the transposition of ecosystem principles.

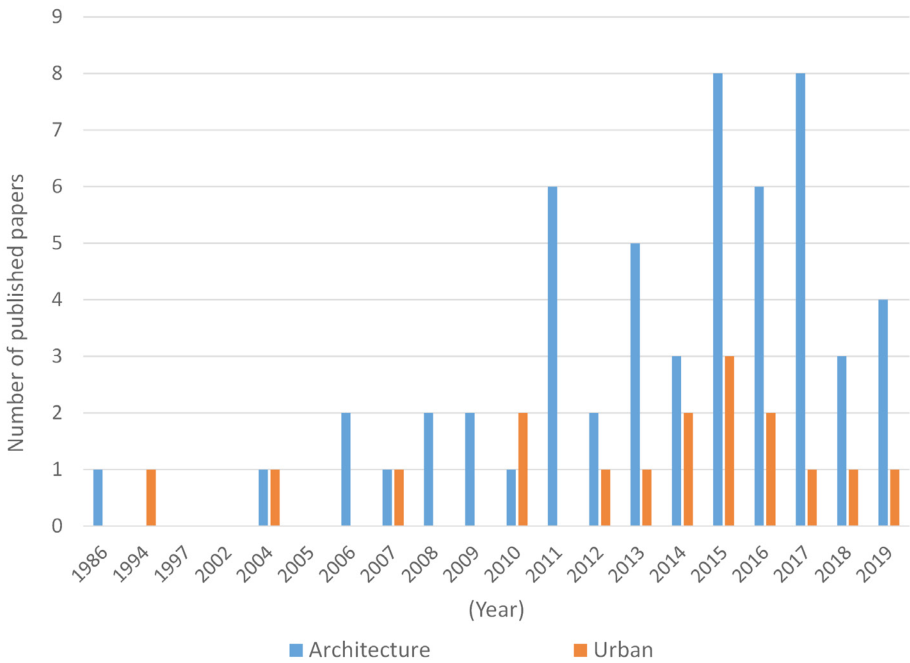

Figure 5: Number of papers published in individual years concerning architectural and urban design biomimicry applications (Uchiyama, Blanco and Kohsaka, 2020).

In order to tackle the main operational barriers of regenerative design, Pedersen Zari proposed an urban design method based on ecosystem-level biomimicry. The method, named "Ecosystem Services Analysis", relies on understanding the functioning of the local ecosystem through ecological metrics. As ecological metrics, the method uses the notion of ecosystem services. In a comparative approach (comparing the pre-development situation with the designed project), these metrics help to define regenerative design objectives and inform the selection of interventions on the space (Pedersen Zari, 2015, 2018).

Despite other methods to promote ecosystem-level biomimetic urban design, a case study highlighted that indicator-based approaches, such as those relying on ecosystem services assessment, were the most used in practice (Hayes, Desha, & Gibbs, 2019). While the approach has been applied in a few projects worldwide, such as the Lavasa Hill in India and the Lloyd Crossing in the USA, it holds limitations related to integrating ecosystem services theories on urban design and their assessment, requiring further development (Pedersen Zari, 2018).

iv. Ecosystem services

The ecosystem services concept is a subject of extensive research and application in sustainable urban sciences. The notion, developed in the 1990s, has been proposed as a framework to facilitate understanding human dependencies on ecosystems and provide elements on the economic valuation of these benefits (Abbadie, 2020; Costanza et al., 1997; Daily, Postel, Bawa, & Kaufman, 1997)..

In 2005, the Millennium Ecosystem Assessment report popularised the concept, presenting the following definition:

> *"Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling" (Millenium Ecosystem Assessment, 2005).*

More recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report from 2019 proposed the adoption of a new term, namely "Nature's contribution to people", enlarging the notion:

> *"Nature's contributions to people refers to all the contributions that humanity obtains from nature. Ecosystem goods and services, considered separately or in bundles, are included in this category. Within other knowledge systems, nature's gifts and similar concepts refer to the benefits of nature from which people derive good quality of life. Aspects of nature that can be negative to people (detriments), such as pests, pathogens or predators, are also included in this broad category"(IPBES, 2019).*

Despite its development in the economic field, ecosystem services found several applications in conservation and planning disciplines. Thus, assessing ecosystem services to inform decision making has become a focal point in research and practice, and various methods, for the most diverse territorial scales have been developed (Bagstad, Semmens, Waage, & Winthrop, 2013; Harrison et al., 2018).

However, to assess the benefits it is important to understand the ecosystem services production process and their connection to the human and social sphere. Haines-Young & Potschin (2010) explored the ecosystem services theory to propose an ecosystem services framework: the ecosystem services cascade. The cascade defines and organises the critical elements on the provision of ecosystem services, constituting a unified analytical framework that highlights the environmental and social sides of this process. The cascade framework helped advance the concept, its operational implementation, and the definition of assessment methods and indicators (Haines-Young & Potschin, 2010; Potschin et al., 2018).

The ecosystem services cascade comprises five elements: biophysical structures/processes, functions, services, benefits, and values. It represents the necessary sequence in socio-ecosystems to create the goods and benefits from the ecosystems. The framework accents the role of ecosystems structures as the starting point of services supply (Figure 6). Biophysical structures are the biotic and abiotic elements that constitute the ecosystem and its patterns, ecosystem processes or functions are the ecological interactions that take place over time, services are the flows of benefits created by ecosystem processes and functions, and finally, goods and benefits are the material or immaterial results of this chain that contribute to increasing human well-being (La Notte et al., 2017).

In summary, the cascade framework highlights two main essential components to the final perceived benefits from ecosystem functioning. They are (1) the quality/integrity of the ecosystem structure and (2) the human pressure that impacts the state of these same structures (Potschin et al., 2018; Puppim de Oliveira et al., 2011). Further, the framework has been associated with the DPSIR framework (Drivers, Pressures, State, Impact, Response). From an adaptative management perspective, this association highlights the causal pathway from anthropic drivers, leading to pressures on the ecosystem and their state alteration and the development of management responses (Müller & Burkhard, 2012) (Figure 6). From an urban design perspective, these management responses are the interventions selected and implemented during project design and development.

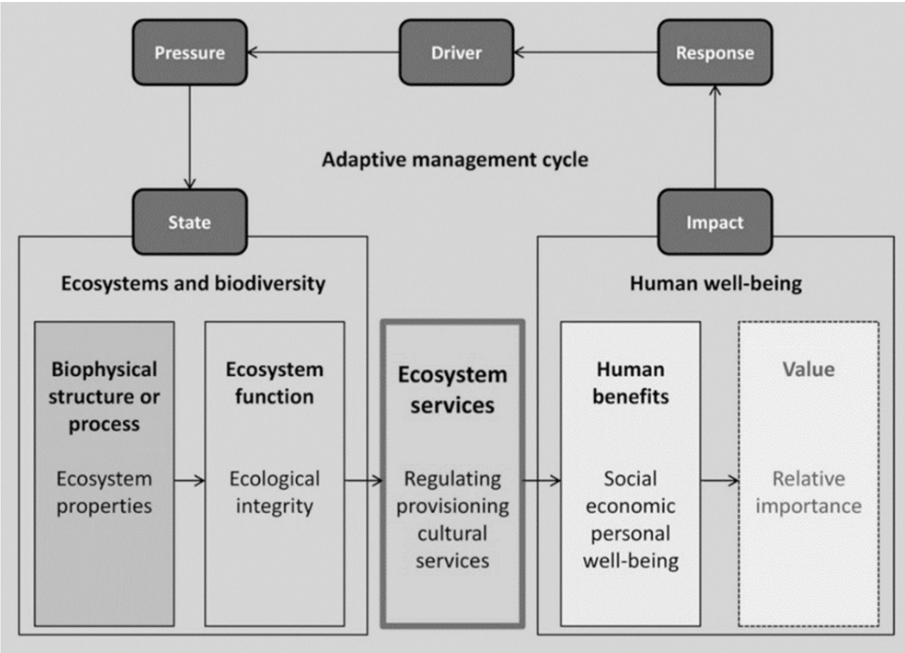

Figure 6: Ecosystem services cascade and the DPSIR framework (Kandziora, Burkhard, & Müller, 2013).

Since the concept formalisation, several research projects have been conducted to develop methodologies and frameworks to assess ecosystem services. However, its operationalisation at the urban scale faces challenges such as the lack of available data (Hermelingmeier & Nicholas, 2017; Kaczorowska, Kain, Kronenberg, & Haase, 2016), and the difficulties in understanding ecosystem services supply and demand on complex socio-ecosystems as cities (Alberti, 2005; Haase et al., 2014). Haase et al. (2014) realised a first systematic review to understand the actual application of ecosystem services evaluation in urban studies. They raised an important issue related to the lack of homogeneity and good use of indicators to illustrate the ecosystems' services.

From an assessment perspective, ecosystem services indicators can refer to different elements of the ecosystem services cascade (such as ecological structure, social benefits, added values, or even pressure on the ecosystem) (Braat & de Groot, 2012; Van Oudenhoven, Petz, Alkemade, Hein, & De Groot, 2012) or the DPSIR framework (like assessing the ecosystem state, the pressures they face or even the responses adopted by society) (Müller & Burkhard, 2012).

Ecosystem services assessment techniques can be organised into four main typologies: biophysical, socio-cultural, monetary, and integrative. Harrison et al. (2018) reviewed 43 different methods for assessing ecosystem services, such as generation models like INVEST, techniques based on mapping and data analysis in GIS platforms, cost-benefit analyses and qualitative narrative analyses (Harrison et al., 2018). Nevertheless, due to their complexity and multidimensionality, ecosystem services remain difficult to measure in an operational context, despite being an essential tool to support planning and decision-making in urban development (Tolvanen et al., 2016; Wright, Eppink, & Greenhalgh, 2017).

Different assessment frameworks and methodologies have recently emerged at the European Union level, mostly relying on a systematic combination of several indicators to represent best their complexity (EC 2012; Naumann et al. 2011). Examples are those developed by the EKLIPSE project (Eklipse et al., 2017) and Nature4Cities project (NATURE4CITIES, 2018), which present a broader focus on assessing the performance of the societal responses and their impact on ecosystem services production.

v. Research objectives

On these bases, this research aims to propose an operational regenerative design framework based on ecosystem-level biomimicry and ecosystems services theories. This framework could help design teams draw urban projects that are net positive in terms of ecosystem services and promote mutual benefits for society and nature.

To reach this objective, answering the following questions is essential:

1. How do theory and practice on regenerative design align and diverge from other sustainable urban design approaches?
2. How are ecological theories on ecosystem services production mobilised on the current practice of ecosystem-level biomimicry for regenerative design? Which are the lacks from an ecological perspective?
3. What urban interventions and solutions can be used on neighbourhood projects to enhance the production of ecosystem services and promote benefits for society and nature?
4. Which governance elements from the urban design process enhance the success of these projects?
5. To what extent are the different strategies to promote urban ecosystem service used in certified sustainable neighbourhoods, and what are the needs for new tools and barriers to implementing them successfully?
6. Which indicators could assist the design of regenerative and ecosystem-inspired neighbourhoods and assess their performance?

To answer these questions, we used different methods, such as bibliographic research, case studies, interviews and surveys. The work is structured in three chapters, as detailed here.

In the first chapter, we will get interested in the theoretical approaches of regenerative design and ecosystem-level biomimicry and their case applications. At first, through a literature review and qualitative analysis, we will understand the underpinnings of contemporary regenerative design, comparing it to other sustainable urbanism schools and defining the term "regenerative urban project". Still, in this chapter, we will analyse two projects that applied ecosystem-level biomimicry approaches for regenerative design to understand how the ecological concepts of ecosystem and ecosystem services are used, their lacks and their limitations.

In the second chapter, we will concenter on the neighbourhood design practice, with a larger focus on projects that somehow find inspiration on ecosystems and try to promote positive impacts. Here we analyse case studies designed under ecosystem-level biomimicry, regenerative design and the EcoQuartier frameworks. Our first step is to identify which kind of interventions are proposed in the design documents to promote their reconnection with local ecosystems and positive impacts. Through typological analysis, we identified larger families of strategies and the lack and trends in these interventions. In a second moment, we got interested in the projects' design and implementation governance aspects, defining potential governance success factors.

Finally, the third chapter concentrates on delineating the aimed design framework. First, we confirm our hypothesis on the preferred strategies that helps to produce ecosystems services at the neighbourhood scale and refine the strategies typologies through a survey with a extensive set of international and certified sustainable neighbourhoods. In a second time, we build an indicator set based on established indicators. We analyse the indicators using a RACER method and a survey with operational stakeholders. Finally we propose an indicators set that is operationnal and could assist regenerative urban design process and assessment.

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Chapter 1

Exploring regenerative design and ecosystem-level biomimicry theories

Summary

This chapter aims to build a base on the two leading theories used in this work: Regenerative Design and Ecosystem-level biomimicry. These two approaches are our starting point toward proposing a neighbourhood design tool. Thus, building a deep understanding of them, their relations to similar approaches, and their real-world applications is fundamental.

We address here our first two general research questions through two different peer-reviewed scientific papers.

1. How do theory and practice on regenerative design align and diverge from other sustainable urban design approaches?

2. How are ecological theories on ecosystem services production mobilised on the current practice of ecosystem-level biomimicry for regenerative design? Which are the lacks from an ecological perspective?

The first one, a review paper published in the "Cahiers de la recherche architectural urbaine et paysagère", concentrate on regenerative design theories. In this paper, we hold a historical and epistemological approach, aiming to understand the origins and evolutions of the term, its correlations and differences with other sustainable urbanism schools, its application through three different operational tools and the principles that should constitute a regenerative urban project.

The second sub-chapter focuses on ecosystem-level biomimicry as a tool for regenerative design at the neighbourhood scale through a review paper published in "Sustainability". This article analyses other urban and landscape design methods that rely on ecosystem data to inform the design process, highlighting differences and convergences. Further, we briefly analyse the concept of ecosystem services and two case studies of urban projects with an ecosystem-level biomimetic approach. These two cases represent the few public available ecosystem-level projects at the neighbourhood scale that reached some level of implementation. Finally, we use the ecosystem services cascade framework to analyse how the concept is used in the projects, helping us to identify lacks and further research questions.

Resumé

*Ce chapitre vise à établir une base sur les deux principales théories utilisées dans ce travail : Le «*regenerative design*» et le biomimétisme de l'écosystème. Ces deux approches constituent notre point de départ pour proposer un outil d'aide à la conception du quartier. Il est donc fondamental d'acquérir une compréhension approfondie de ces approches, de leurs relations avec des approches similaires et de leurs applications dans le monde réel.*

Nous abordons ici, au travers de deux articles scientifiques évalués par des pairs, nos deux premières questions générales de recherche:

*1. Comment la théorie et la pratique du «*regenerative desing*» s'alignent-elles et divergent-elles des autres approches du projet urbain durable ?*

*2. Comment les théories écologiques sur la production de services écosystémiques sont-elles mobilisées sur la pratique actuelle du biomimétisme des écosystèmes pour le «*regenerative design*» ? Quels sont les manques d'un point de vue écologique ?*

*Le premier, un article de synthèse publié dans les «*Cahiers de la recherche architecturale urbaine et paysagère*», se concentre sur les théories du «*regenerative design*». Dans cet article, nous adoptons une approche historique et épistémologique, visant à comprendre les origines et les évolutions du terme, ses corrélations et ses différences avec d'autres écoles d'urbanisme durable, son application à travers trois outils opérationnels différents et les principes qui devraient constituer un projet urbain régénératif.*

La deuxième partie de ce chapitre se concentre sur le biomimétisme de l'écosystème comme outil de conception régénérative à l'échelle du quartier, à travers un article de synthèse publié dans «Sustainability». Cet article analyse d'autres méthodes de conception urbaine et paysagère qui s'appuient sur les données des écosystèmes pour informer le processus de conception, en soulignant les différences et les convergences. En outre, nous analysons brièvement le concept des services écosystémiques et deux études de cas de projets urbains avec une approche biomimétique à l'échelle de l'écosystème. Ces deux cas représentent les quelques projets réalisés avec des approches de biomimétisme de l'écosystème à l'échelle du quartier qui ont atteint un certain niveau de mise en œuvre. Enfin, nous utilisons le cadre de la cascade des services écosystémiques pour analyser la manière dont le concept est utilisé dans les projets, ce qui nous aide à identifier des lacunes et d'autres questions de recherche.

1.1 Regenerative urban design: An emerging concept in urbanism

Blanco, E., Raskin, K., & Clergeau, P. (2021). Le projet urbain régénératif : un concept en émergence dans la pratique de l'urbanisme. Cahiers de La Recherche Architecturale, Urbaine et Paysagère, 0–20. https://doi.org/10.4000/craup.8973.

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Le projet urbain régénératif : un concept en émergence dans la pratique de l'urbanisme

Regenerative urban design: a concept emerging in urbanism

Eduardo Blanco, Kalina Raskin et Philippe Clergeau

Introduction

1 Repenser la forme et le fonctionnement de nos systèmes urbains dans la perspective d'une meilleure relation entre ceux-ci et les systèmes naturels est un enjeu contemporain majeur de l'urbanisme[1]. L'urbanisme organise et transforme l'espace par le biais du projet urbain. Au travers des multiples choix d'aménagement, pondérés par les acteurs du projet, le territoire évolue et se transforme en continu[2].

2 Dans l'histoire de l'urbanisme plusieurs théories et approches pratiques ont essayé d'intégrer des connaissances en écologie dans le processus d'aménagement[3]. Malgré les avancées obtenues, la pratique du projet urbain n'a jusque-là pas réussi à intégrer les connaissances actuelles sur le fonctionnement des écosystèmes[4]. Ainsi, le processus d'urbanisation est à la source de fortes pressions sur les écosystèmes[5] et au centre de l'érosion croissante de la biodiversité et du déséquilibre des systèmes naturels[6].

3 Dans ce contexte, un changement de paradigme dans la conception du projet urbain durable et écologique semble essentiel. Le « *regenerative design* », notion d'origine américaine, s'offre un cadre théorique pour catalyser ce changement. Bien que sa conceptualisation et une mise en pratique se développent rapidement dans le monde[7], le concept reste encore très peu établi et pratiqué en Europe.

4 L'objectif de cet article est d'explorer l'historique et l'épistémologie du *regenerative design*, d'examiner les discours et outils de cette pratique, de les comparer avec d'autres théories de l'urbanisme durable et écologique plus développées en Europe, et ainsi de proposer une liste de principes pour faciliter l'opérationnalité des projets urbains

régénératifs, terme proposé et défini dans cette étude. Pour ce faire, nous utilisons une méthodologie de révision bibliographique du *regenerative design* avec une approche d'argumentation logique et d'analyse du discours par codage thématique[8].

5 Dans la première partie de cet article, nous nous consacrons à une courte généalogie du terme et de la théorie du *regenerative design*. La deuxième partie présente les lectures contemporaines du *regenerative design* et les ressemblances et différences par rapport à d'autres théories de l'urbanisme durable et écologique. La troisième partie présente trois outils pratiques proposés pour la mise en œuvre de ces approches, puis des cas d'application. La quatrième partie présente une révision bibliographique avec l'objectif d'identifier les principes clés du projet urbain régénératif. Enfin, la dernière partie présente des perspectives sur les défis de mise en pratique d'un projet urbain régénératif.

Les racines historiques du *regenerative design* dans l'urbanisme

6 Dans la planification et l'aménagement urbain, l'idée de relier le fonctionnement des systèmes urbains et celui des systèmes écologiques dans le but d'en tirer des bénéfices pour la société remonte au XIX^e siècle, avec les travaux des chercheurs et praticiens américains et anglais comme George Perkins Marsh, John Wesley Powell, Patrick Guedes, Sir Howard Ebenezer et Frederick Law Olmsted[9]. Ces travaux ont été pionniers dans la compréhension des processus écologiques et dans son application dans le projet urbain, avec un objectif d'augmenter la qualité de vie des populations humaines[10]. Par exemple, la pratique urbaine et paysagère de Frederick Law Olmsted (1822-1903) marque un moment important dans l'évolution de cette thématique. Dans plusieurs de ses travaux, comme le Central Park à New York et le Yosemite Valley Park en Californie, Olmsted a proposé une nature de proximité, intégrée dans l'aménagement des espaces urbains, avec une conception appuyée sur la compréhension des aspects écologiques et esthétiques de cette nature[11].

7 Dans les années 1960, après une montée en intérêt des thématiques environnementales dans la société (mise en évidence par exemple par la publication du *Le Printemps silencieux* de Rachel Carlson en 1962)[12], Ian MacHarg, architecte et paysagiste écossais et fondateur du département de *Lansdscape Architecture* de l'*University of Pennsylvania* reprend plusieurs des notions sur l'intégration et la compréhension des éléments de l'environnement dans la pratique de la planification territoriale et urbaine, dans son livre *Design With Nature* (1969). MacHarg a fait valoir qu'une compréhension approfondie des processus écologiques locaux est fondamentale avant de se lancer dans la conception de tout projet urbain ou paysager. Pour cela, il propose une méthode de diagnostic préalable à la conception du projet (*Ecological Method*). Celle-ci s'appuie sur des inventaires des écosystèmes, organisés et analysés selon un modèle en couches qui superpose les facteurs écologiques pertinents pour créer une lecture et compréhension des écosystèmes[13]. La méthode de MacHarg s'est largement consolidée par la suite et est ainsi devenue la base de multiples approches d'« analyse de l'adéquation du paysage » pour l'aménagement (*Landscape Suitabilty Analysis*)[14], courantes jusqu'à aujourd'hui dans les pratiques d'évaluation de l'adéquation de l'usage du sol afin de minimiser ses impacts négatifs[15].

8 Avec le rapport Bruntland en 1987 et la conférence des Nations Unies sur l'Environnement et le Développement en 1992, le besoin de repenser les processus d'urbanisation s'est encore renforcé. Ainsi, en 1994, John Tillman Lyle, professeur d'architecture paysagère à la California State Polytechnic University s'appuie sur les développements préalables de McHarg et d'autres scientifiques et concepteurs américains pour proposer pour la première fois le terme « *regenerative design* » appliqué à l'aménagement.

9 Lyle définit le *regenerative design* de la façon suivante :

> Le design régénératif consiste à remplacer les systèmes linéaires actuels de flux de débit par des flux cycliques au niveau des sources, du centre de consommation et des puits. [...] Un système régénératif prévoit le remplacement continu, par ses propres processus fonctionnels, de l'énergie et des matériaux utilisés pour son propre fonctionnement[16].

10 Avec cette définition, Lyle a remis en question la linéarité de nos systèmes urbains par rapport au fonctionnement des systèmes naturels. Il a ainsi argumenté que l'Homme peut concevoir des systèmes urbains circulaires qui contribuent à la régénération des écosystèmes naturels dégradés. Son approche met l'accent sur l'intégration des processus écosystémiques dans la conception et vise à aller au-delà d'un simple modèle d'analyse macroscopique. Pour cela, Lyle mobilise trois types d'informations pour que chaque projet puisse répondre aux besoins et fonctions vitales du site[17] : la structure des écosystèmes, les processus écosystémiques (comme la conversion de l'énergie, l'épuration des eaux et le cycle des nutriments) et les informations de localisation.

Les lectures contemporaines du *regenerative design*

11 Suite à cette formalisation par Lyle, le concept a été plus largement exploré dans le domaine de la recherche et de la pratique en urbanisme et architecture, essentiellement dans le milieu anglo-saxon. Dans un contexte de fort développement des pratiques de construction et aménagement écologiques (*green building and planning*), ce concept a été l'objet de différentes compréhensions et définitions.

12 Parmi ces différents développements contemporains, il est important de citer ceux plus théoriques menés par des scientifiques comme Raymond Cole et Crhisna du Plessis, ceux plus opérationnels menés par des équipes de conception, comme celle de l'agence Regenesis aux États-Unis, et ceux conduits dans un cadre mixte et européen, comme les travaux développés par l'action de recherche COST RESTORE de 2017 à 2021 (Rethink Sustainability Towards a Regenerative Economy)[18].

13 Dans le milieu académique, plusieurs discussions mettent en valeur le changement de paradigme dans la conception du projet apporté par le *regenerative desing*. Cole (2012)[19], par exemple, promeut le *regenerative design* comme une approche de conception que favorise la coévolution des systèmes humains et naturels dans une relation de partenariat, et non plus de concurrence[20]. L'auteur met aussi l'accent sur l'importance de la notion du « lieu » et de ses spécificités dans le processus de conception, le projet doit être ancré dans cette réalité pour se régénérer et apporter des bénéfices aux systèmes sociaux, écologiques et économiques[21]. Finalement, Cole présente le *regenerative design* comme une alternative aux pratiques de conception et évaluation des projets urbains durables basés sur des approches mécaniques, comme les labels LEED[22]. Dans la même lignée, Du Plessis[23], discute le *regenerative design* dans une optique

plus large, comme un concept qui fait progresser la notion de développement durable appliqué à l'architecture et l'urbanisme. Du Plessis utilise la notion de « changement de paradigme régénératif » (*regenerative paradigm shift*) pour mettre en évidence le besoin de nouvelles compréhensions du développement durable et passer à une vision holistique et systémique du monde et des systèmes vivants[24].

14 Bill Reed et Pamela Mang de Regenesis donnent une définition proche de celle proposée par Lyle, mais avec un regard vers son opérationnalité avec les notions de « stratégies » et de « technologies » pour la production d'impacts positifs. Cela est fondé sur une compréhension du fonctionnement interne des écosystèmes, qui génère des modèles visant à régénérer plutôt qu'à épuiser les systèmes de soutien de la vie et les ressources sous-jacentes dans des ensembles socio-écologiques[25]. Regenesis challenge aussi le terme « *design* » et prône un « développement régénératif » (*regenerative development*), dans lequel les parties prenantes sont centrales dans l'amélioration de la vie par le biais d'une responsabilité durable et partagée de gestion des territoires[26].

15 Finalement, le projet de recherche européen COST RESTORE, présente une définition du *regenerative design* qui synthétise plusieurs éléments du discours contemporain, avec une articulation centrale autour de la notion de la bonne santé des systèmes humains et écologiques et leur coévolution : « Régénératif : Permettre aux systèmes sociaux et écologiques de maintenir un état sain et d'évoluer[27]. »

16 Ces définitions, historiques et contemporaines, présentent plusieurs points de convergence et de divergence avec d'autres approches en urbanisme, en Europe et en Amérique du Nord, comme dans les cas du biorégionalisme, du mouvement territorialiste, du *Landscape Urbanism*, du métabolisme urbain et de l'urbanisme écologique.

17 Parmi les points de convergence, on identifie un processus de planification et de conception du projet urbain dans lequel les sciences écologiques sont proposées comme prisme central. Cette pratique a été largement critiquée par Danneels[28], qui a soulevé les problèmes d'application dans l'urbanisation de Bruxelles, qui entre 1970 et 2016 a été fortement influencé par des courants de l'urbanisme écologique et par des analyses du métabolisme urbain via ses flux de matière et énergie[29]. Selon Danneels, ces approches purement techniques ont été à la source d'une compréhension jugée trop « mécanique » de la ville, dans laquelle les aspects socioéconomiques et sensibles de la production de l'espace ont été négligés[30]. Cependant le *regenerative design* remet en question ces approches mécaniques et purement techniques dans la pratique du projet urbain contemporain (par exemple dans ceux du label LEED)[31]. Pour assurer une analyse holistique et participative, le *regenerative design* a besoin de s'appuyer sur de nouveaux outils[32], comme le Lenses Framework basé sur des approches sensibles et participatives dans les phases de diagnostic et de conception.

18 Un autre élément de convergence est l'ancrage territorial du projet. La compréhension du site dans tous ses aspects (écologie, culture, démographie, économie…) a un rôle majeur dans la pratique du *regenerative design* et doit primer dans la conception du projet. Ce volet peut se référer aux approches biorégionalistes de Kirkpatrick Sale, avec ses unités de planification basée sur les unités écologiques, mais aussi culturelles, souvent délimitées par les bassins-versants et au fort engagement des acteurs locaux dans le processus de planification[33]. Le mouvement territorialiste de Magnaghi, en Italie et en Europe, porte aussi un fort accent à la compréhension et émergence du *genius locci* pour une reconstruction des identités territoriales et pour un changement

de paradigme industriel et mécanique de la production de l'espace[34]. Malgré ces convergences, une divergence majeure avec tous ces mouvements est l'échelle de travail considérée. Les mouvements précédemment discutés ont comme cible l'échelle de la planification territoriale, et impactent par exemple les schémas directeurs, les zonages ou des projets à très large échelle. Le *regenerative design* est plus opérationnel aux échelles intermédiaires de la ville, comme celle du quartier, de la parcelle et du bâtiment.

De la théorie à la pratique : outils contemporains du *regenerative design*

19 Le *regenerative design* interroge les méthodologies et les outils traditionnels de conception de l'espace urbain[35] et de nouveaux outils ont été développés pour faciliter la traduction de ce concept dans la pratique du projet, comme des labels et des outils d'aide à la conception, notamment : (1) La certification Living Building Challenge (LBC), (2) le LENSES Framework et le (3) Biomimétisme des écosystèmes : Ecosystem services analysis (ESA). Le tableau 1 synthétise les informations clés concernant ces trois outils.

Living Building Challenge (LBC)

20 Le Living Building Challenge est un programme de certification et un cadre de conception développé aux États-Unis par l'International Living Future Institute et basé sur les notions du *regenerative design*[36]. Le programme phare est la certification à l'échelle du bâtiment, qui, en 2020, comptait 134 bâtiments certifiés et 690 projets enregistrés qui visent la certification. Il est reconnu pour être une des certifications les plus exigeantes en termes de développement durable.

21 La certification présente sept thématiques (lieu, eau, énergie, santé et bien-être, matériaux, égalité et esthétique) et vingt exigences qui guident les concepteurs vers un projet à impact positif pour son socioécosystème, qui prend les systèmes vivants comme modèle[37]. Parmi les exigences de ce cadre, y figurent, par exemple, l'autonomie en eau potable, en énergie et en traitement des eaux usées, la restriction à l'usage de technologies de combustion, la restriction à l'usage des matériaux nocifs pour la santé humaine et d'autres êtres vivants, la restriction à la construction du projet sur des zones vertes ou sensibles, l'obligation d'inciter le report modal avec des stratégies de mobilité douce ou décarbonée, la provision et la protection de l'accès universel à la nature, entre autres[38]. Un aspect particulier de ce label, qui diffère des systèmes d'évaluation plus conventionnels, est le fait que le label est accordé seulement après une validation des performances réelles du projet après douze mois d'opération, plutôt que celles estimées lors de la phase de conception du projet. Le label est ainsi réattribué chaque année sur la base de l'analyse des performances réelles annuelles.

22 Malgré son développement croissant, surtout en Amérique du Nord, le LBC présente plusieurs barrières à son utilisation et développement. Une barrière majeure est l'aspect réglementaire lié à l'approche d'autonomie du bâtiment central de ce programme de certification, qui va à l'encontre des réglementations et politiques locales existantes dans plusieurs pays européens[39]. Mais le LBC permet aussi des certifications thématiques, plus souples, dans lesquelles seulement certains impératifs clés doivent être respectés.

23 Une autre barrière au LBC est l'échelle d'application. Comme de nombreux cadres et labels de conception du projet urbain durable, il est principalement orienté sur l'échelle du bâtiment, et ce n'est que récemment que ce cadre a commencé à aborder des problèmes à plus grande échelle avec une version pilote adaptée à l'échelle du quartier, le « Living Community Challenge », encore très peu répandu.

24 Un exemple de projet certifié LBC est le projet « The Paddock », à Castlemaine, en Australie, qui compte 26 logements certifiés. Jeff Crosby a conçu le projet pour rendre l'écosystème local plus sain par le biais du projet, présentant des engagements solides envers la biodiversité et la production alimentaire locale. Conformément aux exigences du LBC, le projet présente plusieurs stratégies pour restaurer l'habitat et la biodiversité, être autonome en eau et en énergie, s'appuyer uniquement sur les ressources disponibles localement et créer un impact socioécologique positif sur le site. Le projet s'est appuyé sur un diagnostic écologique participatif du site de trois jours pour établir le fil conducteur du projet, en identifiant les caractéristiques du site liées à l'eau, au sol, à la végétation, aux oiseaux, aux insectes, aux amphibiens, aux reptiles et aux mammifères[40].

LENSES Framework

25 Le Living Environments in Natural, Social, and Economic Systems (LENSES) Framework, initialement développé par l'Institut pour l'environnement bâti de la Colorado State University et maintenant géré par Centre pour les environnements vivants et pour la régénération (CLEAR) organise un processus de conception participative que permet une lecture du socioécosystème en étude, afin de structurer des séances d'échanges, de diagnostics et de planifications stratégiques[41]. Le cadre LENSES vise à guider les équipes dans le processus de développement régénératif et à faire évoluer les mentalités des acteurs engagés dans la conception des projets. Il s'agit d'un cadre applicable à toutes les échelles des projets urbains.

26 Le cadre s'appuie sur des facilitateurs tiers et neutres au projet qui guident les concepteurs et les parties prenantes dans une série d'ateliers pour promouvoir la compréhension du contexte, l'identification du potentiel régénérateur, la formulation d'un plan et la mise en œuvre des initiatives. Le cadre fournit donc un processus flexible, mais structuré pour faire émerger le potentiel de régénération d'un projet[42] mais ce n'est pas un système d'évaluation, donc pas certifiable.

27 Le processus est renforcé par un outil visuel qui guide les utilisateurs à travers la pensée systémique d'une manière accessible, visant à créer un projet qui augmente la vitalité, la viabilité et la capacité à évoluer du site[43]. Le cadre LENSES est composé de trois prismes d'analyse interdépendants (celui de la vitalité du site, celui des flux et celui des fondations) qui vont guider l'équipe dans la création d'une lecture systémique et partagée du site.

28 Un exemple d'application du LENSES Framework est le projet Nunduk-Seacomb West, en Australie. Seacomb West est un grand développement à usage mixte dans le sud-est de l'Australie, sur les rives du lac Wellington, sur une région dégradée en raison des activités anthropiques qui ont permis à l'eau salée de pénétrer dans le système lacustre. Alors que les efforts de conservation précédents n'ont eu qu'un succès limité, le processus de développement régénératif a été envisagé pour ce projet pour son potentiel de revitalisation de la zone. Le cadre LENSES a été facilité par trois ateliers

pour définir les principes directeurs d'aménagement et explorer les flux, l'histoire et les relations de ce site qui sont essentielles pour ce socioécosystème. Sur la base des travaux préliminaires, des ateliers et de recherches supplémentaires, l'équipe a identifié les relations critiques qui devaient être renforcées et les initiatives clés pour la conception, comme la préfabrication, les logements sains, la conception des systèmes de transport, la production alimentaire locale, la responsabilisation des acteurs locaux et le développement du tourisme. Le processus a abouti à un plan directeur innovant, qui comprend environ 800 logements, un parc communautaire, des magasins, un centre d'affaires, une marina, un hôtel, un centre de conférence et des restaurants, et à la définition des stratégies d'aménagement susceptibles d'apporter bénéfices à l'écosystème et à la communauté[44].

Biomimétisme des écosystèmes : Ecosystem services analysis (ESA)

29 Le biomimétisme est une méthodologie d'innovation qui s'appuie sur l'émulation et le transfert de connaissances des organismes vivants et des écosystèmes entiers pour trouver des solutions aux problèmes humains[45]. En architecture, l'application du biomimétisme connait un important essor, dans une logique d'innovation durable[46]. Plusieurs bâtiments ont déjà mis en œuvre cette approche, en passant par des méthodes formelles de développement biomimétique pour la conception, et en intégrant des solutions fonctionnelles pour répondre aux défis du développement durable, comme l'Eastgate Building à Harare (Zimbabwe), et le Council House 2 (CH2) à Melbourne (Australie) qui s'inspirent de plusieurs modèles biologiques dont celui de la termitière pour une régulation thermique passive du bâtiment[47]. À l'échelle urbaine, l'application du biomimétisme a été jusque-là moins explorée [12], mais son application à l'échelle des écosystèmes et de l'urbanisme a été identifiée par la chercheuse Maibritt Pedersen Zari comme un outil pertinent pour l'opérationnalisation du *regenerative design*[48].

30 Maibritt Pedersen Zari a formalisé le premier cadre méthodologique de conception urbaine régénérative par le biomimétisme à l'échelle des écosystèmes, nommé « *Ecosystem Services Analysis*[49] ». L'outil s'appuie sur l'évaluation des services écosystémiques locaux pour comprendre le fonctionnement des écosystèmes et ainsi transposer ces connaissances et performances dans le domaine de la conception architecturale et urbaine.

31 Le cadre proposé se compose en quatre étapes[50] : premièrement, une évaluation des services écosystémiques générés par l'écosystème original qui existait en amont de la construction du projet sur le site ; deuxièmement, une évaluation des services écosystémiques générés par le projet urbain ; troisièmement, une comparaison entre les résultats des étapes 1 et 2, permettant l'élaboration d'objectifs de performance à cibler dans le projet (nouveau ou de rénovation) ; quatrièmement, la recherche et la mise en œuvre de solutions et stratégies d'aménagement pour atteindre les objectifs définis, suivies d'une évaluation et, si nécessaire, d'une étape de reconception. Ce cadre énumère quelques indicateurs qui peuvent être utilisés dans l'évaluation, telle que : la couverture végétale du projet, leur capacité à stocker et à séquestrer le carbone, les taux d'abattement de la pollution atmosphérique par la végétation, la disponibilité des ressources comme les précipitations annuelles, etc.

32 Au-delà du développement théorique de l'approche de Pedersen Zari, quelques projets urbains[51] ont appliqué ces approches basées sur l'émulation du fonctionnement écosystémique en s'appuyant sur des indicateurs écologiques pour promouvoir la régénération[52]. Un exemple est le quartier Lloyd, à Portland aux États-Unis. Lors d'une étude pour le réaménagement du quartier le plan retenu a utilisé une approche de conception qui s'inspire des modèles d'écosystèmes locaux pour catalyser la régénération écologique, sociale et économique au niveau du quartier. Les concepteurs ont utilisé treize paramètres écologiques, comme la couverture végétale, la diversité de la faune et de la flore, les flux d'eau de pluie, l'apport total d'énergie solaire, pour évaluer le projet et l'écosystème préexistant sur place. L'équipe de conception a évalué deux scénarios : 1) la situation écologique avant le développement, qui était un écosystème de forêt de conifères indigène ; 2) l'écosystème urbain existant à l'époque. Grâce à une approche comparative, les concepteurs ont identifié les écarts entre les deux scénarios. Ces informations ont été utilisées pour définir des objectifs de performance écologique et élaborer des stratégies de redéveloppement. Cinq principes structurants du projet ont été définis à partir de ces mesures, afin d'avoir un impact positif sur l'ensemble du socioécosystème : 1) restaurer l'habitat et le couvert végétal ; 2) utiliser uniquement l'eau de pluie disponible sur le site ; 3) utiliser uniquement l'énergie solaire disponible localement ; 4) préserver la densité urbaine ; et 5) assurer la neutralité carbone[53]. Le projet a décliné ces principes en plusieurs stratégies d'aménagement, par exemple l'augmentation de la couverture végétale. Dans l'écosystème d'origine, la végétation couvrait 90 % de la surface, contre 14,5 % au moment de la conception du projet de réaménagement. Une couverture végétale de 30 % a été fixée comme l'objectif du projet à terme. Pour l'atteindre, le projet s'est appuyé sur des stratégies telles que la mise en place de rues vertes, de nouveaux espaces verts publics, des toits végétalisés et la connectivité de la trame verte urbaine avec les corridors écologiques existants aux alentours. L'autonomie en eau est un autre exemple ; pour cela le projet envisage un investissement dans la réduction de la consommation d'eau sur l'ensemble du site et la collecte, le traitement et le stockage de l'eau de pluie. En termes d'énergie, une stratégie similaire a été proposée, en se concentrant sur la production d'énergie solaire et l'amélioration des performances des bâtiments, en limitant la consommation en fonction des ressources disponibles localement.

Tableau 1 : Synthèses des outils présentés

Outil	Pays d'origine	Concepteur	Échelle d'application	Certifiable	Aspects du développement durable pris en compte
LBC	États-Unis	International Living Future Institute (ILFI)	Bâtiment	Oui	Écologiques et sociales
LENSES	États-Unis	Center for Living Environments and Regeneration (CLEAR)	Quartier	Non	Écologiques, sociales et économiques
ESA	Nouvelle-Zélande	Dr Maibritt Perdersen Zari	Quartier/Ville	Non	Écologiques

Du *regenerative design* au projet urbain régénératif

33 Pour mieux saisir la compréhension contemporaine du concept du *regenerative design* et proposer une définition des principes que compose un projet urbain régénératif, nous avons mené une révision bibliographique et une analyse de discours selon une méthodologie de codage thématique.

34 Pour concevoir un corpus bibliographique d'analyse, nous avons mené une recherche des articles scientifiques en anglais sur le moteur de recherche *Web of Science*. Notre requête a été réalisée avec l'expression « *regenerative desin* », dans le champ « *Topic* » (qui comprend titre, résumé et mots-clés des articles), seulement pour des articles scientifiques et sans aucune restriction de date. Cette recherche a produit 74 résultats. Ces articles ont été analysés selon leur titre et résumé, pour concevoir un corpus d'analyse plus restreint. Les articles qui ne discutaient pas en profondeur le *regenerative design*, ses définitions et ses principes ont été éliminés de l'analyse. Le corpus final d'analyse est composé de 25 articles scientifiques.

35 Ces 25 articles ont été lus et, pour chaque document, nous avons extrait des passages que présentaient les définitions et principes du *regenerative design.* 120 différents passages ont été identifiés. Ce corpus de passages textuels a été analysé et codifié avec l'aide du logiciel MAXQDA Analytics Pro 2020, dans une approche méthodologique de « *grounded theory*[54] » en deux tours de codage, sans définition préalable des codes. Nous avons identifié 11 thématiques centrales liées au *regenerative design* associées aux passages et nous avons attribué ces codes thématiques respectifs aux passages analysés. Le tableau 2 présente l'occurrence de ces thématiques dans l'échantillon et les respectives références bibliographiques.

Tableau 2 : Fréquence d'occurrence des thématiques dans l'échantillon de passages analysés

#	Thématiques identifiées	Occurrences	Références
1	Impact positif du projet	47	Attia, 2016 ; Busby & Driedger, 2011 ; Camrass, 2020 ; Cole *et al.*, 2012 ; Cole *et al.*, 2013 ; Du Plessis, 2012 ; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018 ; Lau *et al.*, 2018 ; Naboni *et al.*, 2019 ; Pedersen Zari, 2012 ; Pedersen Zari & Hecht, 2020 ; Robinson & Cole, 2015 ; Svec, Berkebile & Todd, 2012 ; Thomson & Newman, 2018 ; Thomson & Newman, 2020 ; Trombetta, 2018 ; Zhang *et al.*, 2015.
2	Bénéfices mutuels à l'homme et à la nature	40	Benne & Mang, 2015 ; Bonyad, Hamzenejad & Khanmohammadi, 2020 ; Busby & Driedger, 2011 ; Camrass, 2020 ; Cole, 2012b ; Cole *et al.*, 2012, 2013 ; Delpy & Zari, 2020 ; Du Plessis, 2012 ; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018 ; Lau *et al.*, 2018 ; Naboni *et al.*, 2019 ; Pedersen Zari, 2012 ; Pedersen Zari & Hecht, 2020 ; Petrovski, Pauwels, & González, 2021 ; Plaut *et al.*, 2012 ; Robinson & Cole, 2015 ; Trombetta, 2018 ; Vannini & Taggart, 2014 ; Zhang *et al.*, 2015.

3	Conception basée sur le lieu	31	Benne & Mang, 2015 ; Bonyad *et al.*, 2020 ; Camrass, 2020 ; Cole, 2012b ; Cole *et al.*, 2012, 2013 ; Du Plessis, 2012 ; Hoxie, Berkebile & Todd, 2012 ; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018 ; Plaut *et al.*, 2012 ; Robinson & Cole, 2015 ; Svec *et al.*, 2012 ; Vannini & Taggart, 2014.
4	Coévolution des systèmes sociaux et écologiques	23	Benne & Mang, 2015 ; Bonyad *et al.*, 2020 ; Camrass, 2020 ; Cole, 2012b ; Cole *et al.*, 2012, 2013 ; Du Plessis, 2012 ; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018 ; Petrovski *et al.*, 2021 ; Robinson & Cole, 2015 ; Trombetta, 2018 ; Zhang *et al.*, 2015.
5	Amélioration des conditions de santé et vie du lieu	12	Bonyad *et al.*, 2020 ; Cole *et al.*, 2012, 2013 ; Du Plessis, 2012 ; Plaut *et al.*, 2012 ; Robinson & Cole, 2015 ; Thomson & Newman, 2018 ; Trombetta, 2018 ; Vannini & Taggart, 2014.
6	Engagement et participation de la communauté	15	Camrass, 2020 ; Cole *et al.*, 2012 ; Du Plessis, 2012 ; Hoxie *et al.*, 2012 ; Robinson & Cole, 2015 ; Svec *et al.*, 2012 ; Thomson & Newman, 2018 ; Zhang *et al.*, 2015.
7	Processus continu	8	Camrass, 2020 ; Cole *et al.*, 2013 ; Du Plessis, 2012 ; Pedersen Zari, 2012 ; Robinson & Cole, 2015 ; Svec *et al.*, 2012.
8	Pensé systémique	8	Cole et al., 2012, 2013; Delpy & Zari, 2020; Du Plessis, 2012; Plaut et al., 2012; Robinson & Cole, 2015; Zhang et al., 2015.
9	Impacts à travers les échelles	4	Cole, 2012b; Lau et al., 2018; Plaut et al., 2012; Thomson & Newman, 2020.
10	Changement de paradigme	2	Benne & Mang, 2015; Thomson & Newman, 2020.
11	Accent au processus et pas au résultat	2	Benne & Mang, 2015 ; Camrass, 2020.

36 Les thématiques 1 à 8 sont les plus récurrentes dans l'échantillon et ont été considérées comme pertinentes pour la suite du travail. Avec une relecture des passages liés à ces thématiques, il a été possible de les réorganiser en cinq principes du « projet urbain régénératif », terme plus approprié à un public francophone :

37 Principes liés aux objectifs de la démarche :

1. **Un projet à impact positif et mutuellement bénéfique :** le projet urbain régénératif doit cibler un impact positif sur l'ensemble de son système écologique et social. Les bénéfices positifs du projet doivent être mutuels à l'homme et à l'environnement. Concernant le système écologique, le projet doit donc aller au-delà des performances négatives ou neutres des projets conventionnels, il doit catalyser des impacts positifs pour l'écosystème local et le régénérer.
2. **Un projet en coévolution :** le projet régénératif doit retisser les liens entre le système urbain et le système écologique et promouvoir un processus de régénération à long terme.

Le système urbain et le système écologique doivent évoluer ensemble dans le temps vers de meilleures conditions de santé et fonctionnement.

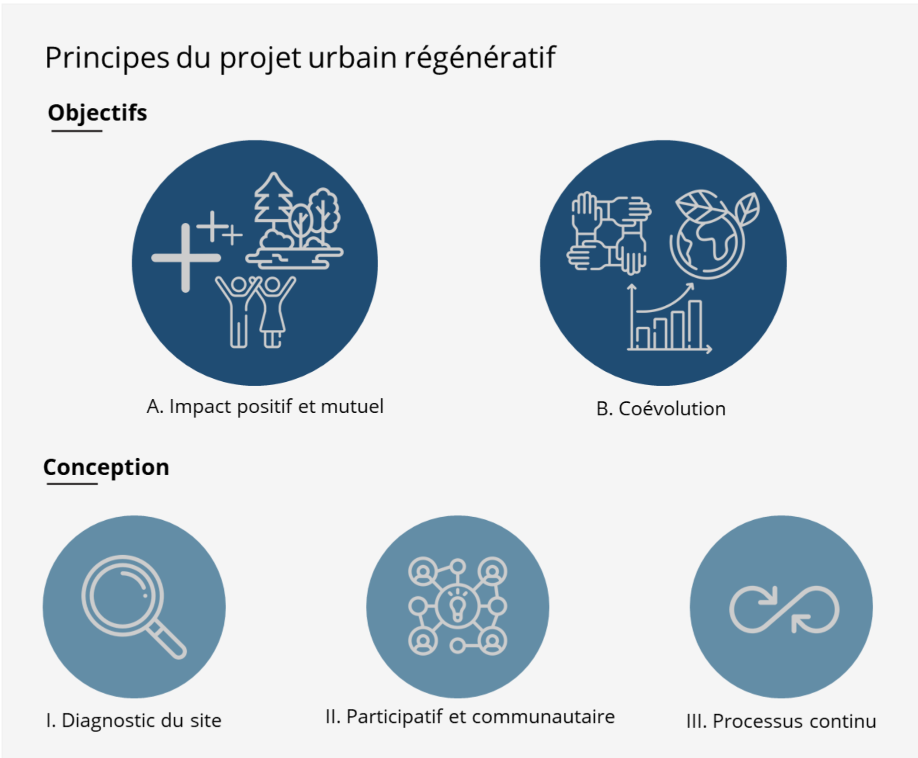
38 Principes liés aux processus de conception :

A. **Une lecture systémique du site :** le projet régénératif doit être basé sur une compréhension systémique de la réalité, de l'histoire et du contexte du site de projet. Il doit comprendre les interrelations entre le système écologique, le système social et le système économique. Il doit accepter et comprendre le système urbain comme un socio écosystème complexe et s'intégrer aux logiques locales et à ses réels besoins. Pour cette compréhension locale et systémique, les projets s'appuient sur des diagnostics socio-écologiques et diverses sources d'information.

B. **Un processus participatif et communautaire :** le projet urbain régénératif doit s'appuyer sur une démarche participative et communautaire. Les acteurs locaux doivent être mobilisés dans les phases de diagnostic et de conception, de façon à capitaliser leurs connaissances sur le contexte local et engager les acteurs locaux à la mise en place et à la continuité du projet.

C. **Un processus continu :** Le projet urbain régénératif est un projet évolutif et continu. La régénération et les impacts positifs envisagés ne sont pas accomplis avec la livraison du projet ; il s'agit d'un processus continu dans le temps.

Figure : Principes du projet urbain régénératif identifiés



39 À partir de ces principes, nous proposons une définition d'un projet urbain régénératif : les projets urbains régénératifs contribuent à une amélioration des conditions de l'ensemble du socio-écosystème du projet. Ils favorisent une intégration profonde des logiques écosystémiques dans les logiques urbaines pour aboutir à des socio-écosystèmes fonctionnels, résilients et évolutifs. Pour cela, ils s'appuient sur un diagnostic systémique du fonctionnement social et écologique du site avant toute conception. Ce diagnostic permet la compréhension des logiques, besoins et aspirations du site et la définition des critères qui vont guider le choix des stratégies

d'aménagement à impact positif. Le diagnostic et la conception doivent être participatifs, de façon à mobiliser les connaissances locales et établir un engagement au projet. Finalement, le projet urbain régénératif catalyse un changement à long terme et demande un engagement et un suivi continu.

Conclusions et perspectives

40 Le *regenerative design* et le projet urbain régénératif montent en intérêt dans le monde, avec une discussion croissante dans le milieu scientifique et dans la pratique. Avec plusieurs principes convergents avec d'autres théories de l'urbanisme durable et écologique, ce concept porte un intérêt particulier à l'échelle du projet architectural et urbain, et nous observons une augmentation des outils disponibles pour les concepteurs, comme ceux discutés dans la présente analyse.

41 Les trois principes identifiés qui sont liés aux processus de conception du projet renvoient aussi aux engagements du référentiel ÉcoQuartier français, qui préconise aussi une démarche basée sur les besoins et contraintes du site, participative et dans une logique d'amélioration continue (engagements 1, 3 et 5 de ce référentiel)[55]. Cependant, les deux principes majeurs de la pratique du projet urbain régénératif, ceux liés aux objectives du projet (l'impact positif mutuel du projet et la coévolution entre système social et système écologique) ne se retrouvent pas dans ce référentiel ni dans les théories préalablement discutées. De plus, même les outils spécifiques au *regenerative design* ici présentés ont du mal à répondre à ces différents principes, en étant souvent réductionnistes concernant la mesure des impacts positifs, la participation sociale et la vision à long terme du projet.

42 Quant à la mesure et le suivi des impacts positifs et des bénéfices mutuels, centrale dans cette approche, l'outil biomimétique des écosystèmes présente une première proposition de méthodologie. Cependant, cette approche, basée sur la notion des services écosystémiques, reste anthropocentrique et réductionniste par rapport au fonctionnement des écosystèmes, avec un oubli du rôle majeur de la biodiversité dans la production de ces services[56]. Pourtant, le biomimétisme des écosystèmes a le potentiel de permettre un transfert de connaissances plus systémiques sur le fonctionnement des écosystèmes, depuis l'écologie jusqu'à la conception urbaine.

43 Cela confirme le besoin de nouveaux outils et cadres de conception régénératifs, point déjà largement discuté dans la littérature[57], que quant à eux doivent être capables d'organiser le processus de conception du projet urbain pour faciliter les diagnostics systémiques du site[58], assurer la participation sociale, garantir un processus d'amélioration continue, préconiser des impacts positifs mutuels à la société et à l'environnement, et finalement abriter la coévolution entre sociétés humaines et systèmes naturels urbains.

44 Ces approches encore émergentes, qu'elles soient théoriques ou pratiques, nécessitent de nouvelles recherches opérationnelles, non seulement pluridisciplinaires, mais surtout transdisciplinaires pour permettre un passage des concepts théoriques du *regenerative design* vers la mise en place de projets urbains véritablement régénératifs.

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RÉSUMÉS

L'urbanisme organise et transforme l'espace par la pratique du projet, qu'ordonnent des choix d'aménagement sur un territoire. Plusieurs initiatives de recherche et de pratique de l'urbanisme projet visent à explorer l'intégration du fonctionnement des écosystèmes naturels dès la conception des projets. Cependant les processus d'urbanisation restent une cause centrale de la dégradation des écosystèmes. Le « *regenerative design* » propose une meilleure compréhension du site pour, associé à un processus participatif et en amélioration continue, aboutir à des projets avec des impacts positifs mutuels à la société et aux écosystèmes, permettant leur coévolution. Au travers de différents outils jusque-là publiés, la mise en pratique du *regenerative design* montre des résultats préliminaires à l'international, mais sa prise en compte en France reste superficielle. Dans cette recherche, nous explorons l'origine et la pratique contemporaine du *regenerative design*, nous mettons en parallèle cette théorie avec d'autres courants de l'urbanisme durable et écologique, et finalement nous identifions les cinq principes théoriques d'un projet urbain régénératif, afin de proposer une définition à ce terme.

Urban design practice organizes and transforms space through the development of urban projects, organizing the choices of intervention on a territory. Several initiatives in research and project practice aim to explore the integration of aspects related to the functioning of natural ecosystems in project design. Nevertheless, urbanization processes are instead a major cause of ecosystem degradation. Regenerative design proposes a better understanding of the site to guide a participatory and continuous improvement process to achieve projects with mutual positive impacts to society and ecosystems, allowing their coevolution. The implementation of regenerative design shows preliminary results internationally through various tools, but its consideration in France remains superficial. In this paper, we explore the origin and contemporary practice of regenerative design, we qualify this theory in relation to other currents of sustainable and ecological urbanism, and finally we identify the five theoretical principles of a regenerative urban project, to propose a definition to this term.

INDEX

Mots-clés : Design régénératif, Projet urbain régénératif, Projet urbain durable, Écosystèmes, Écologie urbaine, Biomimétisme

Keywords : Regenerative Design, Regenerative Urban Project, Sustainable Urban Projects, Ecosystems, Urban Ecology, Biomimicry

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1.2 Urban ecosystem-level biomimicry and regenerative design: Linking ecosystem functioning and urban built environments

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Review

Urban Ecosystem-Level Biomimicry and Regenerative Design: Linking Ecosystem Functioning and Urban Built Environments

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Abstract: By 2050, 68% of the world's population will likely live in cities. Human settlements depend on resources, benefits, and services from ecosystems, but they also tend to deplete ecosystem health. To address this situation, a new urban design and planning approach is emerging. Based on regenerative design, ecosystem-level biomimicry, and ecosystem services theories, it proposes designing projects that reconnect urban space to natural ecosystems and regenerate whole socio-ecosystems, contributing to ecosystem health and ecosystem services production. In this paper, we review ecosystems as models for urban design and review recent research on ecosystem services production. We also examine two illustrative case studies using this approach: Lavasa Hill in India and Lloyd Crossing in the U.S.A. With increasing conceptualisation and application, we argue that the approach contributes positive impacts to socio-ecosystems and enables scale jumping of regenerative practices at the urban scale. However, ecosystem-level biomimicry practices in urban design to create regenerative impact still lack crucial integrated knowledge on ecosystem functioning and ecosystem services productions, making it less effective than potentially it could be. We identify crucial gaps in knowledge where further research is needed and pose further relevant research questions to make ecosystem-level biomimicry approaches aiming for regenerative impact more effective.

Keywords: ecosystem services production; ecosystem-level biomimicry; urban regenerative design; sustainable urban design; urban ecosystems

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1. Introduction

Cities are the primary habitat of human beings. By 2050, 68% of the world's population will likely live in urban centres, representing more than 6 billion urban dwellers [1]. Human settlements are dependent on ecosystem services; that is, the natural benefits, goods, and services derived from ecosystems. Simultaneously, urbanisation and urban activities are a prominent cause of ecological process simplification, biodiversity loss, and ecosystem health reduction [2]. Anthropic alterations to ecosystems reduce their capacity to create benefits, goods, and services that are both vital to and are expected by society [3].

To engage with these challenges, regenerative design aims to create urban projects that promote positive impacts, allowing social and ecological systems to co-evolve and thrive [4,5]. In this context, there is significant evidence that a new regenerative urban design approach is emerging which relies on ecosystem-level biomimicry theories to integrate and more fully take account of ecosystem health alongside urbanisation processes, and therefore contributes to the possibility that the regenerative paradigm shift can 'scale jump' to beyond the building scale to the urban scale [6,7].

Biomimicry draws upon emulation of, and knowledge transfer from, living organisms and whole ecosystems to find solutions to human problems [8]. In the built environment disciplines, its application has been growing at the architectural scale, with the aim of sustainable innovation [9,10]. Several buildings have already employed this approach, going through formal biomimetic development methods for design, and integrating functional solutions to meet sustainable development challenges, as the Eastgate Building in Harare (Zimbabwe), and the Council House 2 (CH2) in Melbourne (Australia) [9,11]. At the urban scale, the application of biomimicry has been less explored [12]. Where it is apparent, design inspiration typically draws upon ecosystems rather than individual organisms [10].

Ecosystem-level biomimicry has the potential to facilitate regenerative design at the urban scale [7,11]. It can have a significant role at the project design phase, guiding design teams to conceive of projects that can work in symbiosis with local ecosystems, allowing net positive outcomes, both ecologically and socially, along with the reconnection and coevolution of urban and ecological systems [11,13]. The aim is to design urban projects or developments that reconnect, emulate, or integrate their functioning with local ecosystems and have a measurable positive impact on those [7,11]. Ecosystem-level biomimicry for regenerative urban design employs an understanding of ecosystem patterns and functioning as models for urban space design. It relies on ecosystem metrics and ecosystem services assessments as the main inputs into the design process [10,11].

With relevant theoretical conceptualization as a basis [5,11,14], ecosystem-level biomimicry for regenerative urban design has increasing examples of built application [7,13,15]. However, even if applied in urban projects with documented results [7], these methods still lack a deeper understanding of ecological theories based on ecosystem functioning [11,16], leading to a simplistic understanding of the ecosystem model. We argue that the approach could be expanded to consider current knowledge and developments related to ecosystem services production, such as the ecosystem services cascade theory and the ecological integrity concept.

2. Methodology

In this paper, we analyse the evolution of regenerative urban design practices that use ecosystems as models. We also review recent research on ecosystem services production and assessment and discuss the application of ecosystem-level biomimicry for regenerative urban design in two urban projects. The literature review was realized using a snowball method [17]. The two case analyses and discussion are based on landscape and urban project case studies method [18] and logical argumentation [19]. These steps allow us to understand trends in practice and identify opportunities for further development of this approach, so that regenerative practices can be translated from primarily the building scale, to larger urban and regional scales.

3. Ecosystems as Models in Urban Planning and Design Practices

The formal integration of urban spaces and natural ecosystems in urban planning and design dates from the 19th century, with work from planners and researchers like George Perkins Marsh, John Wesley Powell, Patrick Guedes, Sir Howard Ebenezer, and Frederick Law Olmsted [20]. These works firstly emphasised the health and recreational properties of green and blue infrastructures alongside aesthetics in the design of urban parks [21].

In the 1960s, McHarg further developed these concepts, proposing that human-designed landscapes should replicate natural systems' performance and logic [22]. McHarg argued that a deep understanding of local ecological processes is fundamental before embarking on the design of any landscape or urban project [23]. McHarg's 1969 *Design with Nature* contributed to the basis of "landscape suitability analysis" approaches [20,23]. These are the foundations of modern urban and landscape design practices such as landscape ecology and geodesign that use ecological system comprehension at some level [20,24]. Within these methods, ecosystems are studied to determine the optimal location of a project and uses of a given area. From a methodological perspective landscape suitability analysis relies on an inventory of locally relevant ecosystems, usually compiled through aerial images and remote sensing data. This inventory is organised and analysed in a layer-cake model, superimposing relevant ecological factors to create a suitability map. Finally, this analysis, based on macroscale ecosystem information is used to assess the fitness of uses for a particular area in order to minimize negative impacts [20,24]. It is important to note that remote sensing is one inventory method used on landscape suitability analysis and ecosystems services assessments, among several others that are also relevant and complementary, as field inventory methods and other qualitative and socio-cultural approaches [25].

John Tillman Lyle proposed, in 1994, the regenerative design concept as a tool for sustainable urban development. Lyle's work questioned urban systems' linearity compared to ecosystems, anchoring his work in ecology and ecosystems comprehension [26]. He suggested that it would be possible to build artificial urban spaces with a circular logic by reincorporating the essential elements of life, such as energy conversion, water treatment, and nutrient cycling in human designed urban spaces [26]. To address the degeneration of natural ecosystems, Lyle proposed twelve central strategies for promoting the regeneration of urban spaces, mainly taking ecosystem functions and processes as models for exploration and emulation [26].

In the same vein, the contemporary practice of regenerative design, largely popularised by the research and practice of Bill Reed and various co-authors [27], proposes a shift from a mechanical understanding of urban systems to an ecological and holistic perspective [14]. It challenges traditional methodologies and tools for sustainable urban design, putting ecosystem functioning and patterns of the site at the centre of the design process, aiming for the mutually beneficial coevolution of social and ecological systems [4,5,11,14,27].

In this context, ecosystem-level biomimicry for regenerative urban design represents a new design approach, relying on holistic knowledge transfer from ecology to built environment design disciplines. Pedersen Zari formalised the first methodological urban design framework using these concepts, called Ecosystem Services Analysis (ESA), and tested the approach at the city scale [7,11]. ESA draws on ecosystem services assessment to understand how ecosystems function and attempts to translate this knowledge into the field of architectural and urban design. The framework consists of four steps: first is a preliminary evaluation of the ecosystem services generated from the original ecosystem that existed on the same site as the current urban setting in question; second is an assessment of ecosystem services currently generated on-site; third is a comparison between the results of steps 1 and 2. This allows elaborating performance goals and objectives based on the site-specific ecological reality; fourth is a search for and implementation of design, technology, and behaviour change solutions to achieve the defined objectives. This is followed by an evaluation, and if need be, a re-design stage [11]. Pedersen Zari's framework lists various metrics that can be used in the calculation processes, such as: vegetation-covered areas and their capacity to store and sequester carbon; air pollution types and rates removed by vegetation; annual rainfall; and nutrient cycling capacities among others. These metrics are useful to understand the evolution of ecosystem functioning and ecosystem services available in an urban area and allow designers to define strategies to regenerate and/or integrate with them and thus create positive impacts on socio-ecosystems [7,11].

Comparing conventional urban and landscape design approaches that use ecosystem information in the design process, such as landscape suitability analysis and derived methods, and ecosystem-level biomimicry for regenerative design practice, we can observe that ecosystems are used as models in design with different perspectives. Ecosystem-level biomimicry offers an opportunity to deeply integrate ecological information into urban design, going beyond analysis of how the project impacts ecosystems and how to minimise this impact. Table 1 summarizes the main differences between these approaches identified in our review by using three main criteria.

Table 1. Comparison between landscape suitability analysis (and derived approaches) and ecosystem-level biomimicry for regenerative urban design.

		Landscape Suitability Analysis	Ecosystem-Level Biomimicry
1.	Objective of the ecosystem analysis	Analyse the fitness of a project for a specific area; select urbanisation strategies that reduce negative environmental impacts [23,24].	Design urban projects that rely on ecological data to deeply connect urban systems with ecological system patterns; reduce negative environmental impacts and catalyse positive ones for both social and ecological systems [10,11].
2.	Level of details and type of data used in the ecosystem model	Macroscopic information, using aerial and remote sensing data [20,23,24].	Detailed information using ecological indicators [7,11].
3.	Analysis of the ecosystem model information	Ecosystem information is treated discretely in a cake-layer approach [23,24].	Ecosystem information is treated holistically with an emphasis on understanding relationships, synergies and trade-offs [7,10,11,13].

Source: Developed by the authors.

Despite the conceptual and theoretical development of Pedersen Zari's framework and others related but different, such as Ecological Performance Standards by Biomimicry 3.8 [13], few built urban projects engaged in sustainable development practices have applied the general idea of emulation of ecosystem services provision. However, examples do exist, and studying these allows an evaluation of the practical application of ecosystem-level biomimicry for regenerative urban design [7,10,11]. The Lavasa Hill and the Lloyd Crossing projects are further discussed in this paper for this purpose.

4. Understanding Ecosystems and Ecosystems Services Provision

In order to critically evaluate ecosystem-level biomimicry for regenerative urban design, it is essential to understand and explore related appropriate contemporary research in ecology and ecosystems. Following Odum's definition in 1969, ecosystems are a biological organisational unit, made up of all organisms in a given area, that interact with physical space and abiotic conditions and substances, and lead to a flow of energy and material cycles within it [28].

Ecosystem services, the entry point to translate ecosystem functioning in the design framework proposed by Pedersen Zari [11], are the benefits that human society derives directly or indirectly from the functioning of ecosystems, which contribute to wellbeing [3]. The concept, developed in the 1990s, is a framework to facilitate understanding human dependencies on ecosystems [29]. Research on ecosystem services has developed widely across multiple disciplines, and the concept has become essential in public policy and conservation sciences [30]. The application of ecosystem services knowledge to urban design and planning is a key emerging research topic related to the ecological transition of cities [22]. However, the generation of ecosystem services in urban settings remains a concept that is difficult to operationalise at the urban scale (suburbs, neighbourhoods, streets). Difficulties are commonly related to the lack of data, the theoretical aspect of the approach, and the lack of homogeneity between the indicators and methodologies used among different studies [31–33]. These difficulties also relate to the application of the ecosystem-level biomimicry for regenerative urban design.

To provide a standardised conceptualisation of ecosystem services production, the Ecosystem Services Cascade Framework was proposed by Haines-Young and Potschin in 2010 [30,34,35]. The cascade, illustrated in an adapted form in Figure 1, defines and organises elements critical for the provision of ecosystem services. The framework starts with the biophysical structures, the biotic and abiotic elements that make up ecosystems and their patterns, and ecosystem processes and functions, which are ecological interactions that take place over time in an ecosystem. They are followed by the services themselves, which are flows of benefits created by ecosystem structures, processes, and functions. Finally, ecosystem services can be converted in goods and benefits for society, that are the material or immaterial results of this chain which contribute to human wellbeing [30,35].

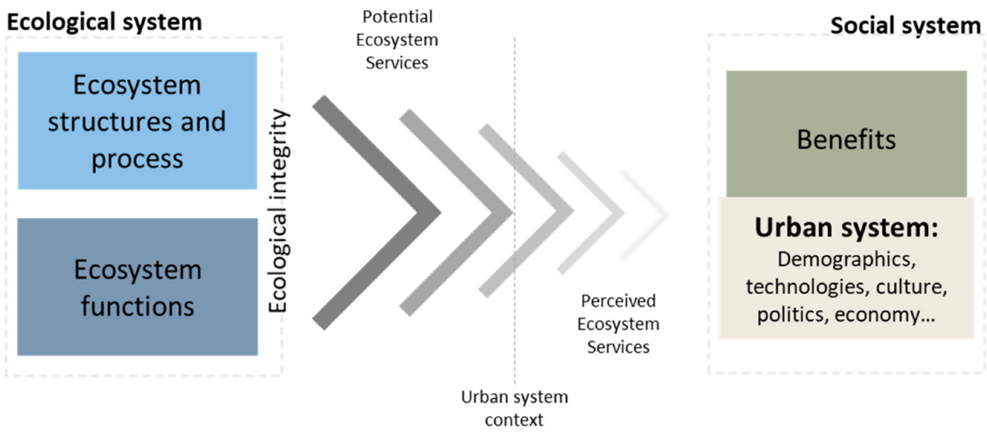

Figure 1. Ecosystem services cascade for an urban socio-ecosystem perspective. Ecosystem structure is the starting point of ecosystem services production. Adapted from [30,35].

The Common International Classification of Ecosystem Services (CICES), which is a standard classification of ecosystem services, uses the ecosystem services cascade concept to propose a broad and hierarchical classification of ecosystem services [31], and introduces homogeneity as part of the classification [31,32].

The Ecosystem Services Cascade Framework throws light on the importance of the ecosystem's biophysical structure to the provision of ecosystem services. Kandziora et al. (2013) explored the relationships and correlations between ecosystem services production and the different elements of the cascade. The authors also highlighted the importance of the biophysical structure in this process and proposed that the concept of ecological integrity could be useful to describe the state of an ecosystem and allow assessment of ecosystem services production [36,37]. While biodiversity is responsible to high levels of ecosystem services provision, urban stakeholders still struggles to integrate this variable comprehensively on urban areas. This fact relates to potential conflict of interests in land use as well as potential ecosystem disservices felt by urban dwellers, as allergies, accident potential related to biodiversity and damages on infrastructure [38,39].

Müller defines an integer ecosystem as an ecological system that can maintain its self-organisation capacity and ecological process after small disturbances, continuing its development [37]. Kandziora et al. proposed an indicator framework to assess ecosystems' ecological integrity and their inherent production of ecosystem services. The framework is composed by eight criteria: exergy capture, entropy production, storage capacity, nutrient cycling, biotic water fluxes, metabolic efficiency, spatial heterogeneity, and biological diversity. Among these variables, biodiversity, spatial heterogeneity, and exergy capture seem to have central importance for ecosystem functioning and ecosystem services production [36].

This overview of ecosystem services production highlights the links between ecosystem biophysical structures, their health and integrity, and ecosystem services provision. Ecosystem structures, processes, and functions have a leading role in facilitating ecosystem services supply [36]. These ecosystem services are a consequence of healthy and integer ecosystems [30]. This understanding of ecology allows us to infer that the theoretical formulation and practice of ecosystem-level biomimicry for regenerative urban design that focuses solely at the end of the ecosystem services cascade, lacks in depth comprehension of the ecological processes behind ecosystem services production. It follows that applying such concepts to urban design, even if inspirational and through a sustainable or regenerative lens, may remain metaphorical, and not as effective as potentially it could be.

5. Case Studies: Using Ecosystem-Level Biomimicry to Catalyse Urban Regeneration

The following case studies were selected because both urban scale projects use ecosystem-level biomimicry in the design phase. They are used here to contrast theory with biomimetic urban design practice. Both case studies have a goal of regenerative impact. Also, both projects reached some level of implementation over time, rather than remaining at a proposed or conceptual level. We acknowledge the differences in these projects' context, mainly regarding size, biomes, and cultures, and thus we concentrate on how ecological information has been used in the design process.

5.1. The Lavasa Hill Project, Maharashtra, India

Lavasa is a planned city in Maharashtra state in India's Mumbai-Pune region, covering over 2000 ha of land. Part of it has been designed or re-designed using the Ecological Performance Standards framework devised by Biomimicry 3.8 (Missoula, USA, a consultancy company offering biological intelligence consulting, and professional training) [10,13,40,41]. Even if not wholly built due to several environmental, equity, and financial management controversies [40] not discussed in this paper, the design approach finds inspiration from local monsoon ecosystems and organisms to solve sustainable urban design challenges, mostly related to rainwater management and erosion control.

Through an ecological diagnostic process, engaging urban designers and ecologists, the HOK Architects and Biomimicry 3.8 design team identified six essential ecosystem services for the site's ecological functioning rendered by the local forest that were relevant to the development of the urban project in the area [10,41]. They were:

- water collection;
- solar gain;
- carbon sequestration;
- water filtration;
- evapotranspiration; and
- nitrogen and phosphorus cycling.

This ecosystem services identification was the first step of Lavasa ecosystem-level biomimetic process. The team aimed to design an urban project that could recreate these ecosystem services, while simulating local ecosystem functions. To translate this into tangible design strategies, the design team focused mainly on understanding local water cycles and identified that in the local ecosystem 20–30% of rainwater evaporates through the tree canopies, 60–65% infiltrates into the soil, and 10–15% is accounted for as runoff [41].

These metrics guided the designers to conceive built infrastructures that could replicate these water-related ecosystem services, facilitating, for example, evaporation on the "built canopy". Through infiltration and managing runoff, values near those derived from the native forest could be reached in the built environment. Among the technical solutions applied were: rooflines designed to create wind turbulence to facilitate evaporation; green roofs to slow water flows; infiltration swales; massive revegetation using hydroseeding; and dams to store rainwater. These solutions contributed to the on-site water management and a slowing down of rainwater runoff to reduce soil erosion, an identified local major issue [10]. This approach aimed to reduce the overall ecological impact of the loss of existing forest due to built environment caused land-use change [10,41], by recreating water-related ecosystem processes and ecosystem services through mimicking strategies seen in the local ecosystem.

5.2. The Lloyd Crossing Project, Oregon, USA

Lloyd is a mixed-use district located in Portland (OR, USA). A sustainable urban development plan was proposed for the existing and mixed-use neighbourhood of over

800 ha in 2004. The plan used a design approach that finds inspiration in local ecosystem patterns to catalyse ecological, social, and economic regeneration at the district level. The project was tasked with pushing the limits of sustainable urban design and deeply integrating the urban system with surrounding ecosystems in a symbiotic way, thus going beyond LEED Platinum performance, which at the time was the most challenging building metric related to sustainability [42]. Mithūn and Greenworks designers used the notion of "pre-development metrics" derived from the local ecosystem (which has similar logic to the ecosystem-level biomimicry approach proposed by Pedersen Zari [11]), to build site-specific ecological comprehension that guided the long term neighbourhood-scale sustainable urban strategy [11,42]. Thirteen ecological metrics were assessed, including vegetation cover, wildlife diversity, water flows, total solar energy input, and energy converted to biomass through photosynthesis (Table 2). The design team assessed two scenarios: 1. the pre-development ecological situation, which was a native conifer forest ecosystem; 2. the urban ecosystem existing at the time. With a comparative approach, the designers identified the gaps between both scenarios. This information was used to define ecological performance targets and devise development strategies over long time periods for the urban development plan. Five structuring tenets of the project were defined using these metrics, aiming to have a positive impact on the whole socio-ecosystem: (1) restore habitat and vegetation canopy; (2) rely only on the rainwater available on site; (3) rely only on the solar energy available locally; (4) preserve urban density; and (5) ensure carbon neutrality [42,43]. The project broke down these tenets into several specific long-term strategies and actions for the neighbourhood. One example was the green canopy increase. In the original ecosystem, vegetation covered 90% of the area, as compared to 14.5% at the time of the project design. 30% coverage was the goal of the project over time. To reach this objective, the project relied on strategies like green street design, new public green spaces, green roofs, and connectivity with the existing urban green grid in the area. Other strategies were the increase of habitat through major green area restoration and riverbank restoration. Also important was the optimisation of water flows, respecting the available rainwater on-site through water consumption reduction, and rainwater collection, treatment, and storage. A similar strategy was proposed regarding energy, focusing on solar energy production and performance improvement for buildings, limiting consumption to match locally available resources. Finally, the project identified 15 benefits that the proposed actions could have for society including improving wellbeing, creating habitat for wildlife species, and regulating pollution, that can also be understood as ecosystem services.

Table 2. Comparison between the Lavasa Hill and the Lloyd Crossing case studies.

	Lavasa Hill	**Lloyd Crossing**
Location	Mumbai-Pune region, India	Portland, Oregon, USA
Motivation for the biomimetic approach	*"To prevent this* [ecosystem disturbance] *from happening, the design team established strict ecological performance standards and specific strategies for maintaining each ecosystem service"* [41].	*"The Lloyd Crossing Sustainable Urban Design Plan looks at an urban ecosystem in which individual properties and the neighborhood public realm function together as an environmentally low- impact unit with high economic potential"* [43].
Ecosystem used as model	Moist deciduous forest [41].	Mixed-conifer forest [42].
Main ecological concepts used in the biomimetic design process	Ecosystems services [41].	Biophysical structure and ecosystem processes [43].

Table 2. *Cont.*

	Lavasa Hill	Lloyd Crossing
Integration of ecological information on the design process	Identification and assessment of main ecosystem services essential for the area and for the project viability. Replication of these ecosystem services metrics mainly using built and technological strategies [10,40,41].	Assessment of original ecosystem biophysical structure and ecosystems process. To reach the original metrics, designers proposed technological and educational strategies to reduce pressures on ecosystems, and nature-based solutions to recover ecological structure and integrity [11,42,43].
Ecological indicators used	Water collection; Solar gain; Carbon sequestration; Water filtration; Evapotranspiration; Nitrogen and phosphorus cycling [41].	Tree canopy cover Wildlife species Total precipitation Stormwater runoff Groundwater recharge Transpiration Evaporation Incident solar energy Energy used by photosynthesis Energy reflected/absorbed/radiated Carbon dioxide used Oxygen released Carbon fixed as biomass [43]
Potential regenerative impact from the biomimetic approach	Efficient rainwater management Mitigation of soil erosion processes [41]	Restore pre-development habitat metrics Water autonomy (only rainwater used) Energy autonomy (only local renewable sources used) Carbon neutrality Increasing urban density with a higher Floor Area Ratio [43]

Source: Developed by the authors.

6. Discussion

Once we analyse these two projects from the perspective of ecosystem functioning, it is possible to observe that while both are innovative and pushing the boundaries of ecological design, they understand and use ecological information in different ways. Table 2 summarizes key information about the projects and their biomimetic approaches.

The Lavasa Hill project started by selecting a few relevant ecosystem services to the urban project, and the Lloyd Crossing project began with an analysis of the site's biophysical structure. From the perspective of the ecosystem services cascade, the Indian project places its focus on the social elements of the cascade, i.e., the benefits that society can perceive from a functional ecosystem. The US project focuses on the ecological, biophysical structure that is necessary to promote a healthier ecological system and, by consequence, a healthier social system. The main difference here relies on Lloyd Crossing project's understanding that benefits from nature are a consequence of the project, acting actively to improve the integrity of these ecosystems.

In this vein, we can also note a difference in the holistic comprehension of site patterns. The Lavasa Hill project mostly concentrates on water flows, a challenge identified for the site in terms of erosion and flood flows. This is an important focus for the project of course, but other ecological structures, processes, and functions are also important and relate holistically to the challenges of a city located on steep hills straddling a river that must cope with monsoon rains. The Lloyd Crossing project deals with ecosystem complexity holistically as a basis for devising initial project performance goals. It addresses biodiversity, physical ecological structure, and energy and material flows. Specifically in the Lloyd Crossing project, we can observe that the thirteen indicators used for ecological diagnostics correlate roughly to the ecological integrity criteria proposed by Kandziora et al., as shown in Table 3.

Table 3. Elements of the ecological diagnosis carried out on the Lloyd Crossing project classified with the ecological integrity criteria proposed by Kandziora et al. [36].

#	Pre-Development Metrics	Related Ecological Integrity Criteria
1	Tree cover	Exergy capture/Entropy production
2	Wildlife species	Biotic diversity
3	Total precipitation	Water flows (abiotic)
4	Stormwater runoff	Water flows (abiotic)
5	Groundwater recharge	Water flows (abiotic)
6	Transpiration	Water flows (biotic)
7	Evaporation	Water flows (abiotic)
8	Incident solar energy	Exergy capture
9	Energy used by photosynthesis	Exergy capture/Entropy production
10	Energy reflected/absorbed/radiated	Exergy capture
11	CO_2 used	Exergy capture/Entropy production/Metabolic efficiency
12	Oxygen released	Metabolic efficiency
13	Carbon fixed as biomass	Exergy capture/Storage capacity

Source: Developed by the authors based on [43].

Even if some of these indicators, like biodiversity, were not thoroughly evaluated during the diagnostic phase, because secondary data on wildlife and vegetation coverage was mostly used, the process promoted a good understanding of ecosystem functioning and the potential production of inherent benefits.

Although more aligned with the ecological integrity concept and with the ecosystem services cascade, most of the metrics and strategies explored at Lloyd Crossing were those related to water and energy flows, and carbon storage. Much like the concentration on water flows observed on the Lavasa Hill project, this focus shows us that projects applying ecosystem-level biomimicry to generate regenerative impacts still tend to lack integrating strategies related to the biological and abiotic structure of these ecosystems. This links to urban metabolism theories [44,45] which concentrate on energy and material flows but do not give attention to biodiversity or the role of non-living structures in ecosystems which are crucial to ecosystem health, and therefore the production of ecosystem services that humans are dependent on [46].

It is also possible to identify in both projects that the strategies employed relate to ecosystems in two different ways: 1/reducing built environment caused pressures on ecosystem structures, processes, and functions; and 2/recovering or regenerating ecosystem structures. Pressure reduction actions included reducing energy and water consumption, the greenhouse gas emissions reduction plan in the Lloyd Crossing project and managing rainwater in the Lavasa Hill project. Among the actions to regenerate ecosystem structures, the recovery of the green canopy and blue and green grid connectivity were key in the Lloyd Crossing proposal [43], as was massive reforestation plans that were part of the Lavasa Hill project. Regarding the ecosystem services cascade, these conjoint actions can increase ecosystem self-organisation capacity (or integrity) and thus potentially increase potential ecosystem services supply [36], and achieve, therefore, the positive ecological impacts that were set as project goals.

Though certainly innovative, and definitely ecosystem-services based, the Lavasa Hill project demonstrates a partial approach to understanding local ecosystems and using these as a design driver. In contrast, the Lloyd Crossing project finds a conceptual base for both design strategies and performance goals in the ecological metrics assessed during the pre-development diagnostic phase, changing the design starting point, and integrating more in-depth ecological knowledge into the design [11,42]. This allows Lloyd Crossing to become a neighbourhood that works in more similar ways to local ecosystem patterns, and to become a district that generates benefits for humans and local ecosystems. This ties in with the regenerative notion of creating potentially positive and symbiotic impacts on local socio-ecosystems through development, not despite it.

7. Conclusions

To move forward with ecosystem-level biomimicry for regenerative urban design, it is essential to integrate understanding of local ecological structures, processes, and functions into design phases. The ecosystem services concept is an interesting entry point, but merely estimating ecosystem services provision guides us to an overly simplistic comprehension of ecosystems. In an ecosystem-level biomimetic approach, the ecosystem biophysical structure and its related processes allow a better comprehension of how ecosystems work, that can guide urban design processes. Our two case studies support this argument.

Compared to previous sustainable urban design frameworks, ecosystem-level biomimicry for regenerative design offers an opportunity to integrate ecology knowledge with urban design deeply. However, our case studies confirm the absence of consistent comprehension and integration of ecological theories into current urban design processes and practice. We also observed that the two analysed projects focus on addressing energy and material (mainly water) flows and lack understanding of other essential ecosystem criteria that are crucial for the dynamic stability of ecosystem services provision, such as biodiversity [3,36].

As Odum described [28], an ecosystem has a biological structure, physical abiotic structures, and material and energy flows. These four elements must be addressed in ecosystem-biomimetic and regenerative urban design if the aim is to concurrently improve society's wellbeing and the integrity of ecological systems.

Finally, the Pedersen Zari framework, as well the two case studies highlight that undertaking a comprehensive socio-ecological diagnostic process before any urban design or performance goal conception should be an unavoidable part of regenerative and biomimetic urban projects. This converges with other environmental management theories such as Strategic Environmental Assessment [47] and Cross Diagnostics [48].

This review sheds light on research questions that could help to scale up the application of ecosystem services-based biomimicry frameworks and regenerative design practices at the urban scale. Some of these questions are:

(1) How are the regeneration and the ecosystem goals of these projects translated into technical solutions? Which strategies can projects implement to work toward human-designed ecosystem services provision and to catalyse socio-ecosystems regeneration and co-evolution?
(2) How do regenerative projects draw on ecosystem functioning? Which ecological information and concepts are useful to urban designers to understand ecosystem functioning better and promote ecosystem regeneration?
(3) How are the outcomes of such projects measured and monitored? Which ecological indicators do projects use to assess the impact of regenerative design on local ecosystems?
(4) How do urban project phasing and stakeholder roles take account of and influence ecosystem properties and the overall ecological performance of a project?

In conclusion, the main finding from this research is that although theories related to ecosystem functioning are starting to be used in urban design and planning settings, there is still room for improvement. Integrating up to date, high quality ecology knowledge into the theoretical basis of these ecosystem-based design concepts and methods along with increased interdisciplinary work in both the conception of and application of these concepts and methods is likely to be key.

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Conclusions Chapter 1

The analysis of the regenerative design theories allowed us to identify five principles, two related to the objectives aimed by regenerative projects (namely, the net-positive impacts for nature and society and co-evolutionary perspective for these two systems and three related to their design process (the use of diagnostic to inform decision making, a participatory design process and continuous improvement perspective). These principles are essential in informing the design framework, the main objective of this work.

Moreover, the ecosystem-level biomimicry approach for regenerative design show opportunities in the operational aspects, such as the potential to assess the positive impact using ecosystem services metrics. Nevertheless, the two case studies present limitations on their applications.

We observed that the ecosystem services theories are not fully acknowledged in project design. Namely, we identified a trend to address mostly material and energy flows, with less interest in ecosystems' biophysical structure. This fact potentially leads to projects that only metaphorically find inspiration on ecosystems and remain anthropocentric, not aiming for mutual benefits.

These analyses also pointed us to highly technocratic design approaches, with the design process informed by ecological science but neglecting social aspects. Despite that, regenerative design theories, demands a participatory and holistic design process. This creates a contradiction and incoherece between theory and practice

Finally, these results attracted our attention to the following topics of interest that are further discussed in this thesis: (1) the variety of strategies and solutions used as interventions on the space to enhance the production of ecosystem services, (2) the urban design process and its impacts on the outcome, such as the practice of ecological diagnostics and the difference governance arrangements around the projects, and (3) the operational indicators that can be used to define project objectives and assess the expected positive outcomes.

Conclusions Chapitre 1

L'analyse des théories du «regenerative design» nous a permis d'identifier cinq principes, deux liés aux objectifs visés par les projets régénérateurs (à savoir, les impacts positifs nets pour la nature et la société et la perspective coévolutive pour ces deux systèmes) et trois liés à leur processus de conception (l'utilisation du diagnostic pour informer la prise de décision, un processus de conception participative et une perspective d'amélioration continue). Ces principes sont essentiels pour informer le cadre de conception, l'objectif principal de ce travail.

En outre, l'approche biomimétique de l'écosystème pour le «regenerative design» présente des opportunités dans les aspects opérationnels, comme le potentiel d'évaluation de l'impact positif en utilisant des mesures de services écosystémiques. Néanmoins, les deux études de cas présentent des limites quant à leurs applications.

Nous avons observé que les théories des services écosystémiques ne sont pas pleinement prises en main dans la conception des projets. En effet, nous avons identifié une tendance à traiter principalement les flux de matières et d'énergie, avec un intérêt moindre pour la structure biophysique des écosystèmes. Ce fait conduit potentiellement à des projets qui ne s'inspirent que métaphoriquement des écosystèmes et restent anthropocentriques, ne visant pas les bénéfices mutuels.

Ces analyses nous ont également mis en évidence des approches de conception hautement technocratiques, informés par la science écologique, mais négligeant les aspects sociaux. Pourtant, les théories de conception régénérative exigent un processus de conception participatif et holistique. Cela crée une contradiction et une incohérence entre la théorie et la pratique.

Enfin, ces résultats ont attiré notre attention sur les sujets d'intérêt suivants qui sont discutés plus en détail dans cette thèse : (1) la variété des stratégies et des solutions utilisées comme interventions sur l'espace pour améliorer la production de services écosystémiques, (2) le processus de conception urbaine et ses impacts sur les résultats, telles que la pratique des diagnostics écologiques et les différentes gouvernances dans la phase de conception et (3) les indicateurs opérationnels qui peuvent être utilisés pour définir les objectifs des projets et évaluer les résultats positifs attendus.

Chapter 2

Regenerative and ecosystemic urban design practice

Summary

This chapter focus on the sustainable and regenerative urban design practice. We aim to understand how projects translate into urban solutions and strategies, their engagements toward reconnecting with natural ecosystems and promoting positive impacts. Moreover, we wish to look beyond technical aspects and identify success levers in the urban design process, namely those related to the governance in the design of these neighbourhoods. To do so, we rely on international case studies of sustainable and regenerative neighbourhood projects, addressing in two papers two other general research questions:

1. What urban interventions and solutions can be used on neighbourhood projects to enhance the production of ecosystem services and promote benefits for society and nature?

2. Which governance elements from the urban design process enhance the success of these projects?

The first question is covered in a peer-reviewed paper published in the "Sustainable Cities and Society" journal. This paper analyses six international sustainable neighbourhoods, based on their project documentation, to identify which solutions and strategies are used to contribute to the production of urban ecosystems services. We also explore the different types of solutions, their goal and how they relate to natural ecosystems, generating hypotheses on the topic.

The second question is tackled in an article submitted to the "Cities" peer-reviewed journal. This paper explores three of the previous case studies through interviews with design team members. Unlike the previous paper, here we are less interested in the technical aspects of the projects. Using a governance analysis framework, we aim to identify levers of success in the design process that are fundamental to implementing urban strategies that contribute to the production of ecosystem services.

Resumé

Ce chapitre se concentre sur la pratique du design urbain durable et régénératif. Nous cherchons à comprendre comment les projets traduisent en solutions et stratégies urbaines leurs engagements vers la reconnexion avec les écosystèmes naturels et la promotion d'impacts positifs. En outre, nous souhaitons aller au-delà des aspects techniques et identifier les leviers de réussite dans le processus de conception urbaine, notamment ceux liés à la gouvernance dans la conception de ces quartiers. Pour ce faire, nous nous appuyons sur des études de cas internationales de projets de quartiers durables et régénératifs, en abordant dans deux articles deux autres questions générales de recherche :

1. Quelles interventions et solutions urbaines peuvent être utilisées dans le cadre de projets de quartiers pour améliorer la production de services écosystémiques et promouvoir des avantages pour la société et la nature ?

2.Quels éléments de la gouvernance de la conception urbaine favorisent la réussite de ces projets ?

La première question est traitée dans un article évalué par les pairs et publié dans la revue «Sustainable Cities and Society». Cet article analyse six quartiers durables internationaux, sur la base de leur documentation de projet, afin de déterminer quelles solutions et stratégies sont utilisées pour contribuer à la production de services écosystémiques urbains. Nous explorons également les différents types de solutions, leur objectif et leur relation avec les écosystèmes naturels, en générant des hypothèses sur le sujet.

La deuxième question est abordée dans un article soumis à la revue «Cities». Cet article explore trois des études de cas précédentes par le biais d'entretiens avec des membres de l'équipe de conception. Contrairement à l'article précédent, nous nous intéressons ici moins aux aspects techniques des projets. En utilisant un cadre d'analyse de la gouvernance, nous cherchons à identifier les leviers de succès dans le processus de conception qui sont fondamentaux pour mettre en œuvre des stratégies urbaines qui contribuent à la production de services écosystémiques.

2.1 Reconnecting neighbourhoods with ecosystem functioning: Analysis ofsolutions from six international case studies

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Reconnecting neighbourhoods with ecosystem functioning: Analysis of solutions from six international case studies

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ABSTRACT

Urban design organises and transforms the space, reflecting human context on cities' shape. Since modernism, designers draw urban projects with the goal to improve cities performances based on a mechanistic worldview, in which living systems are almost not considered. This paradigm led to urbanisation that is prominent in ecological process simplification and biodiversity loss. Different emerging urban design frameworks engage with the challenge of integrating ecological information on the design of sustainable urban projects, using this knowledge to guide intervention choices. With a growing application in practice, as through regenerative design and biomimicry, there is still a lack of knowledge on how ecological urban projects operationalise their engagements. We explored this question with a case study approach, generating hypotheses on the topic. We identified that projects focus on reducing human pressures over the ecosystems instead of regenerating the ecosystem's structure. Furthermore, projects mainly deal with energy and material flows. We identified a taxonomy of 36 urban strategies that could inform new design tools. Finally, we argue that the ecosystem biophysical structure needs to be better addressed on urban projects, and that projects would benefit from better articulation between solutions to reduce human pressures with those regenerating the ecosystem state.

1. Introduction

1.1. Ecosystems logic on urban design

Urban design organises and transforms the space by reflecting human context on our cities' shape (Arab, 2018). The urban design practice is interested in the materiality of space to direct it towards a considered preferable situation from the design team's perspective. For this purpose, urban project stakeholders choose interventions, electing and combining relevant strategies and solutions to transform the space and its socio-economical dynamics (Arab, 2018).

Since modernism (from early to the middle of the 20th century), urban designers draw urban projects based on a mechanistic worldview, aiming to improve our cities performances (Du Plessis & Brandon, 2015; Ellin, 2020), but almost not taking living systems into account (Ellin, 1999; Steiner, Young, Zube & Ndubisi, 2014). This paradigm led our society to an urbanisation logic that reduces ecosystems and human health (Alberti, 2005; IPBES, 2019).

Shifting to an urban design practice that profoundly integrates the natural ecosystems logics in the urban space is a significant challenge for our generation (Alberti, 2005; Du Plessis & Brandon, 2015; Pedersen Zari, 2018; Steiner, 2014).

In the political sphere, the Sustainable Development Goal 11 – Sustainable Cities and Communities invites designers to tackle this question, proposing to strengthen efforts to protect and safeguard natural heritage (Target 11.4) and to reduce environmental impacts of cities (target 11.6) (United Nations, 2018). In the same line, the New Urban Agenda also present engagements towards this paradigm shift, highlighting the need for new tools to assist this process (United Nations, 2017). Nevertheless, on the operational level, sustainable urban projects and sustainable urban design frameworks, as LEED-ND, BREEAM communities and GreenStar Communities, struggle to address this paradigm shift. These frameworks present limitations such as partial coverage of sustainability and a lack of integration of key elements of site context on the design (Grazieschi, Asdrubali & Guattari, 2020; Sharifi, Dawodu & Cheshmehzangi, 2021).

1.2. A new generation of urban design frameworks

However, some emerging urban design frameworks engage with the

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challenge of putting the ecological perspective at the centre of the urban design process (Bayulken & Huisingh, 2015; Benne & Mang, 2015; Ellin, 2020). Regenerative design, ecosystem-level biomimicry and the French EcoQuartier are three examples that operationalise these engagements at different maturity levels (Bayulken & Huisingh, 2015; Blanco, Pedersen Zari, Raskin & Clergeau, 2021; Chastenet et al., 2016; Pedersen Zari, 2018). In this research, we have a particular interest in these three frameworks, aiming to understand how they impact urban projects and their lacks.

Regenerative Design aims to create urban projects that promote positive impacts on the socio-ecosystems, allowing social and ecological systems to co-evolve and thrive (Attia, 2016; Brown et al., 2018; Cole, Oliver & Robinson, 2013; Zhang, Skitmore, De Jong, Huisingh & Gray, 2015). Although the concept got popularised in the 21st century (Benne & Mang, 2015; Brown et al., 2018), there is still a lack of tools to facilitate its operationalisation (Brown et al., 2018; Hes & Du Plessis, 2014). The Living Building Challenge, a North American design framework and rating system, can be cited as the most consolidated tool available nowadays.

Ecosystem-level biomimicry also relates to regenerative design objectives (Attia, 2016). Biomimicry draws upon emulation of, and knowledge transfer from, living organisms and whole ecosystems to find solutions to human problems (ISO, 2015). Emulating local ecosystems functioning on urban projects, through the notion of ecosystem services, has been highlighted to operationalise regenerative impacts (Pedersen Zari, 2018). In this process, designers try to emulate natural ecosystem functioning in the urban space, aiming for a measurable positive impact in terms of ecosystems services production (Hayes, Desha & Gibbs, 2019; Pedersen Zari, 2018).

Finally, the French EcoQuartier is a design framework and labelling program supported by the French government. Like other national frameworks, as the EcoDistrics in the United States and the CityLab in Sweden, it aims to foster sustainable urban neighbourhoods development at the national scale. The framework has a bottom-up approach with 20 holistic engagements, taking into account social, economic and ecological context as inputs for the design process (Chastenet et al., 2016).

1.3. A lack of understanding of the ecological urban design practice

Even with the growing application of these emerging urban design frameworks (Bayulken & Huisingh, 2015; Blanco et al., 2021; Brown et al., 2018; Buck, 2017; Chastenet et al., 2016), a lack of knowledge from an urban design practice perspective persists. All of them aims to inform the urban design team on the design process. However, there is no common understanding of how urban projects translate and operationalise into urbanisation strategies and solutions their engagements to integrate the natural ecosystems logics in the urban system and to produce mutual positive impacts (Pedersen Zari & Hecht, 2020; Steiner, 2014).

Nature-Based Solutions (NBS) have gained a central place on the topic of solutions to face contemporary urban challenges (Almenar et al., 2021; IUCN, 2020). NBS has been widely adopted on policy and projects to foster human well-being while generating biodiversity benefits. The growing deployment and use of the term and allegedly Nature-Based solutions led IUCN to produce a Global Standard presenting eight criteria to frame and foster the application of NBS on urban policy and projects (IUCN, 2020). Nevertheless, NBS are not adapted to tackle all contemporary urban challenges (Almenar et al., 2021), and combining different solutions (as NBS, technological and educational) seems fundamental to reaching wide positive and mutual impacts.

In this context, we are here interested in three operational questions that remain to be explored: 1) Which urbanisation strategies and solutions are being used in the field to fulfil these engagements? 2) Are these solutions mainly aiming to reduce human pressures over ecosystems or to regenerate ecosystems state? 3) Are these emerging frameworks holistically addressing ecosystem functioning, or do they only partially integrate the notion?

Our objective is to generate hypotheses related to these questions through a multiple case study approach, supported by content and typological analysis on projects design phase documentation. We analyse six urban projects designed using the three previously referred design approaches. Our case study sample was chosen using pragmatic and theoretical criteria. Thus, this study does not wish to exhaustively evaluate urban design solutions and strategies to design ecological urban projects. Instead, we propose exploring how these outstanding projects deal with the challenge of reconnecting their functioning to local ecosystem logic.

2. Materials and methods

We used a mixed-method approach, relying on case studies, content analysis and quantitative typological analysis. As an empirical investigation method, case studies help understand contemporary phenomena within their real-life context (Groat & Wang, 2013; Yin, 2018), and it is helpful to generate hypotheses on real-world phenomena (Small, 2009). We used a multiple case studies approach and followed Yin (2018)) framework to design the study, supported by content analysis to generate data and a typological approach to analyse the data. Fig. 1 presents the main steps of our method, described in the following sections.

2.1. Case studies selection and cases description

Our case studies selection relied on pragmatic considerations and theoretical prominence of the projects, such as their scale and phasing, used design framework and documentation availability. Pragmatic approaches of case selection are legitimate in case studies, mainly in exploratory studies when used to generate and explore hypotheses (Seawnght & Gerring, 2008; Small, 2009). Our four pragmatic and theoretical criteria were:

1 Scale and use: Projects should be at the neighbourhood scale. They should have more than one building, public space, be mixed-use and have diverse stakeholders.
2 Design framework: Projects should have robust ecological engagements and use ecosystem-level biomimicry, regenerative design or EcoQuartier design approaches.
3 Project phase: Projects should have reached the implementation phase, even if partially (conceptual projects are excluded);
4 Documentation: Projects should have relevant documented information, in English or French, accessible online or through authors personal and professional network, allowing a deep comprehension of the case;

Following a brainstorming session, the research team identified 32 potential cases (Appendix A), we selected six urban projects that fit the presented criteria (Table 1). Projects are here briefly described.

2.1.1. Lloyd crossing sustainable urban plan

The Lloyd Crossing Sustainable Urban Plan is an urban requalification project for the Lloyd District, a mixed-use district located in Portland, Oregon, USA. Designed in 2004 by Mithun, under the Portland Development Commission's request, the project used a design approach that finds inspiration in the local ecosystem patterns to catalyse ecological, social, and economic regeneration. Using an ecosystem-level biomimetic approach, the design team assessed thirteen ecological metrics from the original ecosystem (a mixed conifer forest) as the first design step. This diagnostic allowed designers to build site-specific ecological comprehension that guided the sustainable urban strategies selection. The final project presents long term engagements and strategies to foster the district development and creates a neighbourhood that

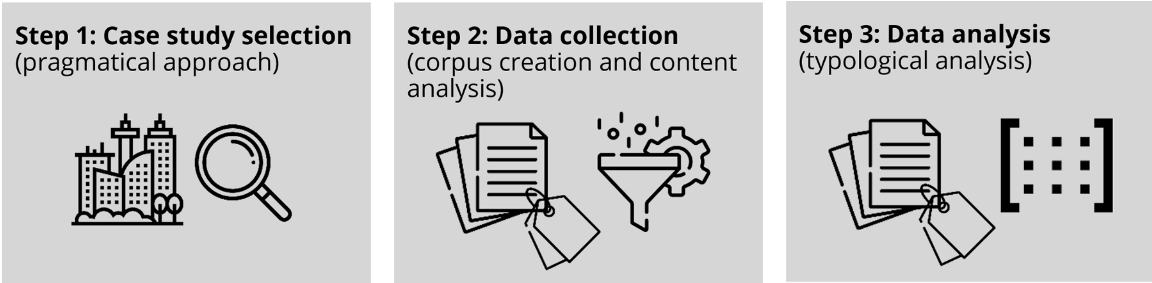

Fig. 1. Methodological framework.

Table 1
Case studies context information.

#	Project acronym	Project full name	Total area (ha)	% of green area	Location	Actual project status	Design approach
1	Lloyd	Lloyd Crossing Sustainable Urban Plan	21,8	30%	Portland, USA	Under implementation	Ecosystem-level biomimicry
2	Lavasa	Lavasa Hill	> 2 000	*	Mumbai-Pune region, India	Partially implemented; Abandoned	Ecosystem-level biomimicry
3	Blatchford	Blatchford Redevelopment Plan	217	27,8%	Edmonton, Canada	Under implementation	Regenerative design
4	Paddock	The Paddock	1,4	65%	Castlemaine, Australia	Under implementation	Regenerative design
5	Clause	Ecoquartier Clause-Bois Badeau	42	26%	Bretigny-sur-Orge, France	Under implementation	EcoQuartier
6	CIGV	Ecoquartier de la Cité Internationale de la Gastronomie et du Vin de Dijon	6,5	35,4%	Dijon, France	Implementation-authorisations requested	EcoQuartier

* No available information.

relies only on water and energy available locally, that regenerates habitats, and that reconnects the district functioning to the local ecosystem patterns (Hayter, 2005; Mithun, 2004; Pedersen Zari, 2018).

2.1.2. *Lavasa hill*

The Lavasa Hill project is a planned city in Maharashtra state in India's Mumbai-Pune region, covering over 2000 ha, designed in 2001. Part of it has been designed using the Ecological Performance Standards framework from Biomimicry 3.8, an ecosystem-level biomimicry design framework that relies on the notion of ecosystem services (Baumeister, Pedersen Zari & Hayes, 2020; Lazarus & Crawford, 2011). The design teams find inspiration from local monsoon ecosystems and organisms to solve sustainable urban design challenges, mostly related to rainwater management and erosion control. Through an ecological diagnostic process, engaging urban designers and ecologists, the HOK Architects and Biomimicry 3.8 design team identified six essential ecosystem services for the site's ecological functioning, rendered by the local forest. The designed project tried to replicate these ecosystem services through innovative bioinspired urban strategies, aiming to render ecosystem services, improve the project's feasibility, and reduce its environmental impacts (Baumeister et al., 2020; Datta, 2012; Lazarus & Crawford, 2011).

2.1.3. *Blatchford redevelopment plan*

The Blatchford Redevelopment project is an urban renewal project designed in 2013 and situated in Edmonton, Canada. The project aims to requalify 217 ha from the old city airport to a sustainable community that relies only on renewable energy, is carbon neutral, significantly reduces its ecological footprint, and empowers residents to pursue sustainable lifestyle choices. Perkins+Will designed the project using a regenerative design mindset and whole systems thinking. The design team creates a deep understanding of site logic and needs in their whole systems and regenerative design approaches. The project aims to restore the local ecosystem's health using several urban strategies to recreate habitat, reintroduce biodiversity and relink the urban site to the local ecosystem flows, aiming for renewable energy and carbon neutrality strategies (Busby, 2015).

2.1.4. *The Paddock*

The Paddock is a small sustainable neighbourhood situated in Castlemaine, Australia, counting 26 homes and designed in 2008 Jeff Crosby designed the project to make the local ecosystem healthier with the urban project, presenting robust engagements towards biodiversity and local food production. The design relies on the Living Building Challenge (LBC) certification, a primary regenerative design framework and certification program. Following the LBC requirements, the project presents several strategies to restore habitat and biodiversity, be autonomous, rely only on locally available resources, and create a positive socio-ecological impact on the site. The project relied on a 3-day participatory site ecological diagnostic to draw the project baseline, identifying site's patterns related to water, soil, vegetation, birds, insects, amphibians, reptiles, and mammals (Pedersen Zari, 2018).

2.1.5. *Clause-Bois Badeau*

Clause-Bois Badeau is a sustainable neighbourhood in Bretigny-Sur-Orge, France, over 42 ha designed in 2005. GermeJAM designed the project aiming for the French EcoQuartier certification, now awarded as a delivered EcoQuartier. The project aims to requalify industrial and agricultural brownfields to reconnect the urban space with the local ecosystem and ecological networks. Claude-Bois Badeau presents meaningful engagements towards biodiversity reintegration, energy sobriety and the creation of a regional green network. A green park with a broad diversity of habitat types is in the centre of the projects and articulates the urbanisation. The project has been designed after several ecological and environmental impacts studies. The ecological studies were key to designing green areas that are functional and complex ecosystems (CEREMA, 2015).

2.1.6. *Cité Internationale de la Gastronomie et du Vin de Dijon*

The Cité Internationale de la Gastronomie et du Vin de Dijon is an urban requalification project in the heart of Dijon, France, over 6,5 ha and designed in 2016. The project integrates a touristic and event infrastructure related to French gastronomy with a sustainable neighbourhood designed by Bechu & Associés and Eiffage. The project relies on the French EcoQuartier framework recommendations but does not aim for the certification. The project has a significant focus on protecting the existing ecological structure, improving the soil permeability, and reducing greenhouse gas emissions. The project also presents engagements related to local food production. The project used environmental impact assessments as a source of information to design relevant site-specific solutions (Eiffage Aménagement, Agence d'architecture A. Bechu, LAND'ACT & OTCI, 2016).

2.2. Data collection

To identify the projects' urban solutions and strategies to reconnect with the ecosystem functioning, produce positive impacts and potential urban ecosystem services, we created a documental collection (corpus) for each project. Relevant documentation related to the design phase was collected through scientific databases (Web of Science), projects websites, web research databases (Google), and directly with project stakeholders by e-mail. For online databases, we used the project names as keywords.

Only documents describing and presenting the project urban solutions in the design phase were retained for analyses, creating a relevant corpus concerning our research questions. As urban solutions, we understand any design solution aiming to reduce the impacts of urban projects over the ecosystems or create a regenerative (positive) impact on them, reconnecting the project to the local ecosystem and potentially producing urban ecosystem services.

The following type of documents composes the corpus:

- Scientific peer-reviewed articles
- Scientific reports
- Projects information available on the official projects websites
- Commercial project booklets and communications
- Urban design plans and related documents
- Public policy documents related to the projects
- Construction authorisations and related documents
- Books excerpts discussing the projects
- Architecture review articles describing the project (non-scientific documents)

Table 2 presents the number of documents analysed for each case study. Appendix B presents the name of each analysed document.

We imported the corpus to MaxQDA Analytics Pro 2020 software, where it was read and coded using thematic coding (Saldana, 2009). Data was coded only by one researcher and validated by the others at the end of the coding process. We coded the data using only one criterion, the urban solution type (described on 2.3). We used a two-round coding process. The first round was based on a grounded-theory approach, in which the corpus was read without any preliminary coding structure. Once an urban solution was identified, it was freely coded, creating a coding class to define its type or using a previously created class. At the second round, all the corpus was verified a second time, and coding classes were merged, leading to a final structure of six different codes describing the solution types (described in Section 2.3).

This step allowed us to identify and register excerpts presenting the different urban solutions proposed by designers with a direct or indirect ecological objective and their types, that would be later typologically classified and analysed.

Table 2
Number of analysed documents and urban solutions identified in each case study.

#	Project	Number of analysed documents	Number of identified solutions
1	Lloyd	5	29
2	Lavasa	11	9
3	Blatchford	14	18
4	Paddock	6	19
5	Clause	20	21
6	CIGV	16	14

2.3. Data analysis

Every urban solution identified was classified using three typological criteria, defined to answer our research questions. They are:

- **Goal:** Each solution was classified regarding its main goal toward the ecosystems. To identify the goal, we based our observation on designers' context in the documents. Three goals were possible:
  - Reduce pressure over the ecosystem: solutions that focus on reducing, minimising and mitigating project impacts and their pressures over the ecosystems;
  - Regenerate the ecosystem structure: solutions that focus on regenerating or protecting the ecosystem structure on-site;
  - Both: solutions that have both previous goals;
- **Type:** Each solution was classified between six possible types:
  - Compensation: Solutions to compensate/mitigate the negative impact of the urban project;
  - Education: Solutions based on education and awareness-raising of final project users;
  - Nature-Based Solutions (NBS): Solutions relying on living systems. We adopted here the Nature4Cities classification for NBS identification (NATURE4CITIES, 2019);
  - Technological: solutions relying on urban technologies;
  - Urban rules and policy: solutions relying on the proposition of public policies, urban prescriptions and urban legislations;
  - Urban form and infrastructure: solutions that directly change the urban form and urban infrastructure.
- **Main ecosystem component:** for each solution, we identified one main ecosystem component that the solutions relate to and aims to deal with the local ecosystem. To this classification, we used Odum (1969) definition of ecosystems, with four main components:
  - Biological structure: Solutions that protect or restore the biotic ecosystem components (fauna, flora and microorganisms), improving its overall health, diversity and resilience.
  - Physical structure: Solutions that protect or restore the abiotic ecosystem components that characterise the ecosystem and their condition., like the soil and rocks composition and quality, the wind dynamics, the air quality, the water resources and the topography;
  - Energy flows: Solutions that deals with the energy flows (renewable energy, electricity, heat transfers…) in the built space and connects human-made flows to ecological ones.
  - Material flows: Solutions that optimise the material flows (water, carbon, food, nutrients, biomass, building resources…) in the built space and connects human-made flows to ecological ones.

Solutions classified as NBS were further analysed and classified to detail the NBS types observed in the sample. For this classification, we relied on the Nature4Cities NBS classification and the factsheets presenting the different classes (NATURE4CITIES, 2019). Each excerpt describing a NBS solution was then reclassified, matching the solution description with a NBS class description from the Nature4Cities NBS factsheets.

Appendix C presents the identified urban solutions and their classification.

2.4. Strategies hierarchical classification

Once all the solutions were classified using the previous criteria, we cross-examined them to identify co-occurrences and convergences. This analysis allowed us to propose a homogenised and hierarchical classification from the solutions observed into larger groups, called strategies. Each strategy is related to a topic and ecosystem component, creating a hierarchical structure. This hierarchical classification aims to summarise in a taxonomy how the analysed projects are operationalising an ecological design.

2.5. Limitations and methodological choices

The identified solutions and strategies discussed here are placed at the end of the projects design phase. The design phase is justified by our interest in the design process, the step in which project teams select the main solutions and strategies. Nevertheless, we are aware that the solutions and strategies may evolve until their implementation. These evolutions and the mechanism behind them are not our objective but are worthy of exploration.

We analyse the number of strategies on each project and their types, not their specific characteristics (like extent, benefits, perceived impacts). The number of solutions and strategies helps understand trends in practice and are not proxies to these projects' ecological performance.

We are aware of the differences between the cases we studied, notably their size and their ecological, social and economic contexts. As we do not assess the project performances but how they deal with urban challenges through concrete solutions to build hypotheses, these questions do not interfere in interpreting our results.

3. Results

In the six case studies, we identified 110 urban solutions (Table 2). The main results are presented in the following topics.

3.1. Solutions goal: a focus on reducing urban pressures over the ecosystems

amongst the 110 identified solutions, 59,1% primarily focus on reducing the urban project impacts and pressures over the ecosystems. Examples are technological and awareness-raising solutions to reduce energy and water consumption in the neighbourhood, transport-orientated design and active mobility strategies to reduce air pollution and CO_2 emissions, and the use of low impact and locally resourced building materials.

In opposition, 31,8% of the identified solutions aimed mainly to regenerate the ecological structure. Nature-Based solutions, like green parks design, green roofs, and native species' reinsertion, are recurrent strategies in this topic.

Finally, 9,1% of the solutions had mixed goals, aiming to regenerate the ecosystem and reduce human pressures over the ecosystems. Examples are bioswales, designed to manage rainwater and recover habitats availability, local urban agriculture zones for food provisioning, and artificial lakes' design to improve the ecosystem complexity and treat grey and rainwater. Fig. 2 presents the distribution of the goals of the solutions on each project.

3.2. Solution types: nature-based and technological solutions as the most frequent types to tackle urban ecosystem challenges

"Nature-Based solution" is the most recurrent solution type in our case studies. They represent 39,1% of the identified solutions, followed by "Technological solutions", representing 29,1%. These two types represent 67,3% of the identified solutions, and both were observed in all cases.

Bioswales, pocket gardens, public urban green spaces, street trees, green roofs and green network connectivity represents 48,8% of all NBS strategies (Fig. 3) and 19,1% of all identified solutions in the sample. amongst the technological solutions, we observe various on-site renewable energy production propositions (through photovoltaic, geothermal, wind and biomass energy production). Other recurrent technological solutions are rainwater management through water collection and reuse, on-site wastewater treatment, waste management and recycling, efficiency upgrade on buildings to reduce energy and water consumptions, and low impact building materials.

"Urban rules and policy" type represents 17,3% of the sample. Examples are urban zoning and urban prescriptions to define high energy and water performances for new buildings in the project area. Codes and prescriptions seem necessary to ensure that the ecological engagements are kept over the project lifecycle and stakeholders changes.

The "Urban Form and infrastructure" type counts for 10,9% of identified solutions. Here we observe solutions to promote active mobility and transit infrastructure, soil management and topography protection. Finally, the "Education" and "Compensation" types represent only 1,8% each (addressed only by two projects). Examples for these two last classes are, respectively, the final user education to reduce energy and water consumption and project carbon emission offset through carbon credits. Fig. 4 illustrates the distribution of the strategy types for each case study.

3.3. Ecosystems components: urban solutions addressing material and energy flows instead of ecosystem biophysical structure

The ecosystem component criteria allow us to understand how the

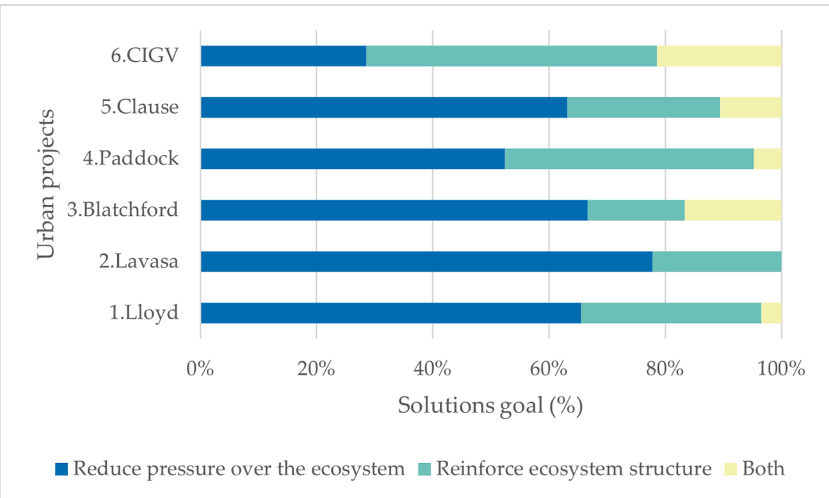

Fig. 2. Distribution of solutions goal for each project.

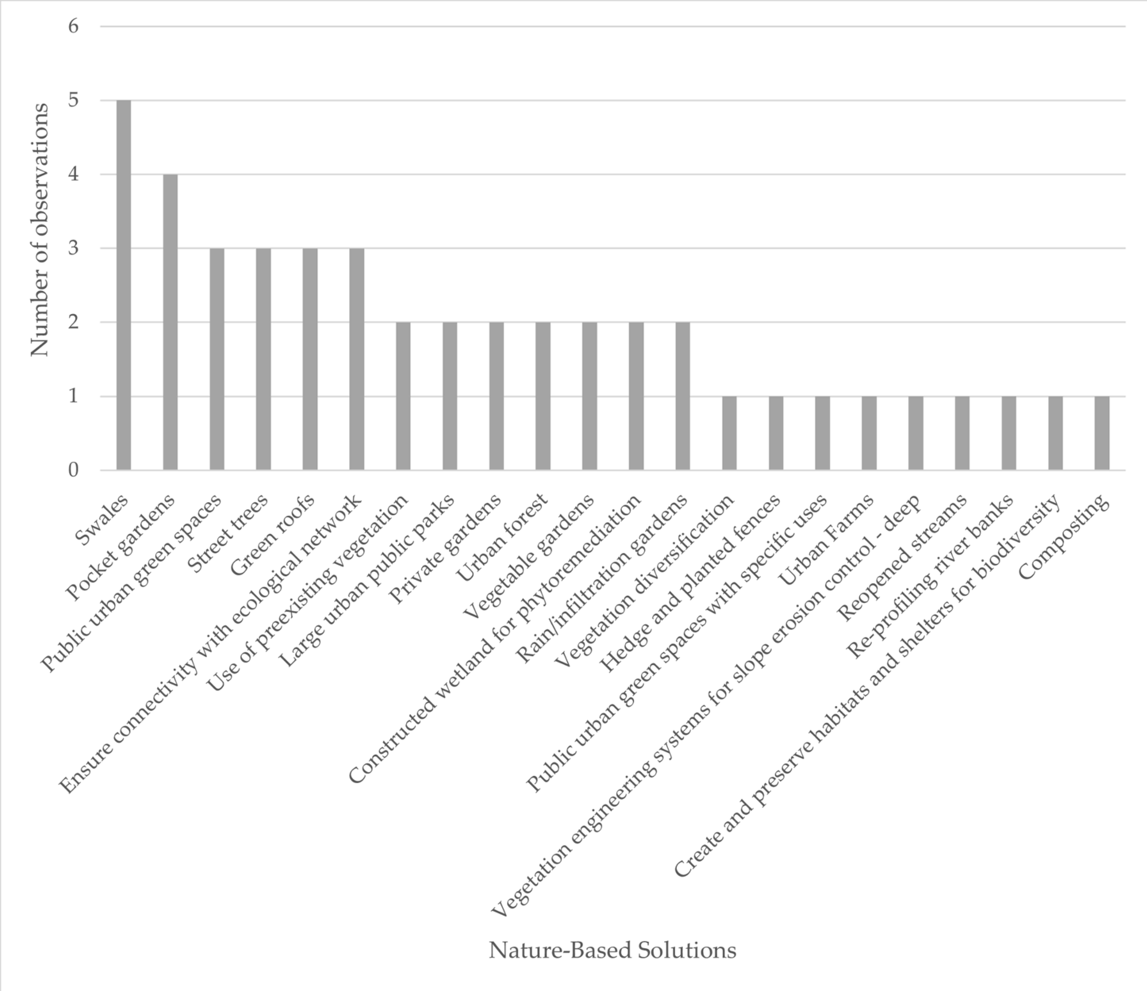

Fig. 3. Different Nature-Based Solutions occurrence (using Nature4Cities (2019) classification).

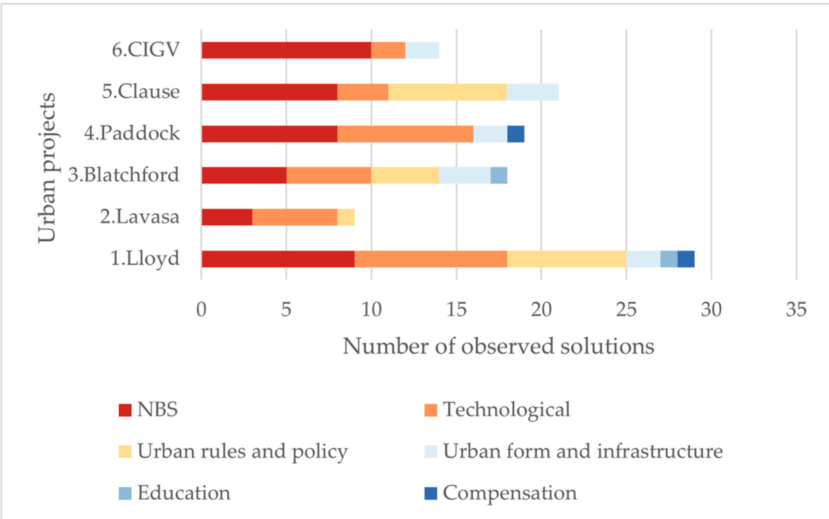

Fig. 4. Types of solutions per case study.

solutions contribute to different elements and processes that compose an ecosystem. We observe that 66,5% of the overall identified solutions deal with flows (energy and materials), while 33,6% will address ecosystems biophysical structure (biotic and abiotic).

The ecosystem component primarily addressed is the materials flows, counting for 45,5% of the identified urban solutions. Material flows strategies deals with diverse flows between urban space and natural ecosystems, like water, food, building resources, waste and carbon.

Examples of identified solutions in this topic are on-site rainfall water management, the reduction and compensation of embodied CO_2 emissions, local food production, the local sourcing of building materials and local organic waste management.

Solutions dealing with energy flows represents 20,9% of the sample. Examples are the local production of renewable energy, reducing energy consumption through fixtures, and optimising solar input and heat transfers between buildings.

Strategies primarily addressing the biological structure represents 27,3% of the observations. Examples are notably the NBS strategies previously discussed, such as green urban areas, bioswales and green roofs. Finally, only 6,4% of the identified strategies address the physical and abiotic structure of the ecosystems. Examples are water bodies design, water quality recovery, soil unsealing and erosion control solutions.

The distribution of strategies amongst the four components of ecosystems is different for each project (Fig. 5). It is possible to observe that none of the projects deals with the four ecosystems components equilibrated and holistically. Material flows is one of the most relevant category in every project.

3.4. *NBSs regenerating ecosystems structures, technological solutions reducing the impacts of human-made flows*

We can note that the NBS type is used mainly to regenerate the ecosystems' biological and physical structure. Technological ones are those that mainly relates to energy and material flows. Urban code and policy and urban form and infrastructure also present a stronger link with flows (Fig. 6).

Furthermore, NBS strategies represent 91,4% of all strategies with a primary goal to regenerate the ecosystem structure. Technological strategies represent 49,2% of all the strategies aims to reduce the pressure over the ecosystem

3.5. *Strategies hierarchical classification: defining an urban strategies taxonomy*

We were able to identify convergences amongst the different solutions in the six case studies. These convergences lead us to propose a hierarchical classification of the identified solutions on 36 urban strategies families used to reconnect urban projects with local ecosystems (Table 3). amongst the most recurrent identified strategies, we can list:

- on-site renewable energy production;
- the reduction of energy consumption;
- on-site stormwater management;
- design for active and low carbon mobility, and
- the design of minor public green areas.

Appendix D presents the identified strategies on each case study.

4. Discussion

This research provided innovative insights into how urban projects address and operationalise the challenge of reconnecting their functioning to natural ecosystems and finding inspiration on ecosystem models. We were able to identify trends in the urban solutions and strategies choices, related to our research questions, synthesised in the following hypotheses:

- Urban projects focus on reducing human pressures over the ecosystems instead of a proactive approach to regenerate ecosystem structures;
- Nature-based solutions have an essential role in ecological and sustainable urban projects, allowing to promote mutual benefits for society and nature;
- Technological solutions are important on the management of human pressures over ecosystems, mainly those related to materials and energy flows;
- Projects primarily address energy and materials flows and tend to give lesser importance to ecosystem biophysical structure;

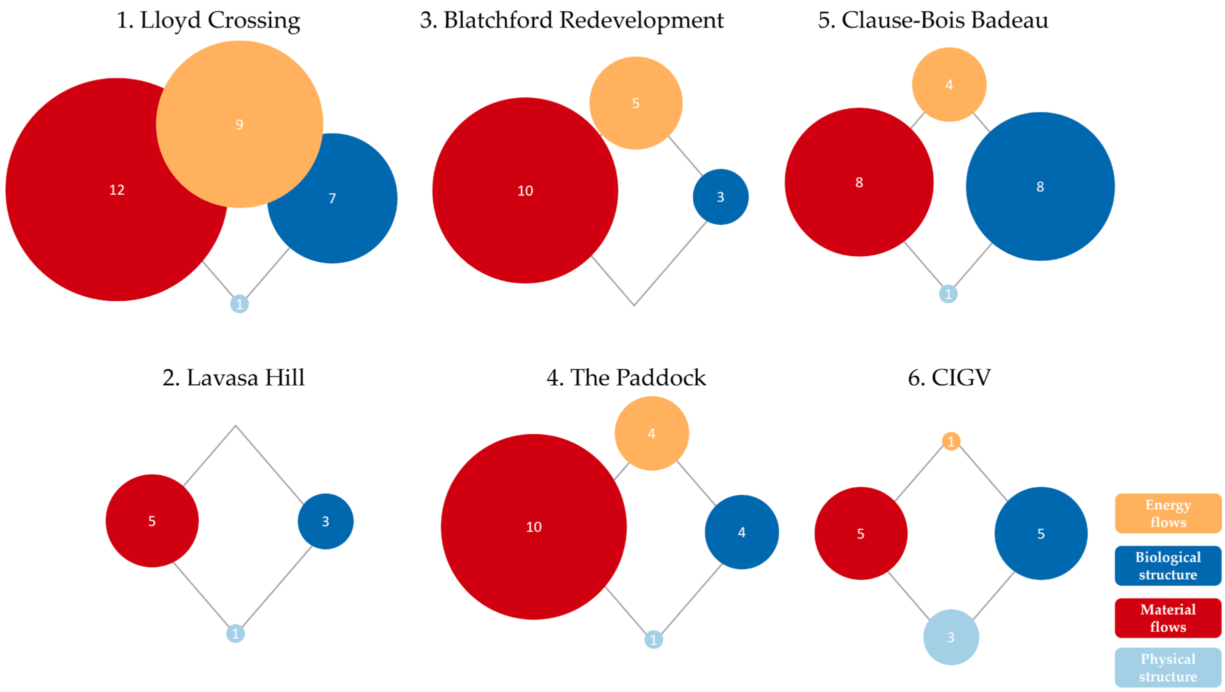

Fig. 5. Distribution of solutions for each ecosystem component per case study (The circles' size is equivalent to the number of strategies on each axe, the number of identified strategies is inside each circle).

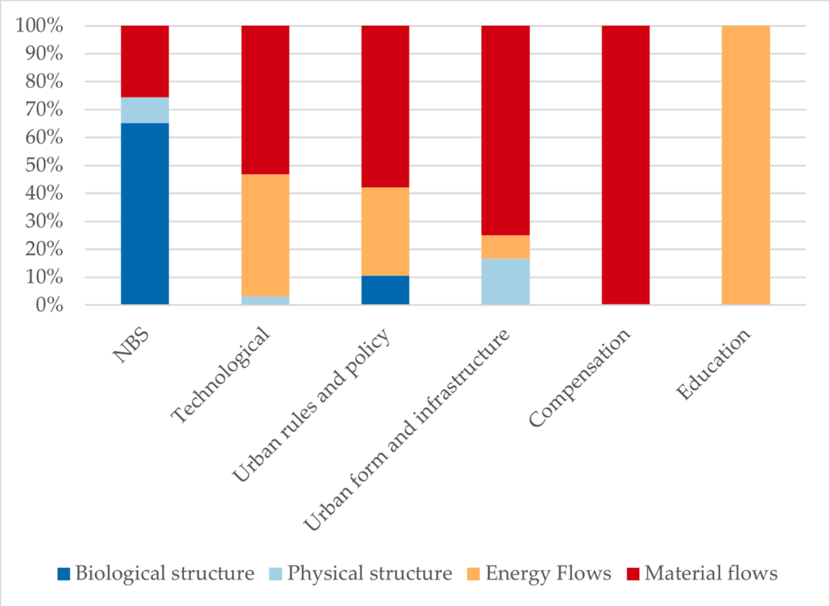

Fig. 6. Relation between solutions types and the ecosystem's elements they are addressing.

4.1. *Enhancing the production of ecosystem services: the need for more solutions to regenerate the ecosystem biophysical structure*

While solutions had distinct objectives, we observed a trend of focusing on reducing human pressures over ecosystems. Furthermore, 65% of the solutions primarily relate to material or energy flows, and ecosystems' biological and abiotic structures were treated with lower priorities.

Focusing on reducing material and energetic flows and their impacts in an urban metabolism manner, lead us toward misleading and simplistic approaches to the ecology of cities for urban design (Golubiewski, 2012). Conventional urban metabolism approaches take organism metabolism as models, in which flows are fundamental, but cities are complex socio-ecosystems and should be addressed as so (Golubiewski, 2012). This metabolic metaphor leads designers to focus only on inputs and outputs from the study area within the exterior, in a discrete body and linear manner. Thus, we tend to ignore the role of the components (the ecosystem biophysical structure) and the pathways of these flows in the urban ecosystem functioning (Golubiewski, 2012).

From the perspective of ecosystem services production, addressing the urban ecosystem components and the flows and their pathways seems fundamental. The ecosystem services cascade and the DPSIR frameworks highlight the importance of two elements on the provision of ecosystem services: (1) the ecosystem's biophysical structure state and (2) the incident human pressure over the existing biophysical structure (Kandziora, Burkhard & Müller, 2013; Kremer et al., 2016; Potschin et al., 2018), pressures that can be linked to the unbalanced flows from social to natural systems.

Better articulating solutions that enhance the ecological structure and reduce human pressures over the ecosystems seems a comprehensive way to improve potential ecosystem services in urban spaces. As we observed a trend in managing energy and material flows in this sample, giving more place for solutions that recover and regenerate the ecosystems biophysical structure could foster designs beyond mechanistic and anthropocentric emulation of nature, creating urban spaces that are supportive and integrated to natural ecosystems (Ellin, 2020; Puppim de Oliveira et al., 2011).

Nevertheless, integrating biodiversity and ecosystems' physical structure into the equation of urban design is more complex than dealing with flows. Much of it is due to the historical humanistic modes of working in urban planning, not acknowledging cities as multispecies spaces (Houston, Hillier, MacCallum, Steele & Byrne, 2018), as well as to the lack of human knowledge on the biophysical structure elements and their complex interrelations (Clergeau, D'Arienzo & Younes, 2018; Golubiewski, 2012; Parris et al., 2018; Puppim de Oliveira et al., 2011).

This complexity is illustrated in our projects by the gaps observed in the 36 identified strategies. In our sample, biodiversity is mainly addressed through green spaces design, but few solutions concerns fauna management. Regarding the abiotic structure, the soil structure and quality have barely been explored.

Nevertheless, to move from only increasing green spaces coverage towards concretely addressing biodiversity, several solutions are available and could be further explored in urban projects. Examples are: 1) the use of native plant species and understory vegetation, that positively impacts birds' richness (Threlfall, Williams, Hahs & Livesley, 2016); 2) the design of green networks, promoting connection between habitat patches inside and outside the project area, positively impacting diversity (Shwartz, Turbé, Julliard, Simon & Prévot, 2014); and 3) exploring soil management strategies to enhance soil quality and biodiversity (Tresch et al., 2018).

4.2. *Nature-based solutions: a central place promoting mutual benefits for society and nature*

NBS has a central place in our sample and amongst the identified solutions directly addressing biodiversity and the physical structure of ecosystems. Nature-Based Solutions is well recognised for its role in urban resilience and human well-being (Zwierzchowska, Fagiewicz, Poniży, Lupa & Mizgajski, 2019). It produces benefits for the whole natural system, not only humans (Raymond et al., 2017) and addresses complex urban challenges, addressing social, economic and environmental issues simultaneously (Dorst, van der Jagt, Raven & Runhaar, 2019).

Nature-based solutions are multifunctional and can tackle several urban challenges simultaneously (Almenar et al., 2021; Dorst et al., 2019), for example, with a single solution dealing with heat islands and rainwater management. However, they are not the answer to all contemporary ecological urban problems, also having trade-offs and blind spots (Almenar et al., 2021; Kotsila et al., 2021). This fact joins our observations in the case studies. NBS has been used to deal with diverse urban challenges and has been associated with other solutions, such as technological and regulatory ones, to solve complex problems.

Table 3
Identified urban strategies and the total number of observations on the sample.

Ecosystem component	Topic	Strategy	Observations
Energy Flows	Electricity	1.On site renewable energy production	9
		2. Reduction of energy consumption	8
	Heat and light	3. Optimisation of solar input on buildings	4
		4. Optimisation of on-site heat and energy transfers	2
Material Flows	Water	5. Reduction of on-site water consumption	3
		6. On-site stormwater management (reuse/drinking)	6
		7. Onsite stormwater management (infiltration/ evaporation)	11
		8. On-site wastewater management	3
	Building materials	9. Reuse demolition materials	1
		10. Reuse existing buildings and infrastructure (renovation)	1
		11. Use building materials with low impact on human and ecosystem health	3
		12. Source building materials locally	2
	Carbon	13. Offset CO2 embodied emissions - building phase	1
		14. Offset CO2 emissions - using phase	1
		15. Promotion of urban densification	3
		16. Design for Transit-orientated development (TOD.)	1
		17. Design for active and low carbon urban mobility	7
	Food	18. On-site food production in small scale (for education and awareness-raising)	3
		19. On-site food production in large scale (for local food provisioning)	1
	Chemical products	20. Phytosanitary products restrictions	1
	Waste	21. On-site organic waste management	1
		22. Recycling and waste management	2
Physical structure	Water bodies	23. Water body restoration	1
		24. Water body design	2
	Soil	25. Erosion control	2
		26. Avoid soil sealing	1
		27. Avoid topography changes	1
	Built space	28. Design artificial abiotic habitat structures	1
Biological structure	Flora	29. Design of major green area using native species	3
		30. Protect existing vegetation area	2
		31. Green streets design	3
		32. Design of in-building vegetation	3
		33. Promote connection with the local green network	3
		34. Design of minor public green areas	9
		35. Design of minor private green areas	2
		36. Use of complex vegetation schemes	3

NBS can help tackle the challenge of regenerating ecosystem bio-physical structure while reducing urban pressure over ecosystems, promoting mutual benefits for society and nature (Zwierzchowska et al., 2019). Nevertheless, NBS still has a minor place on sustainable design frameworks and neighbourhood sustainability assessment, as those aborded here and others as LEED-ND and BREEAM Communities (Xing, Jones & Donnison, 2017). An effort to generalise and expand the use of nature-based solutions on urban design and policy is necessary. Project teams should refer to contemporary scientific productions on the topic as the IUCN Standard for Nature-Based Solutions (IUCN, 2020) and the Nature4Cities toolkits to plan and implement NBS (Jeuken, Breukers, Elie & Rugani, 2020).

4.3. Strategies classification: towards a design tool

The taxonomy of strategies from our case studies could be the first step towards a design tool to foster urban ecological design. Even if not exhaustive, this classification could inform and give insights to such tools. Pedersen Zari and Hecht (2020) proposed a first mapping of strategies to produce ecosystem services on urban projects based mostly on literature review that could benefit from this taxonomy from a case study perspective.

The more frequently observed strategies help us to visualise the main topics being addressed in these projects. These strategies reflect contemporary concerns of our society towards urban spaces and eco-systems. They also represent strategies that have reached a more considerable maturity and operationalisation levels, as energy sobriety, renewable energy production, rainwater management and urban greening.

Nevertheless, the proposed taxonomy presents gaps, as topics such as fauna, soil and air, and ecosystem processes, like species dispersion and trophic chains. Thus, it would benefit from an exhaustive analysis and expansion. Besides, it would also be helpful to identify performance indicators that could help designers assess their project performance and allow improvements and comparisons between projects and scenarios.

4.4. Insights from the urban design process

Even if not the focus of this research, we observed a common point in our six case studies related to the urban design process. A socio-ecological diagnostic supported all the projects design, using distinct methods and detail levels (briefly presented in the project's description). For example, we observed participatory and qualitative diagnostic in The Paddock as well as quantitatively ecological assessment using sec-ondary data on the Lloyd Crossing project.

The realisation and use of diagnostics in the design process seems a pivotal element in these projects. Still, previous research highlighted a significant absence of diagnostics informing urban projects in the urban design practice (Leach, Mulhall, Rogers & Bryson, 2019). Thus, we argue that diagnostics could be a key element in integrating ecological knowledge into the urban design practice (Clergeau et al., 2018, 2019).

Another relevant point observed in our cases was the lack of edu-cation and awareness-raising strategies for urban dwellers and the lack of social participation in the project design process. Nevertheless, the projects probably have indirect influences on users' comportment and lifestyle through their solutions. For example, the Blatchford Redevel-opment project shows this as a primary goal. But, few active education strategies have been identified as well as only marginal stakeholders involvement in the design process.

Users' role in sustainable and regenerative projects is more than necessary for their final ecological performance (Chicca, 2020). More than designed to be sustainable, urban projects have the challenge to help people adopt sustainable lifestyles, accelerating societal change.

Socio-ecological diagnostics and participatory design processes have already been highlighted as pillars of regenerative urban projects (Blanco et al., 2021) and have an important place in other sustainable urbanism theories. Nevertheless, in practice, both seem to struggle to find their place in the project design process.

5. Conclusions

Based on six cases studies, this research delineated hypotheses regarding the ecological urban design practice. These hypotheses still deserve further exploration and validation, but they highlight challenges integrating ecological information and aspects in the urban design practice.

Even when analysing a sample of projects based on frameworks that try to deeply engage with ecosystem logic, we observed an anthropocentric focus, despite the urgent need to systemically tackle urban challenges in the context of climate change and biodiversity loss. Projects aim primarily to manage materials and energy flows and reduce human pressure over ecosystems, neglecting the ecosystems biophysical state and ecosystems processes. The predominance of an urban metabolism approach and the absence of focus on the ecosystem state is reductive and insufficient in terms of sustainability for urban ecosystems. We assume that this trend is still more substantial in conventional sustainable urban projects, like those designed under LEED-ND and other well-established neighbourhood sustainability frameworks.

To reach mutually beneficial projects urban design practice needs to move forward: Addressing the ecosystem biophysical structure and its state needs to gain a central place in the choice of sustainable urban solutions. Integrating this notion into existing urban design frameworks and proposing new tools that can inform the design practice is essential in this challenge. Our taxonomy of strategies is a first step towards more complete and holistic tools and could be further developed to fulfil these gaps. These tools needs to highlight the need to go beyond only increasing the project green surface, addressing species richness, habitat availability and quality as well as connectivity.

Another necessary change in the urban design practice regards socio-ecological diagnostics. The analysed cases seem to integrate diverse forms of diagnostics to inform the selection of solutions and strategies, contradicting the predominant urban design practice, in which diagnostics are understated. We argue that the realisation of diagnostics before any project design must become a wider practice. Diagnostics could even be used to define projects priorities, narrowing down the scope of possible sustainable interventions on pre-project phases.

Finally, articulating different types of solutions and strategies seems essential to achieve urban projects that reconnect with natural ecosystems functioning. From the perspective of the ecosystem service cascade and the DPSIR framework, both the strategies aiming to reduce human pressure and regenerate ecosystems' state are fundamentals to enhance the ecosystem services production and mutual benefits. Nature-Based solutions had an important role in our sample, and we believe their popularisation and integration on urban projects and urban policy play an essential part in this challenge.

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Declaration of Competing Interest

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

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Appendix

Appendix A. List of pre-selected projects and their suitability to selection criteria

#	Project name	Scale and use	Design Framework	Project phase	Documentation
1	Lloyd's Crossing	Mixed-use neighbourhood	Ecosystem-level biomimicry	Partially built	Available online and through project team
2	Lavasa Hill	Mixed-use neighbourhood	Ecosystem-level biomimicry	Partially built	Available online.
3	Terres de Versailles	Mixed-use neighbourhood	EcoQuartier	Under construction	Not available online and project team did not answer our information request.
4	CIRS	Educational building	Regenerative Design	Built	Available online.
5	Vale Living with Lakes	Educational building	Regenerative Design	Built	Available online.
6	Pôle du Biomimétisme Marin de Biarritz	Office building	Ecosystem-level biomimicry	Not built	Available through project team
7	Langfang	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
8	RegenVillages	Mixed-use neighbourhood	EcoQuartier	Not built	Not available online.
9	Tour Hyperion	Residential building	EcoQuartier	Under Construction	Not available online.
10	Groupe Scolaire de la Science et de la Biodiversité	Educational building	Ecosystem-level biomimicry	Built	Available online and through project team
11	La vallée - Chatenay Malabri - Eiffage	Mixed-use neighbourhood	EcoQuartier	Under Construction	Not available online.
12	Ecoquartier de l'Eau Vive	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
13	Docks de Ris	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
14	Claude Bernard	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
15	Clichy-Batgnolles		EcoQuartier	Built	

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#	Project name	Scale and use	Design Framework	Project phase	Documentation
		Mixed-use neighbourhood			Not available online and project team did not answer our information request.
16	Seguin - Rives Seine	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
17	Bel Air - Grands Pêchers	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
18	Camille Claude	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
19	Fréquel-Fontarabie	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
20	Clause-Bois Badeau	Mixed-use neighbourhood	EcoQuartier	Built	Available online and through project team
21	Dong Tan	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
22	Wanwhuang	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
23	20/20 Park	Business Park	Ecosystem-level biomimicry	Built	Not available online.
24	Blatchford Redevelopment	Mixed-use neighbourhood	Regenerative Design	Partially built/Under construction	Available online and through project team
25	Darwin Ecosystème	Mixed-use neighbourhood	Regenerative Design	Partially built	Not available online and project team did not answer our information request.
26	Dockside Green	Mixed-use neighbourhood	Regenerative Design	Under Construction	Not available online and project team did not answer our information request.
27	Point Weels	Mixed-use neighbourhood	Regenerative Design	Not built	Not available online.
28	Chaudière Island (Zibi)	Mixed-use neighbourhood	Regenerative Design	Not built	Available online.
29	Cap Roger Curtis	Mixed-use neighbourhood	Regenerative Design	Not built	Not available online.
30	Smartseille	Mixed-use neighbourhood	EcoQuartier	Partially built	Not available online and project team did not answer our information request.
31	Cité de la Gastronomie et du Vin à Dijon	Mixed-use neighbourhood	EcoQuartier	Partially built/Under construction	Available through project team
32	The Paddock	Mixed-use neighbourhood	Regenerative Design	Partially built/Under construction	Available online

Appendix B. Analysed documents for each case study

#	Project	Documents tittles
1	Lloyd	Request for Proposals #03–16 - Lloyd Crossing Sustainable Design and Development Project
LLOYD CROSSING - Sustainable Urban Design Plan & Catalyst Project		
AIA TopTen - Lloyd Crossing Sustainable Design Plan Case Study		
Lloyd Crossing Sustainable Urban Design Plan and Catalyst Project - Portland, Oregon [2005 EDRA/ Places Award – Planning]		
Lloyd District Development Strategy		
2	Lavasa	Lavasa MasterPlan
Lavasa to become the World’s first city to set standards using biomimicry		
The art of imitating life: The potential contribution of biomimicry in shaping the future of our cities		
Biomimicry: nature’s design process versus the designer’s process		
Lavasa: An Emerging Smart City		
Lavasa: Life in full Brochure		
Returning Genius to the Place		
New Urbanisms in India – Final Report		
The Private City: Planning, Property, and Protest in the Making of Lavasa New Town, India		
India’s ecocity? Environment, urbanisation, and mobility in the making of Lavasa		
Lavasa: A mushrooming paradise		
3	Blatchford	Busby: Architecture New Edges
Request For Qualification Number 917843 - Edmonton City Centre Airport Lands - The Master Plan		
Negotiated Request for Proposals - Edmonton City Centre Airport Lands - The Master Plan		
City Centre Area Redevelopment Plan Consolidation		
Blatchford Concept Plan Implementation Analysis		
Blatchford Business Case		
Blatchford Plan and graphics		
Strategic Alignment with The Ways		
Blatchford Redevelopment Scenarios		
Financial Analysis of the Blatchford Development Scenarios		
Blatchford Development Governance Model		
Potential Advisors to the Blatchford Redevelopment Project		
Blatchford West Architectural and Urban Design Guidelines		
Blatchford West - Stage One Green Building Codes		

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#	Project	Documents tittles
4	Paddock	The Paddock – About
Living Building Challenge: Enhancing the local environment		
Landscape Plan		
Site plan – Final		
Owners Corporation Rules "The Paddock" Ecovillage Castlemaine		
Fair Share		
5	Clause	Ekopolis: EcoQuartier Clause-Bois Badeau
SORGEM : Clause-Bois Badeau		
Projet de modification n°2 du PLU – 2. OAP Clause Bois Badeau modifié		
Fiche n°38 Brétigny-sur-Orge/Essone ZAC Clause Bois-Badeau		
Clause – Bois-Badeau, un quartier qui évolue		
Amenagement Durable En Essonne: Quelles Avancées Du Label Écoquartier ? Comment Produire Du Logement Durable Abordable ?		
Bienvenue à Clause-Bois Badeau Votre livret d'accueil		
Germe et Jam : Clause Bois Badeau plans et visuels		
Germe et Jam : Clause Bois Badeau plan masse		
Germe et Jam : Clause Bois Badeau projet urbain tissu		
Projet d'Amenagement Des Terrains Clause Bois Badeau - Zac Clause Bois Badeau Et Zac Des Sorbiers - Cahier General Des Prescriptions Paysagères Et Ecologiques		
Projet d'Amenagement Des Terrains Clause Bois Badeau - Zac Clause Bois Badeau Et Zac Des Sorbiers - Cahier General Des Prescriptions Paysagères Et Ecologiques pour les Ilôts Du Mesnil		
Tribu : ZAC Clause Bois Badeau – Brétigny-sur-Orge (91) Assistance à la maitrise d'ouvrage et suivi de la conception des projets architecturaux		
Projet urbain, Clause Bois Badeau - germe&JAM		
Nature en ville La nature comme élément du projet d'aménagement urbain		
BRÉTIGNY-SUR-ORGE / Essonne L'écoquartier Clause-Bois Badeau		
EcoQuartier Clause Bois Badeau, Brétigny-sur-Orge (91) Retour d'expérience synthétique		
INTEGRATION DES ENJEUX DE BIODIVERSITE DANS LES ÉCOQUARTIERS Analyse des pratiques d'ÉcoQuartiers labellisés « étape 3 » en 2016 et 2017 et recommandations		
Label EcoQuartier et biodiversité Evaluation de 7 EcoQuartiers		
Plan Local d'Urbanisme Commune de Brétigny-sur-Orge 2b- Justifications des choix et impacts sur l'environnement		
6	CIGV	A.M.I. Réalisation du projet de la cité internationale de la gastronomie sur e site de l'hôpital général
Cahier Des Charges En Vue De La Création De La Cite De La Gastronomie		
Dossier de candidature – La cité internationale de la gastronomie à Dijon – Présentation		
La cité internationale de la gastronomie à Dijon – Dossier de candidature – Compléments d'informations Partie 1		
La cité internationale de la gastronomie à Dijon – Dossier de candidature – Compléments d'informations Partie 2		
La cité de la gastronomie à Dijon		
Etude d'impact – Evolutions du projet		
Dijon Le projet de territoire Grand Sud		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 1–2–3–4–5–6–7–9 DOCUMENT PRINCIPAL		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 2–4–5 ANNEXES DOCUMENT PRINCIPAL		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 8 : ANNEXES		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 8 : NOTICE ASSAINISSEMENT		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 8 : NOTICE VRD		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 11 : GFA		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 14 : ETUDE D'IMPACT		
PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21,000) PA 14 : EVALUATION APPROPRI2E DES INCIDENCES		

Appendix C. Identified Urban solutions and their classification following the research criteria

#	Project	Solution	1. Goal	2.Type	3.Ecosystem component
1	Lloyd	Implementation of mixed conifer forest "patches" within the district through urban parks	Reinforce ecosystem structure	NBS	Biological structure
2	Lloyd	Create a green corridor connecting Sullivan's gulch to habitat "islands" within the study area	Reinforce ecosystem structure	NBS	Biological structure
3	Lloyd	Design of green corridor streets using understory and three-level vegetation	Reinforce ecosystem structure	NBS	Biological structure
4	Lloyd	Creation of rooftop gardens	Reinforce ecosystem structure	NBS	Biological structure
5	Lloyd	Creation of two pocket parks	Reinforce ecosystem structure	NBS	Biological structure

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#	Project	Solution	1. Goal	2.Type	3.Ecosystem component
6	Lloyd	Implementation of bioswales on the street corners	Reinforce ecosystem structure	NBS	Material flows
7	Lloyd	Stream Restoration along Sullivan's Gulch Wildlife Corridor	Reinforce ecosystem structure	NBS	Physical structure
8	Lloyd	Create the Sullivan's Gulch Wildlife Corridor	Reinforce ecosystem structure	NBS	Biological structure
9	Lloyd	Efficiency Upgrade on existing installations to reduce water consumption	Reduce pressure over the ecosystem	Technological	Material flows
10	Lloyd	Stormwater harvesting, detention facilities and treatment plant	Reduce pressure over the ecosystem	Technological	Material flows
11	Lloyd	Blackwater harvesting and treatment plant	Reduce pressure over the ecosystem	Technological	Material flows
12	Lloyd	Efficiency Upgrade on existing installations to reduce energy consumption	Reduce pressure over the ecosystem	Technological	Energy Flows
13	Lloyd	Efficiency by design strategies for new buildings - Water	Reduce pressure over the ecosystem	Urban code and policy	Material flows
14	Lloyd	Efficiency by design strategies for new buildings - Energy	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
15	Lloyd	Implementation of a district thermal sharing system	Reduce pressure over the ecosystem	Technological	Energy Flows
16	Lloyd	Installation of photovoltaic capacity	Reduce pressure over the ecosystem	Technological	Energy Flows
17	Lloyd	Installation of wind turbine capacity	Reduce pressure over the ecosystem	Technological	Energy Flows
18	Lloyd	Biogas production from waste processing	Reduce pressure over the ecosystem	Technological	Energy Flows
19	Lloyd	Purchase of wind power for 100% of imported electricity	Reduce pressure over the ecosystem	Technological	Energy Flows
20	Lloyd	Purchase of carbon offset credits for remaining imported fossil fuels	Reduce pressure over the ecosystem	Compensation	Material flows
21	Lloyd	Encourage urban agriculture at residential developments with raised planters on terraces	Both	Urban code and policy	Material flows
22	Lloyd	Implementation of vegetated plazas on open spaces	Reinforce ecosystem structure	NBS	Biological structure
23	Lloyd	Create pedestrian and bicycle-friendly streetscape using livability structures as benches, gathering spaces, playgrounds	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
24	Lloyd	Optimise solar access to all buildings and open spaces through a solar massing study and zoning changes	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
25	Lloyd	Preserve urban density near infrastructure by utilising as much of allowable FAR as possible, avoiding urban sprawling and reducing transport-related emissions	Reduce pressure over the ecosystem	Urban code and policy	Material flows
26	Lloyd	Implement a sustainable materials strategy to help the choice of high-performance materials, durable and with low maintenance (Use LCA as a tool for choice, reduce materials consumption, use renewable resources, upgradable components, materials that contribute to indoor air quality)	Reduce pressure over the ecosystem	Urban code and policy	Material flows
27	Lloyd	Source building materials from 500 miles only	Reduce pressure over the ecosystem	Urban code and policy	Material flows
28	Lloyd	Education program to reduce energy consumption	Reduce pressure over the ecosystem	Education	Energy Flows
29	Lloyd	On-site parking displacement to the underground, to release surface for the other strategies and facilitate modal shift	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
30	Lavasa	Masterplan and zoning developed using local ecosystem information aiming to protect green areas (landscape suitability analysis)	Reinforce ecosystem structure	Urban code and policy	Biological structure
31	Lavasa	Design of tiles shapes to collect rainwater and slow down runoff and facilitate evaporation	Reduce pressure over the ecosystem	Technological	Material flows
32	Lavasa	Construction of underground reservoirs tanks to manage and reuse rainwater	Reduce pressure over the ecosystem	Technological	Material flows
33	Lavasa	Design of a drainage system with radiating grooved earth dams to redirect water away in multiple directions	Reduce pressure over the ecosystem	Technological	Material flows
34	Lavasa	Design of infiltrations solutions (Nalla bunding, contour trenching)	Reduce pressure over the ecosystem	NBS	Material flows
35	Lavasa	Hydroseeding for erosion control through revegetation	Reinforce ecosystem structure	NBS	Biological structure
36	Lavasa	Rooflines designed to create wind turbulence and facilitate evaporation	Reduce pressure over the ecosystem	Technological	Material flows
37	Lavasa	Use of green roofs to manage rainwater and prevent soil erosion	Reduce pressure over the ecosystem	NBS	Biological structure
38	Lavasa	Application of polymer on the soil to slow down the erosion process	Reduce pressure over the ecosystem	Technological	Physical structure
39	Blatchford	Bioreactors for energy production based on organic waste recycling	Reduce pressure over the ecosystem	Technological	Energy Flows
40	Blatchford	District Stormwater collection using natural systems and low-impact development strategies (culverts -daylight streams)	Both	NBS	Material flows
41	Blatchford	District stormwater treatment using lake systems and water reuse	Both	NBS	Material flows
42	Blatchford	Restoration of native aspen parkland ecosystem trough a green park	Reinforce ecosystem structure	NBS	Biological structure

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#	Project	Solution	1. Goal	2.Type	3.Ecosystem component
43	Blatchford	Urban zoning includes a major agricultural area	Both	Urban code and policy	Material flows
44	Blatchford	Geothermal energy production	Reduce pressure over the ecosystem	Technological	Energy Flows
45	Blatchford	Zoning for urban density increase	Reduce pressure over the ecosystem	Urban code and policy	Material flows
46	Blatchford	Transport orientated Development strategies to reduce CO_2 emissions	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
47	Blatchford	Promote green ecological connectivity using furrows and stormwater gardens	Reinforce ecosystem structure	NBS	Biological structure
48	Blatchford	Prevision of climate-responsive built form with staggered blocks and windrows that break the dominant winds and allow for massing variation and sunlight	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
49	Blatchford	Waste management strategies and recycling using pneumatic systems	Reduce pressure over the ecosystem	Technological	Material flows
50	Blatchford	Green streets design	Reinforce ecosystem structure	NBS	Biological structure
51	Blatchford	Exigence for high-performance building envelopes on the masterplan and construction codes	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
52	Blatchford	Education program for sustainability and lower energy consumption	Reduce pressure over the ecosystem	Education	Energy Flows
53	Blatchford	On-site wastewater treatment system and wastewater reuse	Reduce pressure over the ecosystem	Technological	Material flows
54	Blatchford	Irrigation systems reusing rainwater	Reduce pressure over the ecosystem	Technological	Material flows
55	Blatchford	Reuse existing buildings for cultural and recreational uses	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
56	Blatchford	Design of a walkable community - Active transportation strategies to reduce CO2 emissions	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
57	Clause	Renewable energy production for heating using wood biomass (partial production)	Reduce pressure over the ecosystem	Technological	Energy Flows
58	Clause	Design for active mobility - pedestrian streets, bike lanes, near local train network station	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
59	Clause	Bioclimatic design prescriptions for construction phase - optimisation of solar inputs, massing and building design	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
60	Clause	Design of a main park, recreating local ecosystem and linking the project to local green network and creating diversity of habitat for identified local species	Reinforce ecosystem structure	NBS	Biological structure
61	Clause	Design for high urban density and mixed-use zoning	Reduce pressure over the ecosystem	Urban code and policy	Material flows
62	Clause	Collective gardens	Reinforce ecosystem structure	NBS	Biological structure
63	Clause	Private gardens	Reinforce ecosystem structure	NBS	Biological structure
64	Clause	Transversal parks/alleys	Reinforce ecosystem structure	NBS	Biological structure
65	Clause	Green streets design	Reinforce ecosystem structure	NBS	Biological structure
66	Clause	Bioswales to manage rainwater on the surface and reuse for irrigation	Both	NBS	Material flows
67	Clause	Reuse local soil during the construction phase	Reduce pressure over the ecosystem	Technological	Material flows
68	Clause	Partial energy production on buildings using solar panels	Reduce pressure over the ecosystem	Technological	Energy Flows
69	Clause	Car parking reduction and car-sharing strategy	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
70	Clause	No phytosanitary products allowed on the green area management	Reduce pressure over the ecosystem	Urban code and policy	Material flows
71	Clause	Elaboration of design prescriptions to integrate biodiversity at the building/plot scale (mostly flora)	Reinforce ecosystem structure	Urban code and policy	Biological structure
72	Clause	Elaboration of design prescriptions to assure building energetic performance	Reduce pressure over the ecosystem	Urban code and policy	Energy Flows
73	Clause	Elaboration of design prescriptions to assure high water use performances on buildings	Reduce pressure over the ecosystem	Urban code and policy	Material flows
74	Clause	Soil unsealing	Reinforce ecosystem structure	Urban form and infrastructure	Physical structure
75	Clause	Utilisation of three states of vegetation and local species whenever possible, creating complex ecosystems	Reinforce ecosystem structure	NBS	Biological structure
76	Clause	Prescriptions to avoid PVC and prefer wood structures in buildings	Reduce pressure over the ecosystem	Urban code and policy	Material flows
77	Clause	Creation of a green network connecting to a local park (Jonc marins)	Reinforce ecosystem structure	NBS	Biological structure
78	Paddock	Active mobility infrastructure (walking paths + bike parking)	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
79	Paddock	Collective food gardens and orchards	Both	NBS	Material flows
80	Paddock	Wetlands design	Reinforce ecosystem structure	NBS	Physical structure
81	Paddock	Design of native gardens		NBS	

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#	Project	Solution	1. Goal	2.Type	3.Ecosystem component
			Reinforce ecosystem structure		Biological structure
82	Paddock	Design of energy-efficient buildings (insulation, isolation on wall and windows)	Reduce pressure over the ecosystem	Technological	Energy Flows
83	Paddock	Use of local materials and reused wood for buildings construction	Reduce pressure over the ecosystem	Technological	Material flows
84	Paddock	Use of materials that are safe for human health and ecosystems	Reduce pressure over the ecosystem	Technological	Material flows
85	Paddock	100% Solar energy with smart grid	Reduce pressure over the ecosystem	Technological	Energy Flows
86	Paddock	Rainwater collection on roofs and storage for reuse	Reduce pressure over the ecosystem	Technological	Material flows
87	Paddock	On-site composting	Reduce pressure over the ecosystem	NBS	Material flows
88	Paddock	Private gardens	Reinforce ecosystem structure	NBS	Biological structure
89	Paddock	Biophilic approach on buildings to improve air flows and natural lighting	Reduce pressure over the ecosystem	Urban form and infrastructure	Energy Flows
90	Paddock	Use of native species of flora on green areas	Reinforce ecosystem structure	NBS	Biological structure
91	Paddock	CO2 offset for project embodied carbon	Reduce pressure over the ecosystem	Compensation	Material flows
92	Paddock	Link project green area with the outside green network	Reinforce ecosystem structure	NBS	Biological structure
93	Paddock	Wastewater treatment plant	Reduce pressure over the ecosystem	Technological	Material flows
94	Paddock	Bioswales for stormwater management	Both	NBS	Material flows
95	Paddock	Reuse of greywater on garden irrigation	Reduce pressure over the ecosystem	Technological	Material flows
96	Paddock	Fixtures to assure low energy consumption on buildings and urban space	Reduce pressure over the ecosystem	Technological	Energy Flows
97	CIGV	Walkable district design (Human scale and active mobilities without parking)	Reduce pressure over the ecosystem	Urban form and infrastructure	Material flows
98	CIGV	Use of diverse vegetation schemes with local species	Reinforce ecosystem structure	NBS	Biological structure
99	CIGV	Bioswales all the long of pathways to manage rainwater	Both	NBS	Material flows
100	CIGV	Design of a humid zone using natural topography (V-shaped garden)	Reinforce ecosystem structure	NBS	Physical structure
101	CIGV	Protection of semi-dense vegetated area (EBC)	Reinforce ecosystem structure	NBS	Biological structure
102	CIGV	Ornamental gardens	Reinforce ecosystem structure	NBS	Biological structure
103	CIGV	Vegetable gardens	Both	NBS	Material flows
104	CIGV	Living "fences" associated with bioswales to delimitate the separation amongst public and private areas	Reinforce ecosystem structure	NBS	Biological structure
105	CIGV	Low impact transitions between private and public space avoiding barriers and topography alterations	Reduce pressure over the ecosystem	Urban form and infrastructure	Physical structure
106	CIGV	Grass covered paving	Both	NBS	Material flows
107	CIGV	Artificial bird nests	Reinforce ecosystem structure	NBS	Physical structure
108	CIGV	Connection to municipal heat network	Reduce pressure over the ecosystem	Technological	Energy Flows
109	CIGV	Green roofs	Reinforce ecosystem structure	NBS	Biological structure
110	CIGV	Waste management strategies and recycling using voluntary segregation systems	Reduce pressure over the ecosystem	Technological	Material flows

Appendix D. Identified strategies on each case study

Class	Subclass	Strategy familly	Total	1. Lloyd	2. Lavasa	3. Blatchford	4. Paddock	5. Clause	6. CIGV
Energy Flows	Electricity	1.On site renewable energy production	9	4	*	2	1	2	*
		2.Reduction of energy consumption	8	3	*	2	2	1	*
	Heat and light	3.Optmisation of solar input on buildings	4	1	*	1	1	1	*
		4.Opmisation of on-site heat and energy transfers	2	1	*	*	*	*	1
Material Flows	Water	5.Reduction of on-site water consumption	3	2	*	*	*	1	*
		6.Onsite stormwater management (reuse/drinking)	6	1	1	2	2	*	*
		7.Onsite stormwater management (infiltration/ evaporation)	11	1	5	1	1	1	2
		8. On-site wastewater management	3	1	*	1	1	*	*
	Building materials	9.Reuse demolition materials	1	*	*	*	*	1	*

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		10.Reuse existing buildings and infrastructure (renovation)	1	*	*	1	*	*	*
		11.Use building materials with low impact on human/ ecosystem health	3	1	*	*	1	1	*
		12.Source building materials locally	2	1	*	*	1	*	*
	Carbon	13.Offset CO2 embodied emissions - building phase	1	*	*	*	1	*	*
		14.Offset CO2 emissions - using phase	1	1	*	*	*	*	*
		15.Promotion of urban densification	3	1	*	1	*	1	*
		16.Design for Transit-orientated development (TOD)	1	*	*	1	*	*	*
		17.Design for active and low carbon urban mobility	7	2	*	1	1	2	1
	Food	18. On-site food production in small scale (education)	3	1	*	*	1	*	1
		19. On-site food production in large scale (for local food provisioning)	1	*	*	1	*	*	*
	Chemical products	20.Phytosanitary products restrictions	1	*	*	*	*	1	*
	Waste	21. On-site organic waste management	1	*	*	*	1	*	*
		22.Recycling and waste management	2	*	*	1	*	*	1
Physical structure	Water bodies	23.Water body restoration	1	1	*	*	*	*	*
		24.Water body design	2	*	*	*	1	*	1
	Soil	25.Erosion control	2	*	2	*	*	*	*
		26.Avoid soil sealing	1	*	*	*	*	1	*
		27.Avoid topography changes	1	*	*	*	*	*	1
	Built espace	28.Design artificial abiotic habitat structures	1	*	*	*	*	*	1
Biological structure	Flora	29.Design of major green area using native species	3	1	*	1	*	1	*
		30.Protect existing vegetation area	2	*	1	*	*	*	1
		31.Green streets design	3	1	*	1	*	1	*
		32.Design of in-bulding vegetation	3	1	*	*	*	1	1
		33.Promote connection with local green network	3	1	*	*	1	1	*
		34.Design of minor public green areas	9	3	*	1	1	2	2
		35.Design of minor private green areas	2	*	*	*	1	1	*
		36.Use of complex vegetation schemes	3	*	*	*	1	1	1

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2.2 Designing sustainable neighbourhoods: levers for successful governance arrangements

Blanco, E., Raskin, K., & Clergeau, P. (Under review). Designing sustainable neighbourhoods: levers for successful governance arrangements.

Title: Designing sustainable neighbourhoods: governance success levers on the urban design process

Abstract: Worldwide we observe many initiatives in designing and implementing sustainable neighbourhoods. Despite the increasing number of studies on the topic, current research got interested primarily in technical aspects, such as design frameworks, indicators and sustainable solutions. However, socio-political aspects of the design and implementation of sustainable neighbourhoods profoundly impact the urban project design process and its outcomes. Nonetheless, the governance of these early phases has been largely overlooked in research. To bridge this gap, we applied in this study the Police Arrangement Models (PAM) framework to analyse the governance of the design and implementation of three sustainable neighbourhoods. The framework allowed us to identify key elements associated with the rules of the game, the actors, the resources and the narratives of these projects. As a result, we delineated four levers predicting success in delivering sustainable narratives, namely 1) the stability of the stakeholders over the design and implementation process and the central role of the public stakeholder in supporting sustainable narratives, 2) the need to engage in real participatory design process, 3) the importance of informal rules, such as design team internal policies on the definition of sustainable narratives and 4) the need of a financial feasibility perspective. These results open new research opportunities regarding the governance of this design process that could foster advancements in practice.

Keywords: sustainable neighbourhoods; governance arrangements; urban design; policy arrangement models.

1. Introduction

Worldwide we observe an increasing number of initiatives in designing and implementing sustainable neighbourhoods (Grazieschi et al., 2020). Several factors can justify this trend, such as raising societal awareness of sustainability, the deployment of international and local policies to tackle sustainability challenges at the urban scale or the consolidation of different sustainable neighbourhoods design frameworks in the last two decades (Neighbourhood Sustainability Assessment Frameworks - NSA) (Reith and Orova, 2015; Sharifi et al., 2021; Zhang et al., 2016).

Given the role of sustainable neighbourhoods in tackling contemporary urban challenges, such as those highlighted in the Sustainable Development Goals and the New Urban Agenda, innovative approaches to assist sustainable urban design are emerging (Blanco et al., 2022; United Nations, 2017). These new approaches aim at promoting better environmental and social performances, bringing to light topics such as net-positive projects, social equity and mutual benefits for society and nature (Brown et al., 2018; Cole, 2012). In this research, we focus on regenerative design, ecosystem-level biomimicry and the French EcoQuartier frameworks, which are three examples operationalising these engagements at different maturity levels (Bayulken and Huisingh, 2015; Blanco et al., 2022; Chastenet et al., 2016; Cole, 2012; Fenker and Zetlaoui-Léger, 2017; Pedersen Zari, 2018).

Despite the increasing number of studies, current research on sustainable neighbourhoods got interested primarily in technical aspects. For instance, there is an extensive research corpus on the role of NSA frameworks in promoting sustainability, highlighting their forces and limitations (Boyle et al., 2018; Komeily and Srinivasan, 2015; Sharifi et al., 2021; Subramanian et al., 2021). Also, indicators to assess neighbourhood sustainability are as well widely explored. Several NSA frameworks and urban sustainability policies rely on indicators assessments to promote sustainable practices (Boquet et al., 2020; Naboni et al., 2019; Reith and Orova, 2015). Finally, a significant number of studies have also focused on the different technical solutions to promote neighbourhood environmental sustainability, analysing their uses, performances and feasibility, namely those related to energy, water, waste and biodiversity (Blanco et al., 2022; Parris et al., 2018; Puchol-Salort et al., 2021).

However, socio-political aspects of the design and implementation of sustainable neighbourhoods have been largely overlooked in research. Nonetheless, they profoundly impact urban project design and its outcomes (Arab, 2018; Carmona, 2016). Thus, in this research, we are interested in a particular socio-political aspect of sustainable urban neighbourhoods: the governance arrangements during their design and implementation.

Despite its different interpretations, governance can be defined as the process and rules that allow different stakeholders to influence decision-making, coordinating their needs to affect an outcome (Lemos and Agrawal, 2006; Ordóñez et al., 2020). It means that the final project (that is eventually implemented) results from the interactions among several actors in a decision-making process. In the particular case of sustainable neighbourhoods, these decisions are often translated as an assemblage of strategies and solutions that creates a sustainable narrative in an urban design project. This assemblage will be responsible for moving the site from an initial situation to a new desired sustainable one.

Research on urban governance has mostly focused on the established urban neighbourhood's governance schemes and not their design process governance. One example is the study by Keil (2006), that analysed the impact of urban redevelopment projects on the daily life governance of redeveloped German neighbourhoods. A few other research explored urban projects' "design governance", focusing on public tools and mechanisms that influence and guide urban design, assuring societal benefits (Carmona, 2016).

The only study (to our knowledge) that focused on the governance of sustainable neighbourhood design (Medved, 2017) had merely and superficially explored the intricated governance arrangements. It investigated how different implementation approaches (bottom-up and top-down) influenced and conditioned the outcomes in sustainable urban redevelopment projects. The author highlighted that while the design approach does not seem to affect the form of the neighbourhood, it does impact the neighbourhood's daily life. It indicated that the participative bottom-up approach helps promote more robust local governance systems and more socially sustainable neighbourhoods.

However, studying the different governance arrangements is a lever to understand and foster the successful implementation of sustainable initiatives (Arts et al., 2006). In order to facilitate studying governance arrangements and their impacts on the implementation of such initiatives, the Policy Arrangement Model (PAM) have been proposed. This framework presents four dimensions that inextricably affect governance and decision-making: rules of the game, actors, resources, and discourses (Arts, Leroy, & van Tatenhove, 2006).

The PAM framework has already been used to assess governance arrangements and identify success factors in a few sustainable initiatives. Examples are the sustainable management of urban cemeteries (Quinton et al., 2020), the management of urban forests (Lawrence et al., 2013) and the deployment and use of communal gardens as Nature-Based solutions in Europe (van der Jagt et al., 2017). Despite its convenience, the framework has not yet been applied to analyse the governance in sustainable neighbourhoods.

We aim in this study to apply the PAM framework (Arts et al., 2006) to a sample of urban projects. Its application will help overcome the lack of knowledge on the governance arrangements for sustainable neighbourhoods design and create a base for further studies. We use a comparative and international case-study approach (Yin, 2018) to identify transversal governance success levers. This approach is helpful to identify trends, minimising local cultural and political interferences from each case.

2. Methods

The Policy Arrangements Model (PAM) highlights four dimensions that inextricably affect governance and the decision-making process: 1) The rules of the game, which are formal or informal procedures and rules that guides and affects the decision-making process; 2) The actors involved in the process, with the different division of power and influence to affect the outcome; 3) the available resources (financial, intellectual, material…) used in the process; and 4) the discourses, that represents the views and narratives that are consolidated in the outcome.

As an empirical investigation method, case studies help understand contemporary phenomena within their real-life context (Groat & Wang, 2013; Yin, 2018) and generate hypotheses on real-world phenomena (Small, 2009), which is the main objective of this work.

In this context, we applied the PAM framework to selected case studies. To generate and analyse data, we relied on content analysis. The following sections describe the different methodological steps.

2.1. Case selection

The case studies were selected based on pragmatical considerations and the theoretical prominence of sustainable neighbourhood projects. Pragmatic approaches to case selection are legitimate when generating hypotheses on real-world phenomena from exploratory case studies, not requiring statistical representativity (Seawnght and Gerring, 2008; Small, 2009). Our selection criteria were:

1. Scale and use: Projects should be at the neighbourhood scale. They should have more than one building, public space, be mixed-use and have diverse stakeholders.
2. Design framework: Projects should have robust ecological engagements and use ecosystem-level biomimicry (Pedersen Zari, 2015), regenerative design (Cole, 2012), or EcoQuartier (Ministère de la Transition Écologique et Solidaire and Ministère de la Cohésion des territoires et des relations avec les collectivités territoriales, 2020) design approaches.
3. Project phase: Projects should have reached the implementation phase, even if partially (conceptual projects are excluded);
4. Documentation: Projects should have relevant documented information, in English or French, accessible online or through the author's personal and professional network, allowing a deep comprehension of the case;
5. Availability for interview: At least one project team member should contribute with one 1-hour online interview.

Following a literature review and a brainstorming session, the research team identified 32 potential cases worldwide (Appendix 1). Among those, only six urban projects fit the first four criteria. The design teams of these six cases were e-mailed to request a 1-hour interview with their members. Only three accepted to participate in the study: the Lloyd neighbourhood in Portland (USA), the Blatchford neighbourhood in Edmonton (Canada) and the Cité Internationale de la Gastronomie et du Vin (CIGV) in Dijon (France).

We highlight that this work does not aim to create a statistical representation of the governance arrangements of sustainable neighbourhoods. For this objective, a systemic and non-pragmatic case selection method would be necessary, as well as a larger sample of case studies. Despite this fact, analysing three cases in a comparative approach is definitely useful in delineating hypotheses on exploratory studies on real-world phenomena, the main objective of this work (Small, 2009; Yin, 2018).

2.2. Data collection

We created a documental collection (corpus) containing project details and realised semi-structured interviews with each project's design or implementation team members to identify governance arrangements. Relevant documentation was collected through scientific databases (Web of Science), projects websites, web research engines, and directly with project stakeholders by e-mail. For online databases, we used the project names as keywords.

Appendix 2 presents the name of each analysed document. It is important to note that not every analysed document had relevant information to the research and also that the density of information on each document is different.

We interviewed nine team members, three of whom participated in the Lloyd neighbourhood project, two related to the Blatchford project, and four related to the CIGV project. The interviews were done following a first round of documental analysis, when the main stakeholders were identified. At least two different teams per project have been contacted by e-mail to participate in the interviews. We used a semi-structured protocol (Appendix 3), highlighting the four dimensions of governance arrangements (rules of the game, actors, resources, and discourses).

2.3. Data analysis

We imported the documental corpus and the interview transcriptions to MaxQDA Analytics Pro 2020. In this software, the corpus was read and coded using thematic coding (Saldana, 2009) to identify and register excerpts presenting the different aspects composing the governance arrangements. We used four codes, one for each governance dimension (rules of the game, actors, resources and discourses). Coded data were analysed to identify the links between the governance arrangement dimensions and the convergences and divergences among the case studies, delineating our success levers. To understand the projects governance arrangements evolutions over time, we kept in mind three different design steps: 1) the request for proposals (RFP): the phase in which the project sponsor defines the desired project outcomes and request proposals; 2) the design phase: the moment in which design teams propose a first version of the project, presenting a strategy and sustainable urban solutions; 3) the implementation phase: phase in which the project sponsor further detail the project (when needed) and starts its implementation.

3. Results and discussions

3.1. Case studies description and background

3.1.1. The Lloyd neighbourhood, Portland, Oregon, USA

The Lloyd eco-district history started in 2004 when the Portland Development Commission and local landowners launched a request for proposals (RFP) to requalify the mixed-use district. The RFP presented high sustainable engagements and was won by the urban design company Mithun, which delivered The Lloyd Crossing Sustainable Urban Plan in the same year, presenting the strategies and solutions to promote a sustainable redevelopment. The project was issued from a biomimetic design approach. The design team relied upon an ecological assessment to define project objectives, comparing the current site situation with the previous existing forest. This analysis indicated the local ecosystem limits and guided the selection of urban solutions proposed to catalyse ecological, social, and economic regeneration. After the project design, the implementation stayed on hold for a few years. In 2010 the implementation started, following an update and a new roadmap that downgraded the engagements presented in 2004. From that time on, the implementation responsibilities have been held by the EcoLloyd association, a small local NGO (Hayter, 2005; Mithun, 2004; Pedersen Zari, 2018).

3.1.2. Blatchford neighbourhood, Edmonton, Alberta, Canada

The Blatchford Redevelopment project is an urban renewal project dating from 2013 in Edmonton, Canada. The project was the object of an RFP launched by the city to requalify 217 ha from the former city airport to a sustainable community that would rely only on renewable energy, be carbon neutral, significantly reduces its ecological footprint, and empowers residents to pursue sustainable lifestyle choices. The Perkins+Will architects agency won the international competition and designed the project using a regenerative design mindset and whole systems thinking. Their approach explored urban metabolic flows to promote circularity and biotope regeneration (Busby, 2015). After the design phase, the project faced a few updates by the City Council, which created a public agency to ensure the project's development, which phase 1 is now completed.

3.1.3. CIGV, Dijon, Bourgogne, France

The Cité Internationale de la Gastronomie et du Vin (CIGV) de Dijon is an urban requalification project in the heart of Dijon, France over 6.5 ha. The RFP was won by a group led by Eiffage Aménagement, responsible for the project development and construction, associated with Bechu & Associés architects who designed the project. The project integrates a touristic equipment related to French gastronomy associated with a sustainable neighbourhood. The project focuses on protecting the existing on-site ecological structure, improving the soil permeability, and reducing greenhouse gas emissions (Eiffage Aménagement, Agence d'architecture A. Bechu, LAND'ACT, & OTCI, 2016). The project, now under construction, relies on the French EcoQuartier framework recommendations but does not aim for ministerial certification.

3.2. Analysis of governance arrangements

In the following sections, we present the main observations regarding the four dimensions of the governance arrangements of the analysed projects.

3.2.1. Rules of the game

We identified formal and informal rules affecting the project design and its outputs. Among the formal rules stand the public laws and regulations. For instance, the projects relied on local urban development masterplans and nature protection laws to align the design with existing public policies and development strategies. Other formal rules that supported the design process were green building and NSA frameworks, such as the Leadership in Energy and Environmental Design (LEED), the BRE Environmental Assessment Method (BREEAM) and the EcoQuartier Framework. Especially for the CIGV project, the environmental impact assessment (mandatory in France for this kind of project) had an essential role in informing the decision-making process in later design phases.

All three projects had a formal RFP issue by public authorities, specifying design rules and outcomes expectations. In all cases, these documents presented a short brief of the existing local laws that should support the design process and drafted the expected sustainable and environmental outputs of the projects, setting the first projects narratives and discourses. It is essential to highlight that we observed very distinct levels of detail regarding the expected outcomes on these documents.

These formal elements create a set of "rules of the game", representing the state-sanctioned interventions and tools that shape the process and outcomes (also known as design governance tools) (Carmona, 2016). Despite the existence and use of such tools on our projects, we did not observe robust social participation approaches. The analysed cases had only marginal participation in the design process, mainly in an informative manner in the late design phases.

On the informal side, we observed that the design team's "philosophy" (that can be understood as their mindsets, values and missions) and internal practices and policies also create rules that impact the project outcome and sustainability narratives. The CIGV case is an interesting example since the project RFP did not present high engagements for sustainability. However, the design and development teams' philosophy and internal policies enriched the project with their sustainable approaches and solutions during the different project phases. The two following quotes from the interviews highlight this:

> *"The overall situation of this project is the starting point of the structure and the project geometry, and of course, a bit of the philosophy of the project, the agency's philosophy. The environmental approaches are always more or less based on the same principles, it is the observation of the site, the orientations, the wind etc. [...] All these points were taken into account to anchor the structure of the project."*[1] - CIGV design team member.
>
> *"Our internal process integrates the classic sustainable development approaches. However, this is a slightly older operation, so we were in the early stages. There were already the first indicators, the first schemes that existed at Eiffage, much less structured than what we see today"*[2] - CIGV development team member.

3.2.2. Actors

Concerning the actors involved in the design and implementation of these projects, we observed three types of stakeholders: 1) the local government/state, 2) the design team (usually represented by a private urban design company), and 3) the project development/implementation team.

Dynamic relation between actors is observed through time, with evolving interest and influence on the project's different phases (RFP, design, implementation). This dynamic relation directly impacts two other governance dimensions, the resources mobilised on the project and the dominant sustainable discourse. In the first project phase (RFP), we observed a strong influence from the local governments. Subsequently, private design teams enter the game and gain influence in the design phase, bringing their knowledge and narratives, consolidating the project and its sustainable solutions. Finally, very different configurations seem to exist among the three projects in the implementation phase, affecting the concretisation of the sustainable discourses.

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[1]Translated by the authors. Original text: "La situation globale de ce projet, c'est le point de départ de la structure et de la géométrie, et bien sûr, un peu la philosophie du projet, la philosophie de l'agence. Les approches environnementales sont toujours plus ou moins basées sur le même principe, c'est l'observation du site, les orientations, le vent etc. […] On a tenu compte de tous ces points pour ancrer un peu la structure du projet."

[2] Translated by the authors. Original text: "Notre process interne intègre les démarches de développement durable classique. Mais c'est une opération qui est un peu plus ancienne, donc on était un peu sur les prémices. Il y avait quand même, déjà les premiers indicateurs, les premiers schémas qui existaient chez Eiffage, beaucoup moins structurée que ce qu'on peut voir aujourd'hui.

During the implementation phase, the Lloyd neighbourhood project faced a withdrawal of important actors. The government (represented by the Portland Development Commission) and the local landowners lost interest in the project after the design delivery, impacting the financial and human resources available. The project implementation is delegated to a new actor in the game, the EcoLloyd association, an NGO that relies on its own resources. These evolutions hinder the implantation of previously designed sustainable solutions, implying important changes in the project discourse.

Contrary to what we observed in Portland, in the Blatchford and the CIGV projects, the initial sponsors' stakeholders remain highly interested in the project across all three phases. The Blatchford project had a few evolutions in its discourse between design and implementation. However, those are justified by the project appropriation by the local development team and an effort to assure its financial viability. Finally, in the CIGV project, the partnership between the city, the project developer and the design team remained stable all over the three phases, assuring continuity in the project resources and discourses. As previously highlighted, the projects lacked active civil society participation.

3.2.3. Resources

We identified three types of key resources in the project design and implementation: land, expertise and funding. Land relates to the availability and ownership of the project site area. Expertise concerns the different knowledge on urban design, sustainability and environmental sciences that were mobilised in the design process. Finally, funding describes the financial resources and mechanisms necessary to design and implement the project and its narratives. In all three cases, these resources have been fundamental to the project development, and their absence configured barriers to sustainable discourses.

The projects had different configurations regarding land ownership. In CIGV and the Blatchford cases, the land belonged to the municipality. In the Lloyd project, the land belonged to several distinct private landowners, and the municipality only owned public spaces. This specific configuration of the Lloyd impacted the project development since it was impossible to implement the project unless all the landowners stayed engaged with the project proposition.

Concerning the expertise, all three designs have been done by private companies with considerable experience and knowledge in urban design, usually regrouping architects, urban designers, environmental engineers, ecologists, landscape architects, economists and others. The dominant logic is that the public sponsors rely on a private group of experts to apport knowledge and design the project, externalising the expertise.

Regarding the financial resources, we identified three distinct configurations. Blatchford was mainly done through public funds. The city council accorded an initial budget to the project design and implementation. Subsequently, private builders invested, buying parcels and constructing their units following public prescriptions. The profit obtained during the first development phase is then reinvested to construct the following phases. The CIGV project had a public-private partnership context, with the public project sponsor aiming to minimise public investments, so the project is built on public land and exploited by a private actor. Finally, the Lloyd project is inserted in a market-based logic, in which the real estate actors were expected to invest to realise the project, which turned into a major barrier to the project development.

3.2.4. Discourse

The dominant discourses and narratives concerning the sustainable features of the analysed projects have largely and distinctly evolved over the different project steps. The evolution had an intricated link with the other governance dimensions, being a direct consequence of them.

The Lloyd project narrative started with high engagements for the sustainable neighbourhood. The RFP delineated the expected outcomes in energy consumption and renewable energy production, storm and wastewater management, sustainable building retrofitting, sustainable materials choices, reduction of GHG emissions, green infrastructure and the ecological network. These topics remained during the design phase, and a few others emerged, like water consumption, materials sourcing, food production, and the aquatic ecosystem structure. Yet, in the implementation phase, only a few discourses could reach maturity, namely reducing energy consumption and GHG emissions, sustainable waste management, and smaller green infrastructure for pollination. This trend resulted from the lack of human and financial resources in the implementation phase, a consequence of the stakeholder's withdrawal.

The CIGV project discourses had an opposed trajectory to that observed at the Lloyd. It started with non-specific engagements, only referencing an eco-neighbourhood, green infrastructure, and local food production. Nevertheless, several other topics emerged during the design and implementation phases, such as the quality and structure of the soil, stormwater management, energy consumption, GHG emissions, waste management, and natural habitat provision. These changes are mostly related to the formal and informal rules of the game that influenced the design. The three main elements that positively affected the sustainable project discourse are the environmental impact assessment study, the design team philosophy, and the project developer's internal policies.

Finally, the Blatchford project had a stable discourse trajectory. The project already presented several sustainable engagements on the RFP related to energy consumption and renewable energy production, water consumption, stormwater management, sustainable building materials, GHG emissions, waste management, and the quality and structure of terrestrial and aquatic ecosystems. The engagements evolved slightly over the project design and implementation, adapting to the socio-economical context, gaining more maturity and guaranteeing financial viability. This discourse steadiness is related to a solid institutional engagement in the project. The City of Blatchford has been a central actor throughout the different project phases, keeping the narrative, resources, and rules stable over time.

3.3. Success levers on governance arrangements

Exploring the governance through the PAM framework in the three different case studies allowed identifying key elements composing the governance arrangements. Regarding the rules of the game, we identified the articulated role of formal and informal rules and the tools used to define them. Concerning the actors, we identified three main actor types, the government, the design team and the project development team, with a lack of civil society participation. In the matter of resources, we noted the influence of land ownership, technical expertise and financial resources. Finally, each project implemented a distinct sustainable narrative with a few recurrent themes: energy, GHG emissions, water management, waste, food, and green infrastructure. Figure 1 illustrates the key elements identified for each governance dimension.

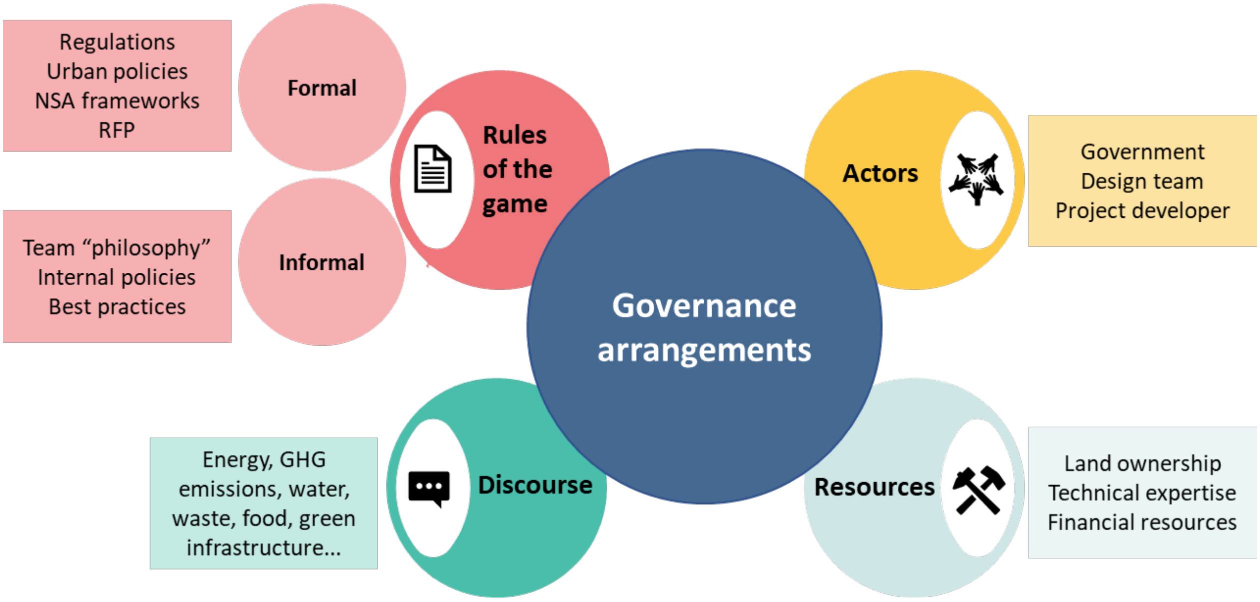

Figure 1 - Key elements observed in the governance arrangements affecting the design and implementation process of sustainable neighbourhoods

The PAM framework and the comparative approach also allowed us to identify four potential levers that could predict success in designing and implementing sustainable neighbourhoods and are key to evolving these emerging frameworks. We understand success as the materialisation of the sustainable discourse on implementation phases, with solutions being applied to address the different local sustainable challenges.

Our first lever relates to the actors' configuration in the project design and implementation. Our findings point out that stability in this configuration is central to successfully implementing sustainable discourses. In Blatchford and CIGV projects, a core group of actors granted stability. These actors remained hinged from the first drafts until later project implementation, and the public actors had an essential role in assuring the project continuity over time and in their narratives. This first lever converges with previous findings highlighting the need for continued political support to consolidate sustainable discourses and the articulation between stakeholders (Fenker and Zetlaoui-Léger, 2017).

Our second lever also relates to the actor's configuration, but it points towards a lack in our cases: civil society participation. We question whether social participation could enrich design processes and sustainability discourses, enhancing ambitions and embracing social sustainability issues. We also wonder if social participation could create a new actor group that could help to assure stability in the project discourse trajectory and public political support in contexts with no stakeholders' stability (like in the Lloyd project). Participatory approaches are fundamental in the design of sustainable urban projects (Fenker and Zetlaoui-Léger, 2017; Zepf and Andres, 2012) and also a significant "design governance" tool (Carmona, 2017). Nevertheless, design teams still fail to integrate it into the decision-making of sustainable urban design, limiting it to the minimum legally required. This lever joins the underpinnings of regenerative development, which stands for robust civil society participation since early project phases, aiming to create beneficial projects for society and nature (Mang and Reed, 2013).

The third lever regards the significant role of informal rules in creating sustainable discourses. Research has focused until now on the formal set of rules, exploring state-sanctioned tools to coordinate and guide the design process. Nevertheless, in our sample, the informal rules, such as the design team philosophy, mission, values and internal policies, highly contributed to enriching and materialising the discourses. Several aspects remain unclear on the role of these informal rules, like how their policies and best practices evolve accordingly to the raising awareness on sustainability, to which extent these informal rules impact the outcomes and how these informal rules are consolidated and appropriated by design teams. In the context in which private design teams are largely mobilised as experts and responsible for designing sustainable neighbourhoods, this point needs much more attention and exploration.

Finally, the last lever regards sustainable neighbourhood projects' financial feasibility. This point seems to be a significant barrier to consolidating sustainable discourses. Thus, there is a need to explore new financial practices, mechanisms and business plans to facilitate the concretisation of sustainable discourses in urban neighbourhoods. Some clues are found on emerging topics in the interface of built sciences and finance. Examples are the EU taxonomy for sustainable activities, which created a high interest in the real estate market, catalysing investments in sustainable projects (OID, 2022), the internalisation of economic externalities through the notion of payment for ecosystem services, a topic still not explored for the neighbourhood scale (Bellver-Domingo et al., 2016), the use of green finance (Debrah et al., 2022) as well as behavioural techniques like nudges, complementing financial strategies (Loewenstein and Charter, 2017).

4. Conclusions

This research presents a novel exploration of sustainable neighbourhood design process using a governance arrangement framework. It allowed us to draw four hypotheses regarding success levers in governance arrangements during the design and implementation of sustainable neighbourhoods. These hypotheses open new research perspectives, holding opportunities to foster sustainability in neighbourhoods design.

It is important to highlight that the PAM framework helped decrypt, organise, and analyse diverse governance arrangements. We call for more cases studies relying on this framework to promote a broader and more structured understanding of this approach. Despite its pertinence, the framework could be adapted to address urban design questions, namely, adding a time dimension to help represent an urban project's different phases and evolution. Another opportunity would be to use dynamic system modelling techniques to understand how the governance elements' relations interfere with the outcomes and narratives (Pejic Bach et al., 2020).

Finally, we argue that besides the technical aspects of urban design and the daily governance of sustainable neighbourhoods, governance arrangements in the design phase are crucial to tackling contemporary urban challenges. Further studies could be fundamental to propose tools to help plan these governance arrangements. Such approaches could contribute to more holistic and sustainable neighbourhood projects reaching implementation phases.

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Appendix 1- List of pre-selected projects and their suitability to selection criteria

#	Project name	Scale and use	Design Framework	Project phase	Documentation
1	Lloyd's Crossing	Mixed-use neighbourhood	Ecosystem-level biomimicry	Partially built	Available online and through project team
2	Lavasa Hill	Mixed-use neighbourhood	Ecosystem-level biomimicry	Partially built	Available online.
3	Terres de Versailles	Mixed-use neighbourhood	EcoQuartier	Under construction	Not available online and project team did not answer our information request.
4	CIRS	Educational building	Regenerative Design	Built	Available online.
5	Vale Living with Lakes	Educational building	Regenerative Design	Built	Available online.
6	Pôle du Biomimétisme Marin de Biarritz	Office building	**Ecosystem-level biomimicry**	Not built	Available through project team
7	Langfang	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
8	RegenVillages	Mixed-use neighbourhood	EcoQuartier	Not built	Not available online.
9	Tour Hyperion	Residential building	EcoQuartier	Under Construction	Not available online.
10	Groupe Scolaire de la Science et de la Biodiversité	Educational building	Ecosystem-level biomimicry	Built	Available online and through project team
11	La vallée - Chatenay Malabri - Eiffage	Mixed-use neighbourhood	EcoQuartier	Under Construction	Not available online.
12	Ecoquartier de l'Eau Vive	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
13	Docks de Ris	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
14	Claude Bernard	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
15	Clichy-Batgnolles	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
16	Seguin - Rives Seine	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
17	Bel Air - Grands Pêchers	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
18	Camille Claude	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
19	Fréquel-Fontarabie	Mixed-use neighbourhood	EcoQuartier	Built	Not available online and project team did not answer our information request.
20	Clause-Bois Badeau	Mixed-use neighbourhood	EcoQuartier	Built	Available online and through project team

21	Dong Tan	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
22	Wanwhuang	Mixed-use neighbourhood	Ecosystem-level biomimicry	Not built	Not available online.
23	20/20 Park	Business Park	Ecosystem-level biomimicry	Built	Not available online.
24	Blatchford Redevelopment	Mixed-use neighbourhood	Regenerative Design	Partially built/Under construction	Available online and through project team
25	Darwin Ecosystème	Mixed-use neighbourhood	Regenerative Design	Partially built	Not available online and project team did not answer our information request.
26	Dockside Green	Mixed-use neighbourhood	Regenerative Design	Under Construction	Not available online and project team did not answer our information request.
27	Point Weels	Mixed-use neighbourhood	Regenerative Design	Not built	Not available online.
28	Chaudière Island (Zibi)	Mixed-use neighbourhood	Regenerative Design	Not built	Available online.
29	Cap Roger Curtis	Mixed-use neighbourhood	Regenerative Design	Not built	Not available online.
30	Smartseille	Mixed-use neighbourhood	EcoQuartier	Partially built	Not available online and project team did not answer our information request.
31	Cité de la Gastronomie et du Vin à Dijon	Mixed-use neighbourhood	EcoQuartier	Partially built/Under construction	Available through project team
32	The Paddock	Mixed-use neighbourhood	Regenerative Design	Partially built/Under construction	Available online

Appendix 2 - Analysed documents for each case study

#	Project	Documents tittles	
1	Lloyd	i.	Request for Proposals #03-16 - Lloyd Crossing Sustainable Design and Development Project
		ii.	LLOYD CROSSING - Sustainable Urban Design Plan & Catalyst Project
		iii.	AIA TopTen - Lloyd Crossing Sustainable Design Plan Case Study
		iv.	Lloyd Crossing Sustainable Urban Design Plan and Catalyst Project - Portland, Oregon [2005 EDRA/Places Award -- Planning]
		v.	Lloyd District Development Strategy
2	Blatchford	i.	Busby: Architecture New Edges
		ii.	Request For Qualification Number 917843 - Edmonton City Centre Airport Lands - The Master Plan
		iii.	Negotiated Request for Proposals - Edmonton City Centre Airport Lands - The Master Plan
		iv.	City Centre Area Redevelopment Plan Consolidation
		v.	Blatchford Concept Plan Implementation Analysis
		vi.	Blatchford Business Case
		vii.	Blatchford Plan and graphics
		viii.	Strategic Alignment with The Ways
		ix.	Blatchford Redevelopment Scenarios
		x.	Financial Analysis of the Blatchford Development Scenarios
		xi.	Blatchford Development Governance Model
		xii.	Potential Advisors to the Blatchford Redevelopment Project
		xiii.	Blatchford West Architectural and Urban Design Guidelines
		xiv.	Blatchford West - Stage One Green Building Codes
3	CIGV	i.	A.M.I. Réalisation du projet de la cité internationale de la gastronomie sur e site de l'hôpital général
		ii.	Cahier Des Charges En Vue De La Création De La Cite De La Gastronomie
		iii.	Dossier de candidature – La cité internationale de la gastronomie à Dijon – Présentation
		iv.	La cité internationale de la gastronomie à Dijon – Dossier de candidature – Compléments d'informations Partie 1
		v.	La cité internationale de la gastronomie à Dijon – Dossier de candidature – Compléments d'informations Partie 2
		vi.	La cité de la gastronomie à Dijon
		vii.	Etude d'impact – Evolutions du projet
		viii.	Dijon Le projet de territoire Grand Sud
		ix.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 1-2-3-4-5-6-7-9 DOCUMENT PRINCIPAL
		x.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 2-4-5 ANNEXES DOCUMENT PRINCIPAL
		xi.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 8 : ANNEXES
		xii.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 8 : NOTICE ASSAINISSEMENT
		xiii.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 8 : NOTICE VRD
		xiv.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 11 : GFA
		xv.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 14 : ETUDE D'IMPACT
		xvi.	PERMIS D'AMÉNAGER Cité internationale de la gastronomie et du vin DIJON (21000) PA 14 : EVALUATION APPROPRI2E DES INCIDENCES

Appendix 3 – Interview protocol

#	Question	Objective
1	Can you tell about the main ecological engagements and the main strategies used in this project to promote its sustainability?	Identify narratives and discourse related to sustainable engagements
2	Considering three main project phases (project request, project design, and project construction), how do you think these strategies evolved?	Identify narratives' evolution over time.
3	Which were the main stakeholders relevant to integrating these ecological solutions in each project phase? Which was their role?	Identify and validate actors mapping
4	Which ones have most supported the sustainable ambition on each project phase among these actors?	Identify actors' roles and power related to our subject/
5	Which one had more decision power related to sustainable design among these actors?	Identify actor's roles and resources
6	How did you decide among possible sustainable solutions?	Identify rules of the game
7	Which resources were mobilised to propose and design these strategies and solutions (as resources, you can understand knowledge, professionals, money, studies, tools, labels, local laws…)	Identify resources and rules of the game
8	Which were the main rules and guidelines that guided the conception? (NSA frameworks, local laws, internal protocols, labels, RFP…)	Identify rules of the game

Conclusions Chapter 2

The case study approach allowed us to identify trends and levers in the urban design practice that can help us move toward net-positive neighbourhoods. These learnings are helpful to inform the proposition of an urban design framework to assist this process and delineate the next research steps.

Among the main results, we can highlight that projects tend still to address human pressures over ecosystems, reducing them through solutions that mostly manage energy and materials flows. The regeneration of the ecosystem's structures is still in the background. From the perspective of regenerative design and ecosystem services production, this lack represents a significant opportunity for improvement. For instance, projects must move from an anthropocentric perspective and include more proactive solutions to regenerate the ecosystem's biotic and abiotic structures. Working on these two fronts simultaneously, reducing anthropic pressures and regenerating ecosystems structure, is crucial to enhancing urban ecosystem services and assuring benefits from and for nature.

Besides, we identified that several different types of solutions could be used to enhance the production of ecosystems services, such as nature-based ones, technological ones and even regulations. Nevertheless, NBS and technological solutions had essential roles in our sample.

This work culminated in the first draft of a taxonomy of solutions and strategies to enhance the production of ecosystems services at the neighbourhood scale. This taxonomy will still evolve until a final version and will be the base of our design framework presented in the discussion. It is important to highlight that after identifying strategies from the field with the case studies, we completed this taxonomy with strategies proposed by different Neighbourhood Sustainability Assessments (NSA). In this task, we relied on the work done in collaboration with the COST RESTORE WG5 (Reith and Brajković, 2021) research project about the scale jump of regenerative design practice. We analysed several tools, including NSA frameworks, that could promote regenerative design at the neighbourhood scale, identifying their proposed strategies. This exercise allowed us to reach a second version of the taxonomy that is more exhaustive in terms of the possible strategies, and that was the base for the work presented in the sequence in Chapter 3.

Finally, more than an assemblage of technical solutions, urban neighbourhoods are outcomes of a design process with particular governance. Analysing these different governance arrangements, we delineated levers of success in implementing the previously discussed strategies. For instance, we can highlight the potential role of social participation in enriching the design process, the need to create stability and continuity in the stakeholders involved, and the importance of the availability of financial resources in successfully implementing the strategies.

Conclusions Chapitre 2

L'approche par étude de cas nous a permis d'identifier les tendances et les leviers dans la pratique de l'aménagement urbain qui peuvent nous aider à progresser vers des quartiers à bilan net positif pour l'environnement. Ces apprentissages sont utiles pour informer la proposition d'un cadre de conception urbaine pour aider ce processus et délimiter les prochaines étapes de recherche.

Parmi les principaux résultats, nous pouvons souligner que les projets ont encore tendance à s'attaquer aux pressions humaines sur les écosystèmes, en les réduisant par des solutions qui gèrent principalement les flux d'énergie et de matériaux. La régénération des structures de l'écosystème reste en arrière-plan. Du point de vue du «regenerative design» et de la production de services écosystémiques, ce manque représente une importante opportunité d'amélioration. Les projets doivent abandonner une perspective anthropocentrique et inclure des solutions plus proactives pour régénérer les structures biotiques et abiotiques de l'écosystème. Travailler sur ces deux fronts simultanément et réduire les pressions anthropiques et régénérer la structure des écosystèmes est crucial pour améliorer la production des services écosystèmiques urbains et assurer des bénéfices de et pour la nature.

En outre, nous avons identifié que plusieurs types de solutions différentes pouvaient être utilisées pour améliorer la production des services écosystémiques, comme les solutions fondées sur la nature (SfN), les solutions technologiques et même les règlementations. Néanmoins, les SfN et les solutions technologiques ont joué un rôle essentiel dans notre échantillon.

Ce travail a abouti à la première version d'une taxonomie des solutions et des stratégies visant à améliorer la production de services écosystémiques à l'échelle du quartier. Cette taxonomie va encore évoluer jusqu'à une version finale et sera la base de notre cadre de conception présenté dans la discussion.

Il est important de souligner qu'après avoir identifié des stratégies sur le terrain avec les études de cas, nous avons complété cette taxonomie avec des stratégies proposées par différentes certifications durables pour les quartiers (NSA). Pour cette tâche, nous nous sommes appuyés sur le travail effectué en collaboration avec le projet de recherche COST RESTORE WG5 (Reith et Brajković, 2021) concernant l'application du «regenerative design» à des échelles plus larges que le bâtiment. Nous avons analysé plusieurs outils susceptibles de promouvoir le design régénératif à l'échelle du quartier, en identifiant les stratégies qu'ils proposent. Cet exercice nous a permis de parvenir à une deuxième version de la taxonomie, plus exhaustive en termes de stratégies possibles, et qui a été la base du travail présenté dans la séquence du chapitre 3.

Enfin, plus qu'un assemblage de solutions techniques, les quartiers urbains sont les résultats d'un processus de conception avec une gouvernance particulière. En analysant ces différents dispositifs de gouvernance, nous avons délimité des leviers de réussite dans la mise en œuvre des stratégies précédemment évoquées. Par exemple, nous pouvons souligner le rôle potentiel de la participation sociale dans l'enrichissement du processus de conception, la nécessité de créer une stabilité et une continuité dans les acteurs impliqués, et l'importance de la disponibilité des ressources financières dans la mise en œuvre réussie des stratégies.

Chapter 3

Strategies and indicators: towards a regenerative neighbourhood design framework

Summary

This final results chapter aims to validate our previously delineated hypothesis and propose an indicator set helpful for design teams to select strategies and assess their impacts. In this task, we will also evolve our taxonomy, understand how these strategies are applied in a large sample of sustainable neighbourhoods, and explore the needs and barriers that design teams face. Two other main research questions are covered here:

1. To what extent are the different strategies to promote urban ecosystem service used in certified sustainable neighbourhoods, and what are the needs for new tools and barriers to implementing them successfully?

2. Which indicators could assist the design of regenerative and ecosystem-inspired neighbourhoods and assess their performance?

The first question is addressed in a peer-reviewed paper published in the "Sustainable Cities and Society" journal. The paper analyse 73 international certified sustainable neighbourhoods through an online survey. In this survey, we identified the trends in using the different strategies to produce urban ecosystems services. Here we explored also the use of ecological diagnostics informing the design process, the challenges perceived by design teams in implementing these strategies and their needs in terms of new tools.

The last question is tackled in a peer-reviewed article submitted to the "Ecological Indicators" journal. This paper focuses on selecting an operational set of indicators that could guide the design process and assess the project performance in producing ecosystem services. Based on existing sustainable urban indicators, we use qualitative methods to select a set of 23 indicators that will compose our design framework.

Resumé

Ce dernier chapitre de résultats vise à valider nos hypothèses précédemment définies et à proposer un ensemble d'indicateurs utile aux équipes de conception pour sélectionner les stratégies et évaluer leurs impacts. Dans cette tâche, nous ferons également évoluer notre taxonomie, nous comprendrons comment ces stratégies sont appliquées dans un large échantillon de quartiers durables et nous explorerons les besoins et les obstacles auxquels les équipes de conception sont confrontées. Deux autres grandes questions de recherche sont abordées ici :

1. Dans quelle mesure les différentes stratégies de promotion des services écosystémiques urbains sont-elles utilisées dans les quartiers durables certifiés, et quels sont les besoins de nouveaux outils et les obstacles à leur mise en œuvre réussie ?

2. Quels indicateurs pourraient aider à la conception et évaluation des quartiers régénératifs et inspirés par les écosystèmes ?

La première question est abordée dans un article évalué par les pairs et publié dans la revue «Sustainable Cities and Society». Cet article analyse avec une enquête en ligne 73 quartiers durables internationaux certifiés. Dans cette enquête, nous avons identifié les tendances dans l'utilisation des différentes stratégies pour produire des services écosystémiques urbains. Nous avons également exploré l'utilisation de diagnostics écologiques pour informer le processus de conception, les défis perçus par les équipes de conception dans la mise en œuvre de ces stratégies et leurs besoins en termes de nouveaux outils.

La dernière question est abordée dans un article soumis à l'examen des pairs dans la revue «Ecological Indicators». Cet article se concentre sur la sélection d'un ensemble opérationnel d'indicateurs qui pourraient guider le processus de conception et évaluer la performance du projet en matière de production de services écosystémiques. Sur la base des indicateurs urbains durables existants, nous utilisons des méthodes qualitatives pour sélectionner un ensemble de 23 indicateurs qu'intègrera notre cadre de conception.

3.1 Towards regenerative neighbourhoods: An international survey on urban strategies promoting the production of ecosystem services

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Towards regenerative neighbourhoods: An international survey on urban strategies promoting the production of ecosystem services

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Net-positive urban design

ABSTRACT

Neighbourhoods are a fundamental urban design unit and the focus of many sustainable design frameworks. Although these frameworks were fundamental to mainstream sustainable practices, problems with their use remain, such as their unbalanced sustainability aspects. To face these problems, innovative design approaches emerge, including regenerative design, aiming for urban projects that are net-positive for society and nature. Nevertheless, there is no common understanding of how sustainable urban projects translate regenerative design principles into urbanisation strategies and produce benefits for society and nature. Through a survey with 73 international and certified sustainable neighbourhoods, we explored the use of 42 different urbanisation strategies, the role of diagnostics, the barriers, and the design teams' needs to move towards regenerative design and neighbourhoods that produce ecosystem services. We observed that projects mostly address fundamental urban challenges related to energy, water flows and vegetation, lacking focus on topics such as circular economy, soil and fauna management. We also found that doing an ecological diagnostic positively impacts the diversity of urbanisation strategies. To move towards regenerative design, it is important to formally integrate diagnostics into the design process and combine innovative strategies, like those related to closed systems, fauna, and habitat management, with conventional ones.

1. Introduction

Neighbourhoods are an important unit of functioning and design in the urban fabric. In the context of climate change, ecological crisis, and growing urbanisation, the design (or redesign) of neighbourhoods has a significant impact on ecosystems (Alberti, 2005; Pickett et al., 2013). The neighbourhood scale allows us to address systemic interactions in urban and socio-ecological systems, holding opportunities to operationalise ecological and sustainable engagements (Grazieschi, Asdrubali, & Guattari, 2020; Sharifi & Murayama, 2014).

Urbanisation reshapes natural ecosystems, reducing their potential production of ecosystems services and nature's contributions to people (Alberti, 2005; IPBES, 2019). The urban design practice transforms the space and its dynamics, directing a site towards a preferable situation through urban interventions and strategies (Arab, 2018; Ataman & Tuncer, 2022). These interventions touch on several aspects: public space, urban morphology, architectural specifications, urban features and services, and even urban regulations.

Given these premises, the urban design practice and its tools are an essential lever of change to tackle contemporary sustainable and ecological challenges (United Nations, 2018), as those presented in the Sustainable Development Goals and the New Urban Agenda (Pickett et al., 2013; United Nations, 2017, 2018). Better articulating urban policies and sustainable engagements into the design phase of urban projects is instrumental to developing neighbourhoods and cities with better environmental performance (Abusaada & Elshater, 2021).

Promoting this articulation, several sustainable neighbourhood design frameworks were consolidated during the first decades of the XXI century (Grazieschi et al., 2020; Sharifi, Dawodu, & Cheshmehzangi, 2021). These frameworks, known as Neighborhood Sustainability Assessments (NSA), were mostly built upon established green building frameworks and rating systems, scaling them up in the area.

Although these frameworks were fundamental to mainstream sustainable building and neighbourhood design (Cole, 2012; Grazieschi et al., 2020; Sharifi & Murayama, 2014), several problems and limitations in their use to promote sustainability remain (Sharifi et al., 2021).

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Nevertheless, new design approaches are emerging and proposing to face such limitations. For instance, the regenerative design theory has a central place in such discussions (Brown et al., 2018; Cole, 2012). The concept proposes the design of urban projects with net-positive impacts, creating mutually beneficial conditions for society and nature (Cole, Oliver, & Robinson, 2013; Hes & Du Plessis, 2014; Pedersen Zari, 2012).

Even though regenerative design got popularised during the XXI century through research and practice (Benne & Mang, 2015; Brown et al., 2018), there is still a lack of tools to facilitate its operationalisation (Hes & Du Plessis, 2014). While regenerative design initiatives seem hard to be operationalised, the urban solutions and strategies to reach positive ecological impacts already exists (Pedersen Zari & Hecht, 2020) and are often promoted by the established NSA tools.

However, it has been rarely directly investigated in what way sustainable urban projects translate their engagements to contribute to the local ecosystem and enhance the ecosystem services production into urbanisation strategies (Pedersen Zari & Hecht, 2020; Steiner, 2014). We also have little knowledge of the barriers that design teams face while implementing strategies to promote urban ecosystem services and the tools that would be useful to assist the design process (Cole, 2012; Pedersen Zari, 2018).

Understanding the contemporary sustainable neighbourhood design practice is fundamental to make established NSA frameworks evolve towards regenerative design (Blanco, Pedersen Zari, Raskin, & Clergeau, 2021; Pickett et al., 2013; Steiner, 2014). Therefore, we are interested in understanding how different urbanisation strategies that could contribute to the production of ecosystem services are being employed in certified sustainable urban neighbourhoods. We are also interested in the role of ecological diagnostics in selecting sustainable urban strategies and in the barriers and tools to implement them better.

Thus, through a survey with international certified sustainable urban neighbourhoods, this research aims to answer the following questions:

- Which urban strategies are being used to contribute to the production of ecosystem services in certified sustainable neighbourhoods?
- How do ecological diagnostics affect and inform the design of sustainable urban neighbourhoods?
- What main challenges do project teams face while implementing these urban strategies?
- What are the needs in terms of new tools to design mutually beneficial projects for society and nature?

2. Literature review

2.1. Lacks and barriers of established NSA Frameworks

NSA frameworks emerged and got relevance during the early 21st century, with frameworks coming from market-based or public backgrounds (Chastenet et al., 2016; Grazieschi et al., 2020). Market-based examples are BREEAM Communities, launched in 2008, LEED-ND, launched in 2010, DGNB Urban Development, launched in 2010, and the Green Star Communities, launched in 2013 (Grazieschi et al., 2020). In the public sphere, we can cite the EcoQuartier framework launched in 2008 in France (Chastenet et al., 2016) and the CityLab Framework developed and proposed by the Sweden Green Building Council in 2010 (Reith & Brajković, 2021).

These different NSA frameworks had a central place mainstreaming sustainable design practices at the neighbourhood scale, with hundreds of sustainable projects certified worldwide (Cole, 2012; Grazieschi et al., 2020; Sharifi & Murayama, 2014). Nevertheless, they have been widely criticized for their lacks promoting sustainability (Chastenet et al., 2016; Grazieschi et al., 2020; Sharifi et al., 2021).

At first, these established NSA frameworks present an unbalanced equilibrium between different sustainable development pillars. Usually, they address only one or two of them, mainly focusing on environmental aspects (Komeily & Srinivasan, 2015; Reith & Orova, 2015; Subramanian, Chopra, Cakin, Liu, & Xu, 2021). Still, in the environmental domain, a few topics have more weight on the analysis, as the project carbon and energy performances (Chastenet et al., 2016), with lesser importance on topics as biodiversity and ecology, that only started to emerge in the last few years (Grazieschi et al., 2020).

Subsequently, some NSA tools have been pointed out as overly prescriptive approaches that do not focus on sustainable performance (Wangel, Wallhagen, Malmqvist, & Finnveden, 2016). Prescriptive frameworks as LEED-ND, which provide the project team with a series of available solutions and measures, seem to be less effective in reaching sustainability goals than performance-based ones, as Green Star, which predominantly uses quantitative information to assess the expected environmental benefits (He, Kvan, Liu, & Li, 2018).

Also, the majority of the NSA frameworks have a top-down approach. They lead the design team to focus on the proposition of features and technological solutions, leaving behind steps like diagnostics and the local needs assessment, which could inform and enrich the design process (Chastenet et al., 2016; Subramanian et al., 2021).

Finally, these frameworks have been criticized for promoting a static and non-systemic understanding of urban spaces (Cole, 2012), for instance, failing to integrate a life-cycle perspective on the neighbourhood design (Grazieschi et al., 2020). All these limitations imply in frameworks that do not fulfil their potential as decision-making tools for sustainable urban design (Subramanian et al., 2021), leading to a growing literature interested in evaluating and comparing them.

2.2. Regenerative design and ecological net-positive impact

The regenerative design was first proposed as an urban design approach in 1994 by John Tillman Lyle. Lyle questioned urban systems' linearity compared to ecosystems and suggested that reincorporating the essential elements of life in designed urban spaces (such as energy conversion, water treatment, and nutrient cycling) would promote urban spaces with a more circular logic (Lyle, 1994).

With increasing awareness on scientific and operational fields, the regenerative design theories have been highlighted as a way to tackle the lacks of existing green building and NSA frameworks (Brown et al., 2018; Cole, 2012; Pedersen Zari, 2018). A literature review on the contemporary regenerative design theories highlighted five recurrent principles around the concept that finds close links to the NSA limitations discussed above: 1) A mutual net-positive impact on ecosystems and society; 2) The co-evolution of the socio and ecological systems to better health states; 3) A design process based on the site context and its socio-ecological diagnostic; 4) A participatory design process; 5) A continuous and adaptative design process (Blanco, Raskin, & Clergeau, 2021).

Nevertheless, regenerative design theory has its own barriers that prevent a more significant adoption of the concept. Examples are its too theoretical approach, lack of applicability (Clegg, 2012), and difficulty assessing the aimed positive impacts on social and ecological systems (Robinson & Cole, 2015). To tackle these barriers, Pedersen Zari (2018) proposed a regenerative urban design method based on biomimicry, called Ecosystem Services Assessment (ESA). In this method, the researcher proposes an operational design process with four steps that allow measuring the positive ecological impacts through the notion of ecosystem services. The first step of the framework is based on a site

Table 1
Strategies taxonomy used on survey

Dimension	Topic	Strategies
Energy flows	Electricity	Uses and/or produces renewable energy
		Has solutions to reduce the energy consumption in the neighbourhood
		Has a local energy storage infrastructure
	Heat and light	It was designed to optimise the solar input on blocks and buildings
		Has solutions to share heat and energy between blocks and buildings
		Minimises light and noise impacts
Material flows	Water resources	Reduces the total water consumption in the neighbourhood
		Manages rainwater locally (reuse, infiltration, evaporation…)
		Manages wastewater/greywater locally
	Building materials	Uses demolition, salvaged and recycled materials for building construction
		Retrofitted existing buildings and infrastructures
		Prioritises the use of building materials with low impact on human and ecosystem health
		Sourced building materials locally
		It was designed to reduce the need for building materials
		It was designed to be adaptable, retrofitted, reused and/or deconstructed
		Sought embodied carbon neutrality
	Carbon	Sequestered/compensated carbon emissions from use phase
		The urban form was designed to reduce carbon emissions (high density, mixed-use…)
		Has sustainable urban mobility strategies to reduce carbon emissions
	Food	Produces food locally
	Chemical products	Restricts the use of phytosanitary products on its management
	Waste	Manages organic waste locally
		Recycles and sustainably manages domestic waste
		Has solutions to reduce the local waste production
Abiotic Structure	Water bodies	Restored water bodies/wet ecosystems
		Limited the development over aquatic ecosystems/wet zones
	Soil	Avoided soil sealing/unsealed soil
		Avoided topography changes
		Limited the development over natural, healthy or sensible areas (as greenlands, farmlands, flood areas, special interest areas...)
		Compensated the urbanised area protecting other natural areas
		Has solutions to improve the soil quality and fertility
	Air	Has solutions to improve the neighbourhood air quality
Biotic structure	Flora	Has solutions to increase the amount and diversity of vegetated spaces
		Connects to the local ecological network
		Uses complex and site-appropriated vegetation schemes
		Reintroduces indigenous flora species
		Manages invasive flora species
	Fauna	Provides natural habitat diversity to host indigenous species
		Reintroduces indigenous fauna species
		Design artificial abiotic habitat structures for fauna
		Avoid the fragmentation of exiting natural habitat
		Manages invasive fauna species

ecological diagnostic, using ecosystems services metrics that will further inform the selection of urban strategies and solutions. The researcher uses the production of ecosystem services as a proxy to the positive impacts of the urban project. The final objective is to emulate natural ecosystem functioning using different urban strategies and solutions, actively contributing to the production of urban ecosystem services (Pedersen Zari, 2018).

While the notion of ecosystem services is well adopted in urban planning and design disciplines, there is a lack of translational work between ecology and urban design. Design teams have little awareness of how to design urban projects that enhance the production of ecosystem services (Pedersen Zari & Hecht, 2020; Steiner, 2014). To bridge this gap, Pedersen Zari & Hecht (2020) made one first identification through a literature review of the different strategies and solutions that could be applied in buildings and urban projects to positively impact ecosystem service production (Pedersen Zari & Hecht, 2020). The authors identified 160 distinct design strategies, concepts and technologies that could enhance the production of ecosystem services in urban projects. Examples are green roofs, promoting habitat provision and rainwater regulation, and carbon sequestration strategies, contributing to global climate regulation (Blanco, Raskin, & Clergeau, 2022). The authors observed that the strategies and solutions identified were rather conventional, highlighting that the challenge to reach net positive impacts was in understanding and integrating these solutions systemically (Pedersen Zari & Hecht, 2020).

With a focus on the neighbourhood scale, and through an international case study methodology, Blanco et al. (2022) identified a taxonomy of 36 different urban strategies used to promote urban ecosystem services that could inform new regenerative design tools. While not exhaustive, this taxonomy covers different aspects of environmental sustainability in neighbourhoods, such as energy and material flows, biodiversity, and the ecosystem's physical structure. The authors highlighted the hypothesis that urban projects primarily address energy and materials flows through different strategies and tend to give lesser importance to ecosystem biophysical structure. Finally, the researchers observed that using an ecological diagnostic in the design process seemed to foster the integration of ecological knowledge and guide the selection of urbanisation strategies (Blanco et al., 2022). Ecological diagnostics are a standard tool on other environmental disciplines, having a fundamental place to assist decision making (Morais et al., 2020), as on the Strategic Environmental Assessment frameworks and Impact Assessment studies (UNECE, 2003). As advocated by regenerative design, data produced on diagnostics can foster an informed urban design process. Nevertheless, in urban design research and practice, the role of diagnostics have been rarely explored (Leach, Mulhall, Rogers, & Bryson, 2019).

Table 2
Declared labels on the sample

Label	Number of projects	% of the sample
LEED-ND (USA)	44	60.3%
EcoQuartier (level 3 or 4) (France)	21	28.8%
BREEAM Communities (UK)	3	4.1%
DGNB Communities (Germany)	4	5.5%
Green Star Communities (Australia)	1	1.4%

3. Material and methods

3.1. Sample definition

Our sample was composed only of certified projects under the five following sustainable urban labels: LEED-ND (US Green Building Council- USA), BREEAM Communities (Building Research Establishment - UK), DGNB Urban Districts (German Sustainable Building Council - Germany), Green Star Communities (Green Building Council Australia - Australia) and EcoQuartier (Ministère de la Transition Écologique et Solidaire & Ministère de la Cohésion des territoires et des relations avec les collectivités territoriales - France, phase 3 and 4). These labels were chosen because they are all well-established sustainable neighbourhood design frameworks, widely used at this scale (Chastenet et al., 2016; Grazieschi et al., 2020; Reith & Orova, 2015; Sharifi et al., 2021). They also offer good international coverage to the sample, and they have an accessible online projects database, allowing us to compose a representative sample of projects to interrogate.

In March 2021, we visited each of these labels official online databases, and we identified a total population of 362 certified urban neighbourhoods that were eligible to answer the survey (Appendix A).

3.2. Data collection

We invited design and project management teams from each identified project to answer an online survey. Invitations were sent only by e-mail and at least for one design or project management team member per project. Only one answer per project was requested.

3.3. Survey structure

The survey was structured in 4 different parts to gather relevant information to our research questions.

The first part aimed to gather basic project information, to help us understand the projects and respondents profiles, like project name, localisation, project status and the respondent position, with multiple choices and short open questions.

The second part aimed to gather information on the realisation of ecological diagnostics on the project design process. Through multiple-choice questions, we inquired respondents if an ecological diagnostic was done or not, by whom, in which project design step and how the diagnostic informed the design process. These questions were developed to gather answers related to the diagnostic practice (our research question n°2).

The third section aimed to gather information on different sustainable urban strategies mobilised by projects that could potentially contribute to the production of ecosystem services and mutually beneficial positive impacts for society and ecosystems (answering our research question n°1). We used a taxonomy of 42 different urban strategies covering different aspects of environmental sustainability in neighbourhoods (Table 1). This taxonomy was adapted from previous work on this topic, developed through a case study approach of six innovative and regenerative urban projects (see Blanco et al. 2021). These 42 strategies are organised in a hierarchical structure with four dimensions (energy flows, material flows, abiotic ecosystem structure, biotic ecosystem structure) and thirteen topics (Electricity, Heat and Light, Water Resources, Building materials, Carbon, Food, Chemical products, Waste, Water bodies, Soil, Air, Flora and Fauna). Respondents were questioned if the project used these strategies and had only binary options (yes or no).

The fourth section interrogated design teams regarding the barriers and needs of tools to implement these urban strategies to explore our research questions n°3 and n°4. Regarding the barriers, respondents evaluated ten different affirmations stating possible barriers. Regarding the needs in terms of tools, respondents evaluate seven other affirmations stating possible tools. We used a Likert scale structure with five options from "Strongly Agree" to "Strongly Disagree" for both topics.

Finally, the survey had two open fields where respondents could add any extra desired information and feedback. The survey is presented in the supplemental files.

3.4. Survey data analysis

The data was analysed using descriptive statistical analysis on Microsoft Office Excel 365, using functions as total count, frequency, quartiles and mode.

We also realised a t-test to verify the hypothesis that projects in which the ecological diagnostic deeply informed the design process had a higher average of different strategies used than the rest of the sample. The t-test was applied to compare the average number of different strategies used between projects that had a diagnostic that deeply informed the design and the remaining projects (no diagnostic, diagnostic that did not deeply inform the project or not sure how it informed).

To analyse the frequency of observation of each of the 42 proposed strategies, we created groups of strategies through quartile analyses. The quartiles were defined on Microsoft Office Excel 365 using the "quartile - inclusive" function.

4. Results

From the 362 invited projects, we obtained 73 complete answers. This sample represents 20.2% of the target population, and it represents a confidence level of 95% and a margin of error of ±10.3%.

In our sample, 50.7% (n=37) of the projects are in America (North, Central and South), 39.7% (n=29) are in Europe, and 9.6% (n=7) are in Asia, Africa and Australia. Most projects are already built, representing 58.9% (n=43), followed by projects still under construction counting for 38.4% (n= 28) and 2,7% (n=2) did not yet entered on the construction phase.

Respondents mainly were design team members (architects, urban designers and landscape architects), counting for 65.8% (n=48) of the answers. Other 26.0% (n=19) of the answers came from project owner/ management teams. Finally, 4.1% (n=3) came from environmental consulting teams, and the other 4.1% (n=3) came from other project stakeholders as builders and city regulators.

LEED-ND and the French EcoQuartier Framework (phase 3 or 4) are the most represented labels in our sample, accounting for 89.1% of the answers (n=65). BREEAM Communities, DGNB Communities and Green Star Communities account for the remaining 11,3% of the sample (n=8) (Table 2).

4.1. Ecological diagnostic

We identified that 54.8% (n=40) of the sample did an ecological

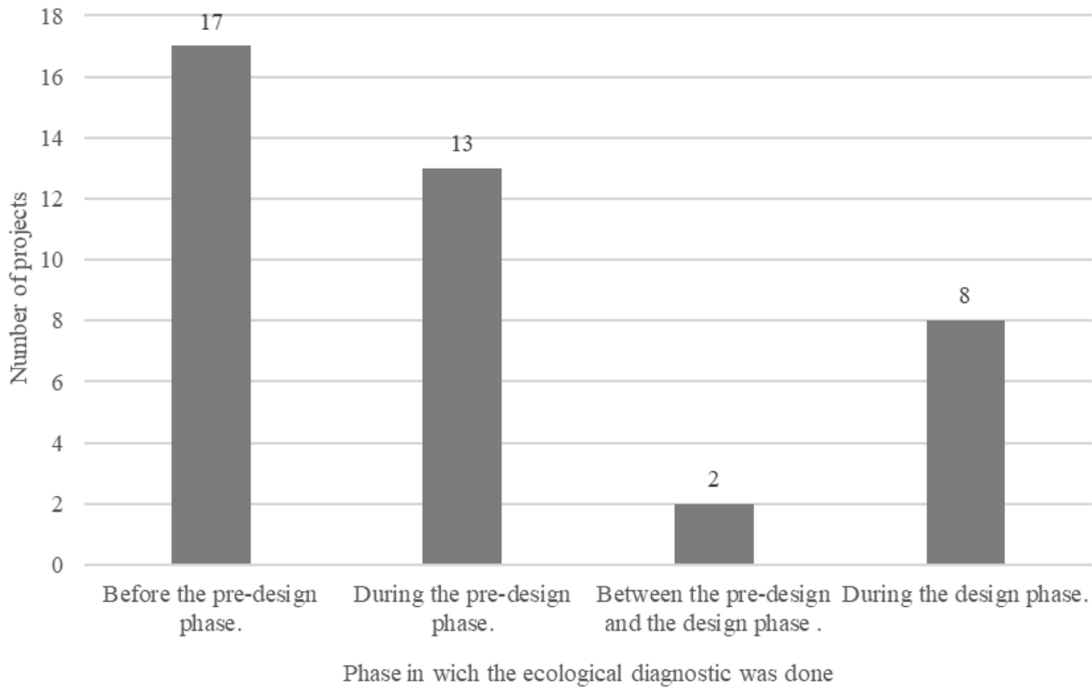

Fig. 1. Specific moment of the ecological diagnostic on the urban design process.

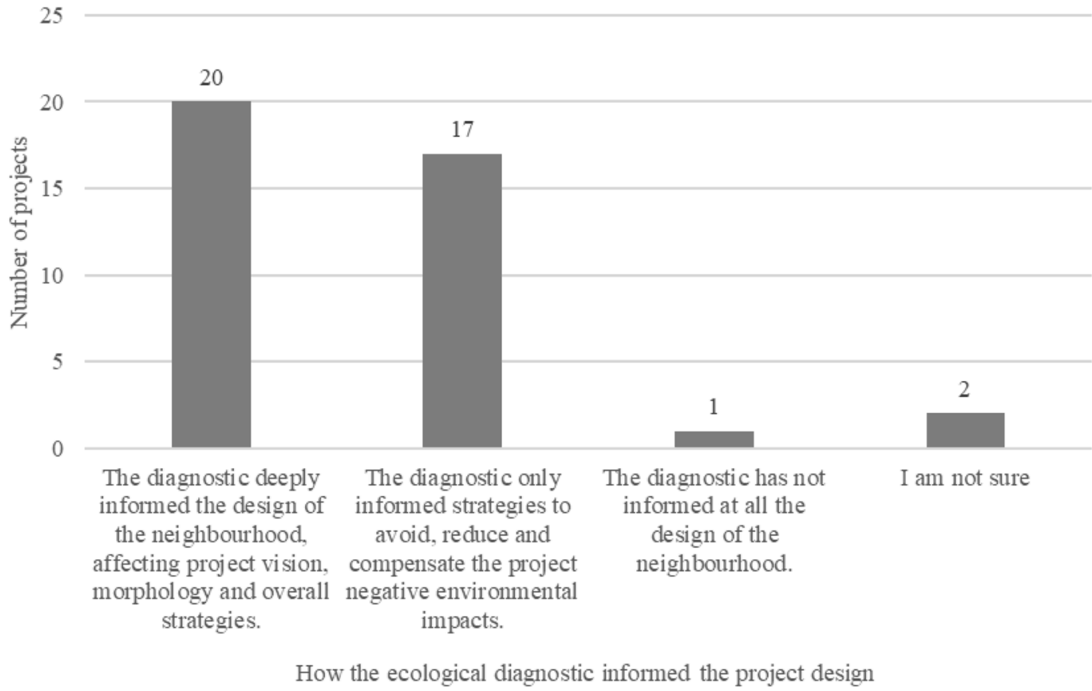

Fig. 2. Realisation and impact of the ecological diagnostic on the sample.

diagnostic to inform the project design. The remaining 45.2% (n=33) declared that an ecological diagnostic was not done or that they were not aware of it.

Among those who realised an ecological diagnostic, 65.0% (n=26) were done by specialised teams. The design team members did the diagnostic themselves only in 35.0% (n=13) of the cases.

Respondents also indicated that the diagnostic had been mostly done before a formal design phase (n=32, 80.0%). The remaining projects that did a diagnostic indicated that it was done simultaneously to the project design (n=8, 20.0%) (Fig. 1).

Among the projects that did a diagnostic (n=40), 50.0% of them (n=20, 27.4% of the sample) declared that they used the diagnostic to deeply inform the neighbourhood's design, affecting the project vision, morphology and overall strategies. Other 42.5% indicated that the diagnostic only informed strategies to avoid, reduce and compensate the project negative environmental impacts (n=17, 23.3% of the sample).

Table 3
Frequency of observation of each strategy in the sample and their quartile

Dimension	Strategies	n	Frequency (%)	Quartile
Energy flows	Uses and/or produces renewable energy	45	62%	3
	Has solutions to reduce the energy consumption in the neighbourhood	64	88%	4
	Has a local energy storage infrastructure	16	22%	1
	It was designed to optimise the solar input on blocks and buildings	46	63%	3
	Has solutions to share heat and energy between blocks and buildings	24	33%	1
	Minimises light and noise impacts	55	75%	4
Material flows	Reduces the total water consumption in the neighbourhood	43	59%	3
	Manages rainwater locally (reuse, infiltration, evaporation…)	67	92%	4
	Manages wastewater/greywater locally	24	33%	1
	Uses demolition, salvaged and recycled materials for building construction	38	52%	2
	Retrofitted existing buildings and infrastructures	35	48%	2
	Prioritises the use of building materials with low impact on human and ecosystem health	46	63%	3
	Sourced building materials locally	45	62%	3
	It was designed to reduce the need for building materials	31	42%	2
	It was designed to be adaptable, retrofitted, reused and/or deconstructed	27	37%	2
	Sought embodied carbon neutrality	13	18%	1
	Sequestered/compensated carbon emissions from use phase	8	11%	1
	The urban form was designed to reduce carbon emissions (high density, mixed-use…)	61	84%	4
	Has sustainable urban mobility strategies to reduce carbon emissions	61	84%	4
	Produces food locally	22	30%	1
	Restricts the use of phytosanitary products on its management	25	34%	2
	Manages organic waste locally	23	32%	1
	Recycles and sustainably manages domestic waste	46	63%	3
	Has solutions to reduce the local waste production	29	40%	2
Abiotic Structure	Restored water bodies/wet ecosystems	23	32%	1
	Limited the development over aquatic ecosystems/wet zones	40	55%	3
	Avoided soil sealing/unsealed soil	48	66%	3
	Avoided topography changes	51	70%	4
	Limited the development over natural, healthy or sensible areas (as greenlands, farmlands, flood areas, special interest areas...)	56	77%	4
	Compensated the urbanised area protecting other natural areas	36	49%	2
	Has solutions to improve the soil quality and fertility	28	38%	2
	Has solutions to improve the neighbourhood air quality	38	52%	2
Biotic structure	Has solutions to increase the amount and diversity of vegetated spaces	57	78%	4
	Connects to the local ecological network	48	66%	3
	Uses complex and site-appropriated vegetation schemes	50	68%	4
	Reintroduces indigenous flora species	53	73%	4
	Manages invasive flora species	44	60%	3
	Provides natural habitat diversity to host indigenous species	44	60%	3
	Reintroduces indigenous fauna species	13	18%	1
	Design artificial abiotic habitat structures for fauna	18	25%	1
	Avoid the fragmentation of exiting natural habitat	36	49%	2
	Manages invasive fauna species	20	27%	1

n: number of observations;
Frequency: % of observations in the sample (from a total of 73 projects)
Quartiles: Observed in (1) 0-24 projects; (2) 25-39 projects; (3) 40-46 projects; (4) 47-73 projects

Finally, 6.5% (n=3, 4.1% of the sample) indicated that the diagnostic did not inform the design process or were unsure how it informed the design (Fig. 2). As presented in the following section, we found that the extent that the diagnostic informed the project design affects the average number of different strategies used in projects.

4.2. Urban strategies

We observed an average of 22 strategies used to contribute to the production of urban ecosystem services per project in the sample, of 42 possible strategies presented in our survey. The minimum observed in a project was 7 strategies, and the maximum was 41 strategies.

When comparing projects that used the diagnostic to deeply inform the project design with the other projects, we noticed a higher average of different strategies on the first ones. Projects that used the diagnostic to deeply inform project design had an average of 25 different strategies. The remaining projects had an average of 20 strategies. A t-test confirmed the hypothesis that using diagnostic to deeply inform the project impacted the overall quantity of strategies in a project, increasing the average, with a p-value of 0.008.

The least observed strategy from the proposed taxonomy was "Sequestered/compensated carbon emissions from use phase", with only 8 observations. On the contrary, the most observed strategy was "Manages rainwater locally", counting 67 observations Table 3. presents the frequency of observations of each strategy and their distribution in four quartiles, according to this frequency. Quartiles allow us to organise the data and create four groups based on the distribution of observations for each strategy. Quartile 4 represents the strategies that have been more observed in the sample, counting with ten different strategies. Quartile 1 represents the less observed strategies, counting with twelve different strategies (Table 3).

4.3. Barriers

Project teams agree that the main barriers to implementing the above-listed strategies to the production of urban ecosystems services are the project financial viability and external governance issues (both with more than 50% of agreement). Respondents disagree that technical knowledge and the design team mindset are barriers to implementing these solutions (with more than 50% disagreement) (Fig. 3 and Table 4).

4.4. Needs

Project teams agree that tools to assist the design process and help

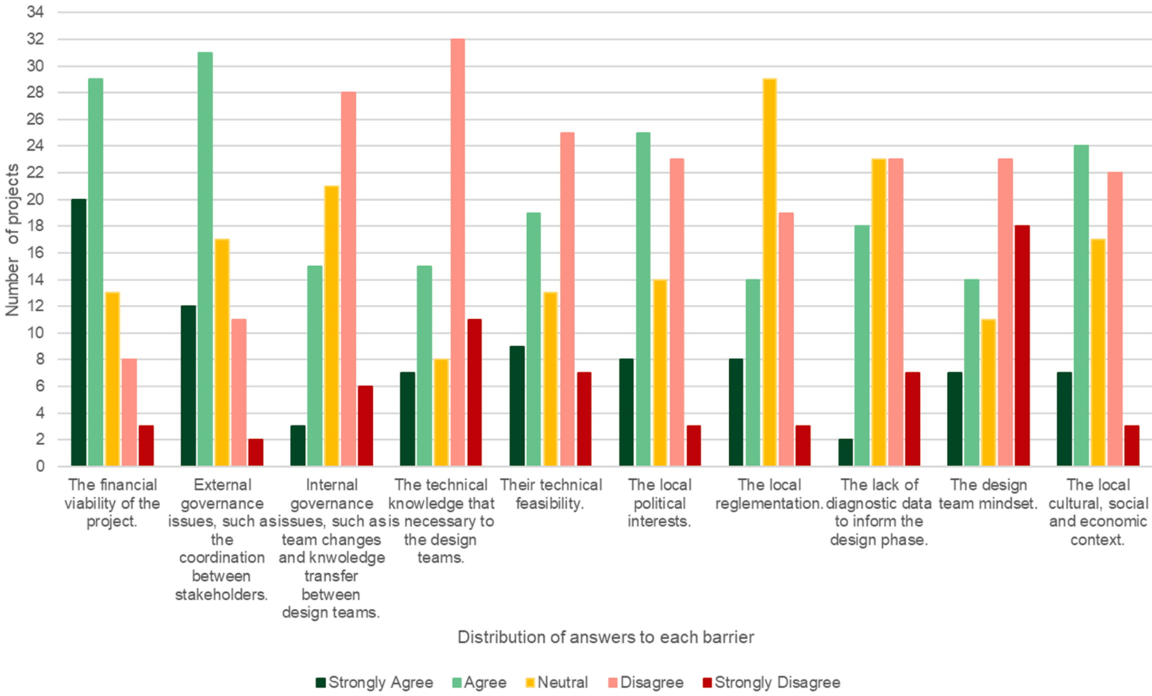

Fig. 3. Answers distribution regarding project barriers ("What are the main barriers to implementing mentioned strategies?").

Table 4
Main trends in the answer regarding barriers

What are the main barriers to implementing mentioned strategies?	Mode	% Strongly Agree/Agree	%Strongly Disagree/ Disagree
The financial viability of the project.	Agree	67,1%	15,1%
External governance issues, such as the coordination between stakeholders.	Agree	58,9%	17,8%
Internal governance issues, such as team changes and knowledge transfer between design teams.	Disagree	24,7%	46,6%
The technical knowledge that is necessary to the design teams.	Disagree	30,1%	58,9%
Their technical feasibility.	Disagree	38,4%	43,8%
The local political interests.	Agree	45,2%	35,6%
The local reglementation.	Neutral	30,1%	30,1%
The lack of diagnostic data to inform the design phase.	Neutral	27,4%	41,1%
The design team mindset.	Disagree	28,8%	56,2%
The local cultural, social and economic context.	Agree	42,5%	34,2%

the design and implementation of the above-listed strategies are necessary. The three answers that most presented positive feedback are the (1) need for self-assessment tools (tools that do not require a third-party evaluation), (2) tools with indicators that help identify improvement opportunities, and (3) tools to help define the project ambitions and objectives. Among the presented options, the "third part certifiable labels" are the only option that did not have an agreement between the respondents, with a scattered distribution and a "neutral" mode in the sample (Fig. 4 and table 5).

5. Discussion

5.1. Contradiction on the practice of ecological diagnostics

In a sample composed only of certified sustainable neighbourhoods, almost half of the projects (45.2%, n= 33) declared they did not realise or were unaware of an ecological diagnostic. Still, among those who did a diagnostic, a large proportion declared not to use the diagnostic to deeply inform the project or not to use it at all. It means that only a quarter of the total sample (27.4%, n=20) systematically used the ecological information to support the design process.

Diagnostics are essential in urban design to raise the design team's awareness and create projects linked to the site's logic. The diagnostic process allows the design team to read the site ecological patterns, potentialities and needs. It helps anchor the urban projects to the site reality, using the local context and data to inform the selection of strategies and solutions that will compose the urban project (Clergeau, 2018; Hes & Du Plessis, 2014; Leach et al., 2019; Vecco, 2020). Furthermore, ecological diagnostics are common and present high value on sustainability's decision-making process, as on the Strategic Environmental Analysis protocol (UNECE, 2003).

Nevertheless, our findings show that ecological diagnostics does not have an established place in the sustainable neighbourhood design practice. This finding converges with Leach, Mulhall, Rogers, & Bryson (2019), which observed that urban diagnostics had been largely overlooked in research and practice as a tool of urban design. Considering the two frameworks more represented in our sample, we note a diversity on the topic of diagnostics. On LEED-ND we observe in general very few process recommendations, and no mention to any kind of diagnostics, while on EcoQuartier the first requirement of the framework highlights the need of diagnostics (social, ecological, territorial…) to create an informed and coherent urban project (Ministère de la Transition Écologique et Solidaire & Ministère de la Cohésion des territoires et des relations avec les collectivités territoriales, 2020).

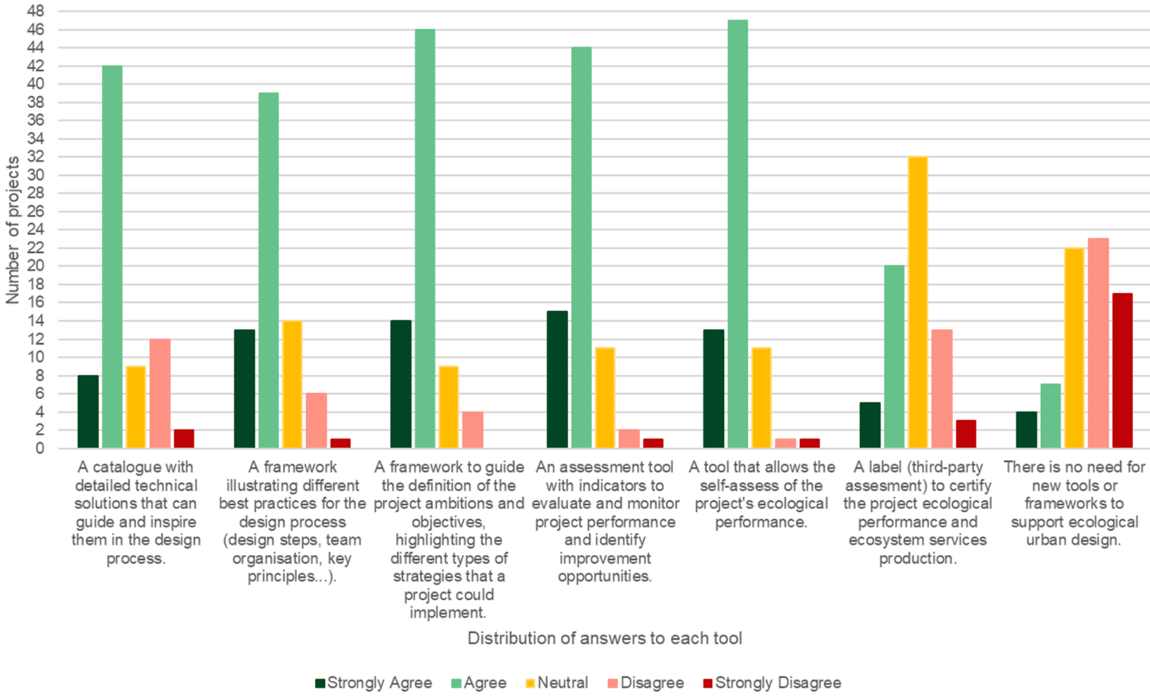

Fig. 4. Answers distribution regarding design tool needs ("Which design tools are needed to design sustainable urban projects that foster a better connection between built and natural spaces and the production of urban ecosystems services?).

Table 5
Main trends in the answer regarding design tool needs

Which design tools are needed to design sustainable urban projects that foster a better connection between built and natural spaces and the production of urban ecosystems services?	Mode	% Strongly Agree/Agree	%Strongly Disagree/ Disagree
A catalogue with detailed technical solutions that can guide and inspire them in the design process.	Agree	68,5%	19,2%
A framework illustrating different best practices for the design process (design steps, team organisation, key principles...).	Agree	71,2%	9,6%
A framework to guide the definition of the project ambitions and objectives, highlighting the different types of strategies that a project could implement.	Agree	82,2%	5,5%
An assessment tool with indicators to evaluate and monitor project performance and identify improvement opportunities.	Agree	80,8%	4,1%
A tool that allows the self-assess of the project's ecological performance.	Agree	82,2%	2,7%
A label (third-party assessment) to certify the project ecological performance and ecosystem services production.	Neutral	34,2%	21,9%
There is no need for new tools or frameworks to support ecological urban design.	Disagree	15,1%	54,8%

In the perspective of regenerative design, some of its frameworks, such as the LENSES Framework (J. M Plaut, Dunbar, Wackerman, & Hodgin, 2012.), the ecosystem-level biomimicry "ESA" approach (Pedersen Zari, 2018), and the Living Building Challenge 4.0 (International Living Future Institute, 2019), acknowledge this importance, requiring a formal diagnostic step before project design (International Living Future Institute, 2019; Pedersen Zari, 2012; J Plaut, Dunbar, Gotthelf, & Hes, 2016.). They highlight that it is impossible to do a regenerative project without understanding the site's climatic, ecological, and even socio-cultural context.

Moreover, we also observed that using an ecological diagnostic to deeply inform the project design impacts the diversity of strategies applied on the urban project, leading to a larger panel of strategies. These findings confirm the hypothesis proposed by Blanco et al. (2021) regarding the central role of diagnostics in designing sustainable and ecological urban projects.

However, our results also showed that 41.1% of the respondents disagree with a lack of diagnostic data to inform the design phase. This fact highlights a contradiction between theory and practice. Design teams do not seem to understand the importance of diagnostics to the urban process, not exploring its potential. This finding indicates a need for change in urban design frameworks to ensure and enforce the formalisation of a diagnostic before any project design (Clergeau, 2018; Leach et al., 2019).

5.2. *Choosing urban strategies: addressing the basics*

When analysing the frequency of use of the strategies, we can observe that some of them are much more represented than others. Strategies to manage some of the main urban energy and materials flows seem well established, while those linked to the ecosystem structure and circular approaches still are less observed.

When addressing energy flows, we found in the top quartile two strategies to reduce human pressure over ecosystems: reducing energy consumption and reducing light and noise impacts. Solutions to reduce the neighbourhood energy consumption were present in 88% of the sample. Nonetheless, strategies aiming a closed loop, as the use and production of renewable energies and the local energy storage were less observed, respectively, 62% and 22% of the sample. The focus on energy sobriety is explained by the importance of this question on environmental policies during the last decades and the maturity of most design frameworks and labels on energy questions, as is the case for LEED-ND (Grazieschi et al., 2020).

Regarding the material flows dimension, we observed in the top quartile three different strategies. At first, the local rainwater management, the most observed strategy in the sample, followed by two strategies aiming to design a less carbon-intensive neighbourhood (during use phase) through urban form and urban mobility strategies. Managing rainwater is also a topic with broad interest and public policies in the last decades, reflecting a good coverage by frameworks and projects, much due to the human dependencies and risks linked to water resources. Regarding the carbon reduction strategies, besides the increasing global awareness on the topic, it finds its operational roots in the New Urbanism and Transport Oriented Development movements, which positively impacted the design of less carbon-intensive urban areas and have been early adopted by NSA tools (Grazieschi et al., 2020). Nevertheless, at the bottom quartile of this dimension, we observe five strategies with innovative engagements linked to the circular economy concept and closed loops systems, they are: embodied carbon neutrality, sequestration of carbon emissions from the use phase, local food production, local organic waste management and local wastewater management.

Regarding the abiotic structure dimension, we observed two strategies to conserve the existing abiotic structure at the top quartile, both deeply affected by local urban regulations: conserve the topography and conserve the sensible green areas. At the bottom, we observe only the restoration of wet ecosystems. Four other strategies that could potentially contribute to higher mutual benefits for society and nature are in the second bottom quartile, observed in less than 55% of the projects, they are: to limit the development over existing wet ecosystems, the compensation of the urbanised area through the protection of other natural areas, to improve soil quality and fertility and to improve air quality. For example, the compensation of urbanised areas joins the net-zero urbanisation objective under discussion in Europe (No net land take, in the 2050 horizon) and France (Zéro Artificialisation Nette). This strategy synergises with several other strategies, such as biodiversity protection, soil quality, and water resources management (Fosse, Belaunde, Dégremont, & Grémillet, 2019).

Finally, concerning the biotic ecosystem structure dimension, we observed three strategies related to vegetation in the top quartile: the augmentation of quantity and quality of vegetation, the reintroduction of indigenous species, and the use of site-appropriate vegetation schemes. In the bottom quartile, we observed fauna reintroduction and management and habitat provisioning strategies, showing a dichotomy on how we address biodiversity on urban design. The vegetation seems to be easily addressed by designers, as they rely on it to answer the increasing demand for biodiversity in cities by urban dwellers (Clergeau, Jarjat, Raymond, & Ware, 2020) and local policies. This particular interest in vegetation strategies can be linked to several factors, such as a better perception of vegetation in urban projects than fauna, the influence of landscape designers on the team and the aesthetics of green solution, that helps make visible "green" engagements of the neighbourhoods (Louis-Lucas, 2021). These and other factors make vegetation be approached as one more "urban equipment" that must be placed in the project. Meanwhile, more complex thinking regarding habitat provision and fauna management strategies seems to be not yet understood and explored by designers.

These results show us that most of the certified sustainable urban projects are still addressing basic points, keeping an "impact reduction" and "anthropocentric" perspective, and not yet focusing on the production of mutual benefits from urban projects (Blanco, Pedersen Zari, et al., 2021; Cole, 2012) or exploring the potential of innovative urban strategies. The anthropocentric perspective is highlighted by the predominance of strategies linked to basic human needs and the viability of urbanisation, such as reducing energy consumption, rainwater management, and vegetation (usually also linked to water management, heat island controls, and aesthetical purposes). This trend reflects a heritage from urban metabolism approaches, addressing primarily energy and water flows (Danneels, 2018; Golubiewski, 2012; Inostroza, 2018; Thomson & Newman, 2018). Although these strategies are of significant importance to contemporary urban challenges and the viability of urban lifestyles in the context of climate change and ecological crisis (and they indeed produce some ecosystem services), several strategies with a higher potential of positive contribution to society and ecosystems remain largely unexplored. This is the case for those related to embodied carbon neutrality, building materials and urban inputs circularity, fauna management and habitat provision for biodiversity and the compensation of urbanised areas through ecological restoration or protection of other equivalent areas (Pedersen Zari & Hecht, 2020).

These findings validate two hypotheses drawn by Blanco et al. (2021) on a case study. After analysing six international ecological urban projects, the authors found that the projects "had a focus on reducing human pressures over the ecosystems instead of a proactive approach to regenerate ecosystem structures" and that they "primarily address energy and materials flows and tend to give lesser importance to ecosystem biophysical structure" (Blanco et al., 2022).

Finally, in the perspective of ecosystem services production, it is important to highlight the central role that the state of abiotic and biotic ecosystem structures plays (Kandziora, Burkhard, & Müller, 2013; Potschin et al., 2018). To enhance the production of urban ecosystem services, it is essential to give more place to strategies that regenerate the health of abiotic and biotic ecosystem structures, associating them to the more conventional strategies, like those managing flows and reducing impacts over these structures (Puppim de Oliveira et al., 2011).

5.3. Financial viability and stakeholder's coordination: the main declared barriers

Respondents highlighted that the main barriers to implementing these strategies are the governance and coordination between project stakeholders and the project financial viability. The technical aspects of the urban design process, as knowledge about the context, technical feasibility of solutions, and the design team mindset, were less pointed as barriers.

These results converge with previous works on impediments and barriers of sustainable development strategies as those from Malekpour, Brown, de Haan, & Wong (2017), which studied a case of water infrastructure for sustainable development and highlighted economic and institutional barriers. These authors also enforced the need of strategic diagnostic and planning to prepare project teams to deal with these systemic problems on project implementation, reducing project risks.

Stakeholders' governance on sustainable urban projects is a subject of extensive research and, indeed, fundamental in their success due to many involved parts (Carmona, 2016; White, 2016). Community participation is an interesting and debated solution to address governance issues and has been highlighted as one pilar of regenerative urban projects (Blanco, Raskin, et al., 2021). However, it still struggles to be a significant component of the urban design process, often reduced to consultative or manipulative approaches on late design phases that do not really legitimate the stakeholders' voices (Jones, 2003). Innovative participatory methods hold opportunities in the field. One example is the Paddock neighbourhood project (Castlemaine, Australia), in which the design team used participative ecological diagnostics of the project site (Blanco et al., 2022) to gather site data and mobilize citizens.

Regarding finance viability, in the context of market-based urban development, projects must seek an economic and financial equilibrium and integrating sustainable strategies can be perceived as an additional cost. For instance, research on nature-based solutions explores new implementation models for these strategies, covering financial mechanisms (Jeuken, Breukers, Elie, & Rugani, 2020). Nevertheless, further research is still fundamental to foster regenerative projects. A clue is the valuation of immaterial benefits created for society and nature by these projects and the payment for the produced ecosystems services (Bellver-Domingo, Hernández-Sancho, & Molinos-Senante, 2016), a mechanism very little explored at this scale. A remarkable example at the building scale is the Bullit Center, in Seattle, USA, a regenerative building certified LBC. Through its solutions over the project lifetime, researchers estimate that the benefits for society produced in the form of ecosystem services are more than eighteen million dollars.

5.4. Tool needs

Our results confirmed the demand for new tools to help project teams to design neighbourhoods mutually beneficial for society and ecosystems. Cole et al. (2012) argue that existing frameworks and labels deals with ecosystems from a mechanical perspective, and Stevens (2016) highlights that urban design needs methodological disruption after half a century without significant changes in the practice. New tools could help design teams better understand and navigate the complexity of urban socio-ecological systems.

Our respondents agree with these arguments, highlighting that technical feasibility is not a barrier, also showing higher rejections for tools with a technical background, as technical solutions catalogues. Nevertheless, respondents seem to be eager for flexible tools, as those with indicators and those that can be used directly by them during the design to help them make choices, understand project lacks, and evaluate project performance.

From practical perspectives, these research results could help to enrich existing and established NSA frameworks. These results could help them fill gaps and foster more strategies to directly address the ecosystem structure (through fauna or soil management) and promote circularity, enhancing the potential production of ecosystem services. Another opportunity is to enrich/promote novel urban design frameworks and tools, as the one proposed by Pedersen Zari and Hecht (2020), presenting 160 different strategies.

5.5. Limitations

Although the results from this research are novel and unique, they have limitations that are important to acknowledge. At first, we discuss sustainability and regenerative design only considering the environmental and ecological aspects. Social and economic aspects are essential in sustainable and regenerative neighbourhood design, but we were only interested in these projects' ecological and environmental outcomes in this research.

Concerning the frequency of the observed strategies, the prominent presence of LEED-ND and EcoQuartier answers in our sample can create bias in the results. Our results relate more to American and European context and policies on urban design and much less to Asian, African and Oceanian realities. Further research could fulfil these gaps, allowing future comparations based on project realities.

Another limitation is related to the research design itself. Our objective was to create a statically representative sample of certified urban neighbourhoods using the most common NSA frameworks. We relied on a short self-reporting survey to achieve this, enhancing participation. This way, consistency problems in the interpretation of the questions can interfere with the results. Nevertheless, our results remain statistically valid considering the margin of error and are a novel approach in the field. Moreover, further research could complement this work, using different research methods, such as interviews, to detail and explore the inner links between strategies selection, barriers, tools and diagnostics.

6. Conclusions

Through a novel approach, inquiring international certified neighbourhoods through a survey, we observed that urban projects still have a large margin of improvement to move towards the operationalisation of regenerative design and the production of urban ecosystem services.

From a technical perspective, projects rely primarily on strategies to address fundamental urban challenges, like energy and materials flow (reducing consumption and emissions) and vegetation (enhancing green coverage). With high implementation rates, these strategies tend to differentiate no longer urban projects but to become the rule in sustainable urban design. Therefore, it is time to move forward and explore and implement less conventional strategies that hold potential for ecosystem services production, like those related to a circular economy, closed systems, soil quality, fauna, and habitat management. Still, the most observed strategies focus on reducing human pressures over ecosystems. However, it is important to enlarge the panel, combining these strategies with those focusing on regenerating ecosystems' abiotic and biotic state, as promoted by Nature-Based Solutions.

Regarding our second research question, we argue that diagnostics (preferably integrated socio-ecological ones) are key to urban design and should be systematically integrated into the urban design process. Our results show a lack in this practice, with marginal integration of diagnostics on the design process. Diagnostics could help urban designers prioritise which strategies are relevant regarding the site reality, local public policies, financial constraints, and societal demand. This approach could enhance mutual benefits for society and nature with the same capital investment, improving the cost-benefit ratio of the projects.

In terms of barriers, governance arrangements and financial viability are central challenges. Integrating governance assessment and management practices to urban project design and engaging in a participatory design process seems to be improvement opportunities in the field. Nevertheless, exploring these barriers in sustainable and regenerative design seems crucial to propose levers to the practice.

Finally, in terms of tools, designing teams declared the need for a tool or urban design framework that organises the design process, helping project teams prioritise their strategies and evaluate the project performance in terms of ecosystems services with indicators. We argue that one quick-win opportunity is to improve established NSA frameworks, integrating novel strategies and an ecosystem services production perspective. Still, novel frameworks and urban design decision-making tools based on these results could be an essential asset to operationalise regenerative design engagements at the neighbourhood scale.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.103784.

Appendix A. List of invited projects

Table A1

Table A1
List of invited projects (in bold those that answered the survey)

#	Project Name	Label	Country
1	Eastside III	LEED-ND	United States
2	Miami Worldcenter	LEED-ND	United States
3	Taikang Community Shen Garden	LEED-ND	China
4	HARUMI FLAG	LEED-ND	Japan
5	NOI Techpark Suedtirol / Alto Adige	LEED-ND	Italy
6	PJ Sentral Garden City	LEED-ND	Malaysia
7	Oriental Bund Foshan	LEED-ND	China
8	North First Campus	LEED-ND	United States
9	Northwest Gardens	LEED-ND	United States
10	PHS District Neighborhood - The Presidio	LEED-ND	United States
11	The Navy Yard at Noisette	LEED-ND	United States
12	Twinbrook Station	LEED-ND	United States
13	Mueller	LEED-ND	United States
14	Aspen Club Living	LEED-ND	United States
15	Dockside Green	LEED-ND	Canada
16	Reston Heights	LEED-ND	United States
17	GARRISON CROSSING	LEED-ND	Canada
18	Good	LEED-ND	United States
19	Harbor Point	LEED-ND	United States
20	Beijing Olympic Village	LEED-ND	China
21	Southeast False Creek Neighbourhood	LEED-ND	Canada
22	Habitat for Humanity East Bay Edes 'B'	LEED-ND	United States
23	Melrose Commons	LEED-ND	United States
24	Edgewater	LEED-ND	United States
25	Whistler Crossing	LEED-ND	United States
26	Constitution Square Phase I	LEED-ND	United States
27	The Gulch	LEED-ND	United States
28	Downtown Doral	LEED-ND	United States
29	Delaware Addition	LEED-ND	United States
30	East 54	LEED-ND	United States
31	Quarry Falls/Civita	LEED-ND	United States
32	Jinshan Project	LEED-ND	China
33	Renaissance Place at Grand	LEED-ND	United States
34	Ever Vail	LEED-ND	United States
35	PARQUE DA CIDADE	LEED-ND	Brazil
36	South Sloans Lake	LEED-ND	United States
37	OneC1TY	LEED-ND	United States
38	Rebecca Street	LEED-ND	Canada
39	CHENGDU DACI MIXED USE COMPLEX	LEED-ND	China
40	ILHA PURA	LEED-ND	Brazil
41	LES BASSINS DU NOUVEAU HAVRE DE MONTREAL	LEED-ND	Canada
42	Hudson Yards - Eastern Yard	LEED-ND	United States
43	Shanghai EXPO UBPA Development	LEED-ND	China
44	Regent Square	LEED-ND	United States
45	WEST BUND MEDIA PORT	LEED-ND	China
46	Junhao Central park plaza	LEED-ND	China
47	QING TANG HOMELAND	LEED-ND	China
48	Pier 70	LEED-ND	United States
49	China Merchants Central Times	LEED-ND	China
50	City Point	LEED-ND	Romania
51	Monzen District Plan	LEED-ND	Japan
52	Foshan Lingnan Tiandi Development	LEED-ND	China
53	KLIFD	LEED-ND	Malaysia
54	Beijing COFCO Hou Shayu Development	LEED-ND	China
55	Jordan Downs	LEED-ND	United States
56	Preston Meadows	LEED-ND	Canada
57	The Village at Griesbach, Stage 8	LEED-ND	Canada

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Table A1 (*continued*)

#	Project Name	Label	Country
58	Crystal City Plan	LEED-ND	United States
59	360 State Street	LEED-ND	United States
60	Cornfields/Arroyo Seco Specific Plan	LEED-ND	United States
61	Midtown Crossing at Turner Park	LEED-ND	United States
62	The Brewery, the former Pabst Brewery	LEED-ND	United States
63	The Waterfront District	LEED-ND	United States
64	Technopole Angus	LEED-ND	Canada
65	Founder's Square	LEED-ND	United States
66	City of Tucson and Gadsden Comp. PPP	LEED-ND	United States
67	Uptown at Falls Park	LEED-ND	United States
68	Depot Walk	LEED-ND	United States
69	Washington Village (fmrly Cedar Commons)	LEED-ND	United States
70	Gold Time Ecological Bay	LEED-ND	China
71	Ward Village	LEED-ND	United States
72	Westlawn Revitalization	LEED-ND	United States
73	Palas Iasi	LEED-ND	Romania
74	Lathrop Homes	LEED-ND	United States
75	Bukit Bintang City Centre	LEED-ND	Malaysia
76	DONG FINANCIAL CITY	LEED-ND	China
77	Beijing CBD Core Zone	LEED-ND	China
78	Brickell City Centre	LEED-ND	United States
79	9th and Berks Street TOD	LEED-ND	United States
80	Lansdowne Park Redevelopment	LEED-ND	Canada
81	Filinvest City	LEED-ND	Philippines
82	The Almono Site	LEED-ND	United States
83	City Ridge	LEED-ND	United States
84	Southwest Waterfront	LEED-ND	United States
85	Chelsea Barracks	LEED-ND	United Kingdom
86	The Village at Market Creek	LEED-ND	United States
87	Harper Court	LEED-ND	United States
88	Minami-machida Grandberry Park	LEED-ND	Japan
89	MFCDC 20/21 Project	LEED-ND	United States
90	Seaport Square	LEED-ND	United States
91	Westfield UTC Revitalization	LEED-ND	United States
92	Strathearn Masterplan	LEED-ND	Canada
93	Barelas Homes	LEED-ND	United States
94	Horizon Uptown	LEED-ND	United States
95	Mosaic at Merrifield	LEED-ND	United States
96	Toronto Waterfront Area 1	LEED-ND	Canada
97	Tassafaronga Village	LEED-ND	United States
98	Silo City	LEED-ND	China
99	Union Park/Symphony Park	LEED-ND	United States
100	South Chicago LEED ND initiatve	LEED-ND	United States
101	Napa Pipe	LEED-ND	United States
102	Hunters View	LEED-ND	United States
103	1812 N Moore Street	LEED-ND	United States
104	Faubourg Boisbriand	LEED-ND	Canada
105	Global Green USA Holy Cross Project	LEED-ND	United States
106	Wuhan Tiandi Mixed Use Development	LEED-ND	China
107	Chongqing Tiandi Xincheng Development	LEED-ND	China
108	Park Avenue Redevelopment-Block 3	LEED-ND	United States
109	The Gateway to Nashville	LEED-ND	United States
110	Rebuild Potrero	LEED-ND	United States
111	Hercules Bayfront	LEED-ND	United States
112	Jackson Square Redevelopment Initiative	LEED-ND	United States
113	Excelsior & Grand	LEED-ND	United States
114	KL Metropolis	LEED-ND	Malaysia
115	The Renaissance	LEED-ND	United States
116	Futakotamagawahigashi Area Redevelopment	LEED-ND	Japan
117	BaoNeng City Garden	LEED-ND	China
118	SHANGHAI TAIPINGQIAO MASTER PLAN	LEED-ND	China
119	Dongguan International Trade Center	LEED-ND	China
120	The Hive	LEED-ND	United States
121	Double Cove	LEED-ND	Hong Kong, China
122	KAPSARC LEED ND	LEED-ND	Saudi Arabia
123	PiyalePasa Istanbul	LEED-ND	Turkey
124	Old Colony Public Housing Redevelopment	LEED-ND	United States
125	Teachers Village	LEED-ND	United States
126	West Village Residences LLC Neighborhood	LEED-ND	United States
127	Pike & Rose Neighborhood Development	LEED-ND	United States
128	Tsunashima Sustainable Smart Town	LEED-ND	Japan
129	Greystone Village	LEED-ND	Canada

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Table A1 (*continued*)

#	Project Name	Label	Country
130	MGM Springfield & Neighborhood	LEED-ND	United States
131	Kashiwa-no-ha Smart City	LEED-ND	Japan
132	Sunnydale Hope SF	LEED-ND	United States
133	UdeM - Campus Outremont	LEED-ND	Canada
134	Ville Verte Mohammed VI	LEED-ND	Morocco
135	City Creek Center	LEED-ND	United States
136	Sustainable Fellwood	LEED-ND	United States
137	METROGATE	LEED-ND	Canada
138	The New Stapleton Waterfront	LEED-ND	United States
139	Old Convention Center Site Redevelopment	LEED-ND	United States
140	Miraflores	LEED-ND	United States
141	Hoyt Yards	LEED-ND	United States
142	Sweetwater	LEED-ND	United States
143	Pointe Nord	LEED-ND	Canada
144	Decker Walk envirowHOMES	LEED-ND	United States
145	3910 Georgia Commons	LEED-ND	United States
146	South Waterfront Central District	LEED-ND	United States
147	Ladd Tower	LEED-ND	United States
148	Newpark Town Center	LEED-ND	United States
149	Township 9	LEED-ND	United States
150	Solea Condominiums	LEED-ND	United States
151	Helensview	LEED-ND	United States
152	Larimer Neighborhood	LEED-ND	United States
153	SEVINA PARK	LEED-ND	Philippines
154	Cafritz Property at Riverdale Park	LEED-ND	United States
155	The Shipyard/Candlestick Point	LEED-ND	United States
156	Former Civic Arena Site Redevelopment	LEED-ND	United States
157	University District	LEED-ND	Canada
158	Terrapin Row Development	LEED-ND	United States
159	Hassalo on Eighth	LEED-ND	United States
160	Sant Pau Recinte Modernista complex	LEED-ND	Spain
161	CFLD Fengtai Science Park	LEED-ND	China
162	Osaka University Minoh Campus	LEED-ND	Japan
163	Navy Green	LEED-ND	United States
164	SHANGHAI RUI HONG XIN CHENG	LEED-ND	China
165	Grandview Yard	LEED-ND	United States
166	CROSS GATE KANAZAWA	LEED-ND	Japan
167	DHA Mariposa Mixed-Use Development	LEED-ND	United States
168	Brightwalk	LEED-ND	United States
169	Miami Design District	LEED-ND	United States
170	Taylor Yard, Parcel C	LEED-ND	United States
171	Celadon	LEED-ND	United States
172	Parkside Mixed-Use Development	LEED-ND	United States
173	MacArthur BART Transit Village	LEED-ND	United States
174	Alliance Town Center	LEED-ND	United States
175	Meadow Ranch	LEED-ND	United States
176	Simpson Wisser Fort Shafter	LEED-ND	United States
177	Flats East Development	LEED-ND	United States
178	Syracuse Art, Life, & Tech. (SALT) Dist.	LEED-ND	United States
179	The Yards	LEED-ND	United States
180	Linked Hybrid	LEED-ND	China
181	Currie Barracks	LEED-ND	Canada
182	Town of Normal Uptown Renewal Project	LEED-ND	United States
183	THE ARBORS	LEED-ND	United States
184	Prairie Crossing - Station Village	LEED-ND	United States
185	Willets Point Redevelopment Project	LEED-ND	United States
186	South Lake Union Urban Center	LEED-ND	United States
187	Legends Park & University Place	LEED-ND	United States
188	Lincoln Park Coast Cultural District	LEED-ND	United States
189	St. Luke's Neighborhood Redevelopment	LEED-ND	United States
190	Emeryville Marketplace	LEED-ND	United States
191	Hawaii Regional Housing PPV Increment 2	LEED-ND	United States
192	West Town	LEED-ND	United States
193	Eliot Tower	LEED-ND	United States
194	Metro Green Residential	LEED-ND	United States
195	55 Laguna Street	LEED-ND	United States
196	Hitch Village	LEED-ND	United States
197	Shanghai Knowledge Innovation Community	LEED-ND	China
198	Panyu Nimble Plaza	LEED-ND	China
199	Alkimos beach	GreenStar Communities	Australia
200	Altrove	GreenStar Communities	Australia
201	Aura	GreenStar Communities	Australia
202	Aurora by Lendlease	GreenStar Communities	Australia
203	Barangaroo South	GreenStar Communities	Australia
204	Bernborough Ascot	GreenStar Communities	Australia
205	Bowden	GreenStar Communities	Australia

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Table A1 (*continued*)

#	Project Name	Label	Country
206	Brabham	GreenStar Communities	Australia
207	Brisgane Showgrounds	GreenStar Communities	Australia
208	Brookhaven	GreenStar Communities	Australia
209	Burwood Brickwoks	GreenStar Communities	Australia
210	Calderwood Valley	GreenStar Communities	Australia
211	Calleya	GreenStar Communities	Australia
212	Carseldine Village by EDQ	GreenStar Communities	Australia
213	Cloverton	GreenStar Communities	Australia
214	Curtin Master Plan	GreenStar Communities	Australia
215	Ecco Ripley	GreenStar Communities	Australia
216	Elliot Springs	GreenStar Communities	Australia
217	Fairwater	GreenStar Communities	Australia
218	Ginninderry	GreenStar Communities	Australia
219	Googong	GreenStar Communities	Australia
220	Greenwood	GreenStar Communities	Australia
221	Life Point Cook	GreenStar Communities	Australia
222	Lot fourteen	GreenStar Communities	Australia
223	Mambourin	GreenStar Communities	Australia
224	Melbourne Quarter	GreenStar Communities	Australia
225	Montario Quarter	GreenStar Communities	Australia
226	Newport	GreenStar Communities	Australia
227	Parklands	GreenStar Communities	Australia
228	Queen's Wharf Brisbane	GreenStar Communities	Australia
229	Springfield Rise	GreenStar Communities	Australia
230	Sydney Olympic Park	GreenStar Communities	Australia
231	The Grove	GreenStar Communities	Australia
232	Tonsley	GreenStar Communities	Australia
233	University of Melbourne Parkville Campus	GreenStar Communities	Australia
234	Victoria Harbour	GreenStar Communities	Australia
235	Waterlea	GreenStar Communities	Australia
236	West Village	GreenStar Communities	Australia
237	Willowdale	GreenStar Communities	Australia
238	Yarrabilba	GreenStar Communities	Australia
239	Aeschbachquartier Aarau	DGNB Communities	Switzerland
240	Melibocusstraße	DGNB Communities	Germany
241	Neu-Schöneberg	DGNB Communities	Germany
242	Sino-German Ecopark Qingdao District C2	DGNB Communities	China
243	Stadtquartier Cloche d'Or	DGNB Communities	Luxembourg
244	Milaneo	DGNB Communities	Germany
245	Le Quartier Central	DGNB Communities	Germany
246	Killesberghöhe	DGNB Communities	Germany
247	Sony Center	DGNB Communities	Germany
248	Bakkebo	DGNB Communities	Denmark
249	Skovbo	DGNB Communities	Denmark
250	CityQuartier DomAquarée	DGNB Communities	Germany
251	Stadtquartier ARBORIA	DGNB Communities	Luxembourg
252	Unter den Linden Hamburg (Ox-Park)	DGNB Communities	Germany
253	Europaviertel West	DGNB Communities	Germany
254	2020park IK/6	BREEAM Communities	Norway
255	Al Zahia Masterplan	BREEAM Communities	United Arab Emirates
256	Ashbourne Court	BREEAM Communities	United Kingdom
257	Boorley Green	BREEAM Communities	United Kingdom
258	BRE 100 Homes	BREEAM Communities	United Kingdom
259	Burakowska 14, Poland	BREEAM Communities	Poland
260	Crowdhill Green (Bloor Homes)	BREEAM Communities	United Kingdom
261	Crowdhill Green (Linden Homes)	BREEAM Communities	United Kingdom
262	Falstaff	BREEAM Communities	United Kingdom
263	Garitage park	BREEAM Communities	Bulgaria
264	Land at Moorgreen Hospital, West End, Southampton ('The Pavilions')	BREEAM Communities	United Kingdom
265	Masthusen (Kv Bilen 7)	BREEAM Communities	Sweden
266	Mon Tresor, Phase 1 Business Gateway	BREEAM Communities	Mauritius
267	Multi Residential Complex With Built-In Facilities And Auto Parking For Participants of Astana Expo - 2017 World Specialized Exhibition	BREEAM Communities	Kazakhstan
268	Norfolk Park	BREEAM Communities	United Kingdom
269	North Stoneham Park - Phase 1	BREEAM Communities	United Kingdom
270	Nové Nivy zone PCR	BREEAM Communities	Slovakia
271	Pylands Lane	BREEAM Communities	United Kingdom
272	Shirecliffe 1	BREEAM Communities	United Kingdom
273	Snowdrop House	BREEAM Communities	United Kingdom
274	Temple Farm	BREEAM Communities	United Kingdom
275	TIVOLI GREENCITY PCR	BREEAM Communities	Belgium
276	Urridaholt - North Phase 3 PCR	BREEAM Communities	Iceland
277	Worcester 6 Business Park PCR 04/12/2019	BREEAM Communities	United Kingdom
278	CLICHY-BATIGNOLLES	EcoQuartier (phase 3 or 4)	France
279	Ecoquartier des Bords de Seine	EcoQuartier (phase 3 or 4)	France

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Table A1 (*continued*)

#	Project Name	Label	Country
280	Grand Coudoux	EcoQuartier (phase 3 or 4)	France
281	Rénovation urbaine de Ravine Blanche	EcoQuartier (phase 3 or 4)	France
282	Projet de renouvellement urbain de la Duchère	EcoQuartier (phase 3 or 4)	France
283	PRU Les Mureaux	EcoQuartier (phase 3 or 4)	France
284	Coeur de bourg de La Rivière	EcoQuartier (phase 3 or 4)	France
285	Zac de Bonne	EcoQuartier (phase 3 or 4)	France
286	Les Rives du Bief	EcoQuartier (phase 3 or 4)	France
287	Bel Air	EcoQuartier (phase 3 or 4)	France
288	ECO-HAMEAU Le Champré	EcoQuartier (phase 3 or 4)	France
289	Quartier de la créativité et de la connaissance…	EcoQuartier (phase 3 or 4)	France
290	Les Akènes	EcoQuartier (phase 3 or 4)	France
291	Tréveneuc - Centre-bourg	EcoQuartier (phase 3 or 4)	France
292	Ecoquartier La Verderie	EcoQuartier (phase 3 or 4)	France
293	QUARTIER CAMILLE CLAUDEL	EcoQuartier (phase 3 or 4)	France
294	ÉcoQuartier de la Brasserie	EcoQuartier (phase 3 or 4)	France
295	Centre Bourg	EcoQuartier (phase 3 or 4)	France
296	ZAC Port Marianne - Rive gauche (tranche…	EcoQuartier (phase 3 or 4)	France
297	Ecoquartier Maragon Floralies	EcoQuartier (phase 3 or 4)	France
298	EcoQuartier de Dun	EcoQuartier (phase 3 or 4)	France
299	Quartier de l'église	EcoQuartier (phase 3 or 4)	France
300	Daval/Saulcy	EcoQuartier (phase 3 or 4)	France
301	Renouvellement urbain du quartier Arago	EcoQuartier (phase 3 or 4)	France
302	Le Grand Hameau	EcoQuartier (phase 3 or 4)	France
303	Eco-village des Noés	EcoQuartier (phase 3 or 4)	France
304	Ecoquartier du Hameau	EcoQuartier (phase 3 or 4)	France
305	Parc Marianne	EcoQuartier (phase 3 or 4)	France
306	Nouveau Mons	EcoQuartier (phase 3 or 4)	France
307	Ecoquartier Croix Rouge Pays de France	EcoQuartier (phase 3 or 4)	France
308	Les Grisettes	EcoQuartier (phase 3 or 4)	France
309	Blanche-Monier	EcoQuartier (phase 3 or 4)	France
310	Requalification du Centre-Ville de Changé	EcoQuartier (phase 3 or 4)	France
311	Docks de Saint-Ouen - Première phase opérationnelle	EcoQuartier (phase 3 or 4)	France
312	Clause-Bois Badeau	EcoQuartier (phase 3 or 4)	France
313	Quartier Fieschi - Tranche 1	EcoQuartier (phase 3 or 4)	France
314	Les Passerelles	EcoQuartier (phase 3 or 4)	France
315	Les Docks de Ris	EcoQuartier (phase 3 or 4)	France
316	Maille II	EcoQuartier (phase 3 or 4)	France
317	Seguin Rives de Seine	EcoQuartier (phase 3 or 4)	France
318	Parc des Calanques	EcoQuartier (phase 3 or 4)	France
319	IVRY_ZAC_DU_PLATEAU	EcoQuartier (phase 3 or 4)	France
320	Projet de rénovation urbaine Derrière-les-Murs	EcoQuartier (phase 3 or 4)	France
321	Quartier du Val Fourré	EcoQuartier (phase 3 or 4)	France
322	ZAC Dolet-Brossolette	EcoQuartier (phase 3 or 4)	France
323	Bel Air - Grands Pêchers	EcoQuartier (phase 3 or 4)	France
324	Quartier EUROPE	EcoQuartier (phase 3 or 4)	France
325	ZAC du Courtil Brécard	EcoQuartier (phase 3 or 4)	France
326	Quartier Eiffel	EcoQuartier (phase 3 or 4)	France
327	EcoQuartier Novaciéries	EcoQuartier (phase 3 or 4)	France
328	Lotissement Les Courtils	EcoQuartier (phase 3 or 4)	France
329	Ecoquartier du Champ de Foire - Îlot Connétable	EcoQuartier (phase 3 or 4)	France
330	Cannes Maria	EcoQuartier (phase 3 or 4)	France
331	Projet Horizons: Viala Est	EcoQuartier (phase 3 or 4)	France
332	Hoche-Université	EcoQuartier (phase 3 or 4)	France
333	Claude Bernard	EcoQuartier (phase 3 or 4)	France
334	Le Plateau des Capucins	EcoQuartier (phase 3 or 4)	France
335	Lotissement des Coccinelles	EcoQuartier (phase 3 or 4)	France
336	Écoquartier de Montévrain - Étape 3	EcoQuartier (phase 3 or 4)	France
337	ZAC Desjoyaux - Ecoquartier	EcoQuartier (phase 3 or 4)	France
338	La Barberie	EcoQuartier (phase 3 or 4)	France
339	ZAC Desjardins	EcoQuartier (phase 3 or 4)	France
340	éco-lotissement du Frêne	EcoQuartier (phase 3 or 4)	France
341	La ferme forgeronne	EcoQuartier (phase 3 or 4)	France
342	ZAC Biancamaria - tranche 1 et 2	EcoQuartier (phase 3 or 4)	France
343	Eco-quartier Hoche	EcoQuartier (phase 3 or 4)	France
344	Ecoquartier de l'Eau Vive - Tranche 1	EcoQuartier (phase 3 or 4)	France
345	BOUCICAUT	EcoQuartier (phase 3 or 4)	France
346	Ecoquartier des Arondes	EcoQuartier (phase 3 or 4)	France
347	Villedieu-Le Puits	EcoQuartier (phase 3 or 4)	France
348	Terre Sud	EcoQuartier (phase 3 or 4)	France
349	Ecoquartier Lefebvre	EcoQuartier (phase 3 or 4)	France
350	Bouchayer-Viallet	EcoQuartier (phase 3 or 4)	France
351	EcoQuartier Historique	EcoQuartier (phase 3 or 4)	France
352	ZAC des Perrières	EcoQuartier (phase 3 or 4)	France
353	Les Rives de la Haute Deûle	EcoQuartier (phase 3 or 4)	France
354	Écoquartier Les Résidences du Parc	EcoQuartier (phase 3 or 4)	France
355	Andromède	EcoQuartier (phase 3 or 4)	France

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Table A1 (*continued*)

#	Project Name	Label	Country
356	Vidailhan	EcoQuartier (phase 3 or 4)	France
357	Fréquel-Fontarabie	EcoQuartier (phase 3 or 4)	France
358	Luciline - Rives de Seine	EcoQuartier (phase 3 or 4)	France
359	Ecoquartier de Monconseil	EcoQuartier (phase 3 or 4)	France
360	Wolf-Wagner	EcoQuartier (phase 3 or 4)	France
361	Ginko - Berges du Lac	EcoQuartier (phase 3 or 4)	France
362	Coeur de Ville	EcoQuartier (phase 3 or 4)	France

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3.2 Indicators for regenerative neighbourhood design: an indicator set definition

Blanco, E., Raskin, K., & Clergeau, P. (Under review). Indicators for regenerative neighbourhood design: an indicator set definition.

Title: Indicators for regenerative neighbourhood design: an indicator set definition

Authors: Eduardo Blanco, Kalina Raskin, Philippe Clergeau

Abstract: Indicators are fundamental in promoting urban sustainability. They are key in public policies, regulations and green labels. Nevertheless, in the context of regenerative design, which aims to design urban projects with mutual net positive impacts on nature and society with holistic approaches, indicators have been pointed out as reductionists, being an undeveloped subject. However, their use could be a critical lever for mainstreaming regenerative design practices, mainly at larger urban scales like the neighbourhood. In this context, a recent study proposed a taxonomy of urban strategies that could contribute to the production of urban ecosystem services at the neighbourhood and be an operational regenerative design tool. Thus, this work was interested in selecting indicators that could assess these strategies implementation, being a proxy to the production of urban ecosystem services, configuring an operational tool. Relying on qualitative methods like RACER analysis and surveys, we analysed different established environmental urban sustainability indicators aiming to select a reduced set that stakeholders could quickly adopt in a regenerative neighbourhood design tool. As a result, we proposed an indicator set with 23 different indicators.

Keywords: sustainable neighbourhoods, ecosystem services, regenerative design, indicators**.**

1. Introduction

Indicators are fundamental in environmental management. They help understand socio-ecosystems' state, assess impacts, and adapt management strategies and responses (Niemeijer & de Groot, 2008). In the urban discipline, they are a critical tool in promoting sustainability. They are essential to translating political and strategical sustainability engagements to operational stakeholders and the urban design practice (Bastianoni, Coscieme, Caro, Marchettini, & Pulselli, 2019; Huang, Wu, & Yan, 2015). For instance, indicators are key elements in several sustainable urban design frameworks like LEED, BREEAM and EcoQuartier. They aim to help design teams propose projects with better sustainable performances and allow their assessment (Reith & Orova, 2015). Indicators also have a central role in public sustainable urban policies and regulations. They set objectives and minimum requirements for urban project performances (Carmona, 2017), contributing to reducing their negative environmental impacts.

The urban sustainability indicators have been the target of extensive research in the last decades. Some focal points have been the assessment of their strengths and lacks (Huang et al., 2015; Reith & Orova, 2015) and their balance covering the different sustainability aspects (Michalina, Mederly, Diefenbacher, & Held, 2021). Furthermore, several indicators frameworks have been proposed and validated in an effort to promote homogeneity and consistency in their use in assessing urban sustainability. Examples are the ISO 37120:2018, ISO 37122:2019 and ISO 37123:2019 norms, the Collection Methodology for Key Performance Indicators for Smart Sustainable Cities by the United 4 Smart and Sustainable Cities (ISO, 2018, 2019a, 2019b; U4SSC, 2017), and scientifical frameworks resulting from European research projects such as the Eklipse and the Nature4Cities projects (NATURE4CITIES, 2018; Raymond et al., 2017).

Nevertheless, in the context of regenerative design, an emerging urban design approach, indicators still require development (Gibbons, Pearthree, Cloutier, & Ehlenz, 2020). Regenerative design has the goal to move beyond impact reduction and the neutral performances of conventional sustainable urban approaches (Brown et al., 2018; Cole, 2012; Hes & Du Plessis, 2014). It aims to design urban projects with mutual net positive impacts on nature and society (Blanco, Raskin, & Clergeau, 2021).

With a systemic and holistic perspective, the regenerative design theories often criticise the use of indicators, pointing them as reductionists (Cole, 2012). Such critics lead to regenerative tools that remain perceived as too complex and non-operational (Clegg, 2012; Tainter, 2012). However, since indicators are essential in supporting decision-making and are usual for sustainable urban design, their use could be a critical lever for mainstreaming regenerative design practices (Bastianoni et al., 2019; Gibbons et al., 2020).

Indicator-based approaches such as the Living Building Challenge (LBC) certification program helped spread the regenerative design concept at the building scale. The LBC relies on twenty project imperatives and several indicators to assess project performances. Nevertheless, a lack of tools and studies remains for larger scales, such as at the neighbourhood level (Blanco et al., 2021; Reith & Brajković, 2021). Aiming to fill this gap, a design framework based on ecosystem-level biomimicry has been proposed (Pedersen Zari, 2015). The framework focuses on promoting and assessing the positive environmental impacts of regenerative projects using the notion of ecosystem services and ecosystem services indicators (Pedersen Zari, 2015).

Ecosystem services are the material and immaterial benefits society perceives from natural ecosystems (Millenium Ecosystem Assessment, 2005). The notion is already widely used in territorial and urban planning disciplines (Haase et al., 2014), counting different indicators and methods to assess its production (Harrison et al., 2018; Potschin et al., 2018). For instance, to estimate the trend in ecosystem services production we can get interested in assessing the anthropic pressures over ecosystems, the ecosystem state or even the responses by society to manage it (Kandziora, Burkhard, & Müller, 2013).

In this context, a recent study focused on the urban strategies used in sustainable neighbourhoods to contribute to the production of urban ecosystem services (Blanco, Raskin, & Clergeau, 2022). The authors established a taxonomy of forty-two strategies that could enhance the production of ecosystems services, creating positive impacts. They also analysed their different maturity levels on certified sustainable neighbourhood projects. This study highlighted that such taxonomy could be the first step toward a neighbourhood design tool and that selecting indicators to assess the strategies' implementation would constitute an essential step toward it (Blanco et al., 2022; Pedersen Zari & Hecht, 2020).

According to these bases, the present study was interested in selecting indicators that could assess these strategies implementation, being a proxy to the production of urban ecosystem services. We aim to select operational indicators that could be rapidly adopted in a regenerative design tool for the neighbourhood scale. To reach our objective, we will rely on existing and established urban sustainability indicators sets that will be analysed qualitatively.

2. Methods

We relied upon a four-step method based on literature review, qualitative RACER analysis and surveys. Figure 1 presents our methodological framework described in the following sections.

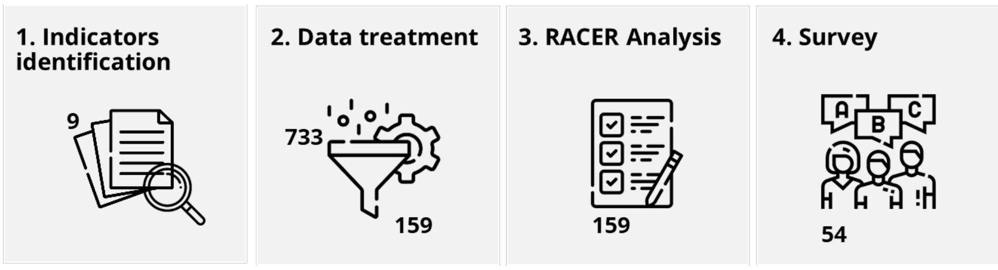

Figure 1 - Methodological framework

2.1. Indicators identification

To identify relevant sources of urban sustainability indicators, we did a scientific and grey literature review. In this review, we were interested in operational indicators sources with empirical orientation, previous validation, field application and penetration in urban sustainability assessments practice. This research was done using The Web of Knowledge and general web research engines.

We gave priority to indicators frameworks aggregating large sets of indicators, aiming to cover a wide diversity of indicators. Purely theoretical or experimental indicators sets were not taken into account. As we are interested in regenerative design practices, we also included the only established operational framework containing indicators on the sample, namely the Living Building Challenge 4.0.

Following this rationale nine different sources of urban indicators have been selected to compose the initial analytical corpus. Although not exhaustive, the sample is certainly extensive, containing more than 700 indicators. We created a Microsoft Excel spreadsheet database containing all the indicators identified on the selected source documents.

The selected sources were:

- Collection Methodology for Key Performance Indicators for Smart Sustainable Cities (U4SSC, 2017)
- Grid for assessing biodiversity in urban projects (in French) (Clergeau & Provendier, 2017);
- ISO 37120:2018 - Sustainable cities and communities — Indicators for city services and quality of life (ISO, 2018);
- ISO 37122:2019 - Sustainable cities and communities — Indicators for smart cities (ISO, 2019a);
- ISO 37123:2019 - Sustainable cities and communities — Indicators for resilient cities (ISO, 2019b);
- System of integrated multi-scale and multi-thematic performance indicators for the assessment of urban challenges and Nature Based Solutions (NATURE4CITIES, 2018);
- National framework for the assessment of "EcoQuartiers" (in French) (Ministère du logement et de l'habitat durable & Cerema Territoires et ville, 2016);
- Synthesis report on current datasets and their applicability of ecosystem services mapping and modelling (Banzhaf et al., 2020);
- The Living Building Challenge 4.0 (International Living Future Institute, 2019).

2.2. Data treatment:

As we started with a large set of urban sustainability indicators from aggregated sources, a data treatment step was necessary. The database had several social and economic sustainability indicators and duplicated indicators. As we are specifically interested in environmental indicators that can be a proxy for ecosystem services production, our first step was to analyze indicator by indicator and remove social or economic ones, since they are out of the scope of this research. Our second treatment step was to eliminate duplicated indicators among the remaining environmental-related indicators (inherent from working with aggregated sources).

Finally, to meet the objective of this work and create an operational indicator set that could assess the production of ecosystems services, we analyzed each indicator to check if they had causal relations with the 42 urban strategies identified as possible to enhance the production of ecosystem services by Blanco et al. (2022) (Appendix 1). In this analysis, the causal relations for each indicator were defined in four classes using the Pressure, State, Response (PSR) model (OCDE, 2001): 1) No direct causal relation, 2) Pressure relation: the indicator asses a pressure that impacts the provision of ecosystem services related to at least one of the strategies taxonomy, 3) State: the indicator asses the ecosystem state involved in the provision of ecosystem services related to at least one of the strategies taxonomy, 4) Response: the indicator asses management responses that that impacts the provision of ecosystem services related to at least one of the strategies taxonomy.

We also matched the indicators presenting causal relations with a specific primary strategy from the taxonomy proposed by Blanco et al. (2022). This exercise helped us identify strategies that were not covered by any indicators. The research team did a short bibliographic review and a brainstorming session to propose potential indicators to fill the identified gaps. This consolidated database followed to the next step of the analysis.

2.3. RACER analysis

We used RACER analysis (European Commission, 2021) to select a smaller set of operational and scientifically sound indicators. The RACER analysis evaluates indicators in five dimensions, using qualitative criteria: (1) Relevant (closely linked to the objectives to be reached, namely being relevant to assess the production of ecosystem services through the taxonomy of 42 strategies), (2) Accepted (by stakeholders and design teams); (3) Credible (for non-experts, unambiguous and easy to interpret), (4) Easy to monitor (feasible to monitor and collect data at low cost and effort); (5) Robust (against manipulation and error).

The RACER method allows evaluating indicators and identifying those relevant to our objective, scientifically sound and operational for field stakeholders. Furthermore, in its toolbox for better regulation, the European Commission preconises using the RACER framework to construct indicators sets for environmental and ecological topics (European Commission, 2021).

In this step, each indicator was evaluated on each of the five dimensions, attributing three possible notes: 1 – Criteria not fulfilled, 2 – Criteria partly fulfilled, 3 – Criteria completely fulfilled. The notations were finally added, giving a final note to the indicator, going from 5 to 15. The lead researcher did the RACER evaluation, and the research team validated it.

We selected the indicators with higher RACER scores to follow to the next step. Again, we assured complete coverage of the strategies taxonomy proposed by Blanco et al. (2022).

2.4. Survey to test the feasibility of the selected indicators

We realised an online survey with urban design stakeholders to evaluate the RACER selected indicators' operational feasibility. In the survey, we inquired about the operational feasibility of the indicators. Each indicator was evaluated using a 5-options Likert scale ("Very feasible", "Feasible", "Neutral", "Not feasible", "Not feasible at all"). Respondents also had the option to declare that they did not know how to evaluate the indicator ("I do not know").

The survey also presented one question regarding the interest and relevance of a design tool based on the proposed indicators for the neighbourhood scale. Finally, the survey had an open text field to gather feedback from stakeholders regarding the proposed indicators.

The survey was done in French and only diffused to French stakeholders. We made this choice to reduce cultural and contextual interferences in the results, as the feasibility is highly context-dependent and may reflect local practice and policies. The survey was diffused through urban design professional mailing lists, social networks, specialised professional websites, and the research team network (especially LinkedIn, Construction 21 website, Biomim'City Lab workgroup, Ceebios newsletter and geotamtam mailing list). The survey questionnaire is presented in Appendix 2.

The survey results were treated with descriptive statistics in Microsoft Excel, calculating the answers' frequency of observations, quartile distribution and mode for each indicator. We also used hypothesis tests (bilateral t-test) to verify that the respondents perceived indicators based on surface ratios as more operational and feasible than the others.

Finally, we used the survey results to select a smaller indicator set and adjust a few indicators, following the respondents' feedback. This allowed us to select a final sample of operational indicators that could be used on a design tool.

3. Results and discussion

3.1. Indicators identification and analysis.

On our corpus, composed of nine different documents, we identified an initial sample of 733 indicators (Appendix 3). After treating the data (removing not environmental related, duplicated indicators and those without causal relation to Blanco et al. (2022) taxonomy), we pre-selected 159 indicators that followed the analysis.

These 159 indicators were evaluated using the RACER method. The detailed RACER evaluation is presented in Appendix 4. Based on the RACER notes and using the taxonomy with the 42 strategies proposed by Blanco et al. (2022) as a selection grid, we selected a sample of 39 indicators to follow the analysis with the survey. At this step, we adapted a few indicators to match better the taxonomy of strategies (for instance, merging or splitting indicators). Table 1 presents the 39 selected indicators submitted to the survey, their sources, and index number to facilitate their identification in the RACER results presented in Appendix 4. This selection is composed of the indicators with the highest RACER note and cover the majority of strategies presented in the taxonomy proposed by Blanco et al. (2022)

Table 1 - Selected indicators following the RACER method and submitted to survey validation

#	Indicator	Source	RACER # (Appendix 4)
1	Renewable energy: The share of total annual energy consumption derived from renewable sources (non-combustion only) - (%).	ISO 37120:2018	1
2	Decentralised energy production: The share of total annual energy derived from decentralised or on-site production systems - (%).	ISO 37122:2019	4
3	Abiotic resource depletion - fossil fuels: The depletion of fossil energy resources promoted by the project - (calculated via life cycle assessment method, MJ equivalent).	Nature4Cities	8
4	Electricity consumption: The total annual consumption per capita - (kWh / year / capita)	U4SSC	11
5	High albedo surface: The share of the project area covered by high albedo materials (>0.75) - (%).	ISO 37123:2019	25
6	Water consumption: The daily water consumption per capita (L/day/capita).	ISO 37120:2018	31
7	Rainwater management: The proportion of annual stormwater managed at the site level (reused, infiltered, evapotranspired…) - (%).	Brainstorming	41
8	Pervious surface: The share of permeable surface in relation to the total project surface - (%).	ISO 37123:2019	39
9	Onsite wastewater management: The share of total annual wastewater generated that is managed on-site with low impact techniques - (%).	Living Building Challenge	55
10	Material Circulatory Indicator: The indicator measures the degree of circularity of a system, with a value from 0 to 1. It is calculated from the estimated amount of virgin, recycled and reused materials used in construction, the amount of waste generated at the end of the life cycle and a factor related to the project's usage rate.	Nature4Cities	56
11	Retrofitting rate: The share of the project's floor area targeted for retrofitting, redevelopment or rehabilitation of existing infrastructure- (%).	Brainstorming	63
12	Low-risk materials: The share (in mass) of building materials that avoid toxic chemicals listed in the RED list of the International Living Future Institute.	Living Building Challenge	60
13	Average distance from materials source: The weighted average (by mass) of the distance from the source of the building materials to the project site.	Brainstorming	63
14	Embodied carbon: The total embodied carbon balance in the construction, accounting for emissions (including energy consumed in construction and material production), sequestrations and offsets (tonnes eq. CO_2).	Brainstorming; REGREEN; Nature4Cities	66,68,69,70
15	Annual GHG balance: Annual GHG footprint (in project use phase), accounting for emissions, sequestration and offsets on a per capita basis - (tonnes CO_2 eq/inhabitant).	Brainstorming;Nature4Cities	72,73
16	Food production area: The share of the project surface dedicated to different urban agriculture solutions - (%).	REGREEN	79
17	Fertilisers and pesticides: The share of the project area managed under a zero pesticide, biocide and petrochemical fertiliser policy - (%).	Plante&Cité	80
18	Specific waste generation: The annual production of solid waste per capita (kg/year/capita).	Nature4Cities	96
19	Organic waste recovery: The share of total collected organic waste that is recovered (composting, methanisation...) - (%).	ISO 37120:2018	88

20	Local organic waste management: The share of organic waste collected and recovered on site (composting, anaerobic digestion...) - (%).	Brainstorming	81
21	Waste energetic recovery: The share of total collected waste that is recovered energetically - (%).	ISO 37122:2019	90
22	Rate of landfilling: The share of total annual waste collected that is landfilled - (%).	Nature4Cities	91
23	Rate of recycling: The share of total annual waste collected that is recycled - (%).	Nature4Cities	92
24	Protection and restoration of wet ecosystems: The share of project wetlands protected or targeted for ecological restoration - (%).	Brainstorming	100
25	Protection of sensitive terrestrial areas: The share of the project's terrestrial areas designated as protected - (%).	ISO 37120:2018	105
26	Restoration of terrestrial areas: The share of project land areas targeted for ecological restoration - (%).	ISO 37123:2019	111
27	Project area built on urbanised areas: The share of the project area built on brownfields and already urbanised areas - (%).	Brainstorming	110
28	Compensation of artificialisation: The share of the equivalent project area set aside for protection or restoration (outside the project site) in the form of compensation for artificialisation caused by the project - (%).	Living Building Challenge	112
29	Topography: The proportion of the project area that has undergone topography changes - (%).	Brainstorming	103
30	Soil restoration: The share of the project area targeted for restoration of soil structure or quality - (%).	Brainstorming	159
31	Captured air pollutants: Annual amount of pollutants captured by vegetation or other treatment techniques - (kg/ha/year)	Nature4Cities	126
32	Availability of natural areas: The area of green space per inhabitant - (m2/inhabitant).	Plante&Cité	132
33	Urban green space: The share of natural areas in the total project area - (%).	Nature4Cities	141
34	Ratio of native vegetation: The ratio of the number of native plant species to the total plant richness (total number of species) of the project site - (%).	Nature4Cities	144
35	Ratio of native vegetation: The ratio of the number of native fauna species to the total fauna richness (total number of species) of the project site - (%).	Nature4Cities	144
36	Biotope Area Factor: The amount of area available for nature and vegetation in relation to the total area under consideration, weighted by a specific coefficient for each type of cover, related to its potential for vegetation growth and hosting biodiversity.	Nature4Cities	146
37	Connectivity of green spaces (within the plot): Integral index of connectivity within the project area, calculated on the basis of the area of habitat plots and links to other paths, ranging from 0 to 1 (calculated on geographic information software or Graphab).	Nature4Cities	156
38	Connectivity of green spaces (outside the plot): Integral connectivity index within the project area, calculated on the basis of the area of habitat plots and links to other paths, ranging from 0 to 1 (calculated on geographic information software or Graphab).	Nature4Cities	156
39	Shannon Diversity Index of Habitats: Calculated on the basis of the presence and abundance of different biotope types in the project area. It indicates the complexity of the vegetation structure and the potential for biodiversity (ideally calculated on geographic information software).	Nature4Cities	145

3.2. **Survey results**

The survey obtained 54 answers, representing a sampling with 95% confidence and an error of ±13,4%. The respondents came from different operational and scientific backgrounds, as demonstrated in figure 2. Around 63% of the respondents (n=34) had roles directly related to the urban design process (urban design teams, consultancy firms, private and public urban project owners).

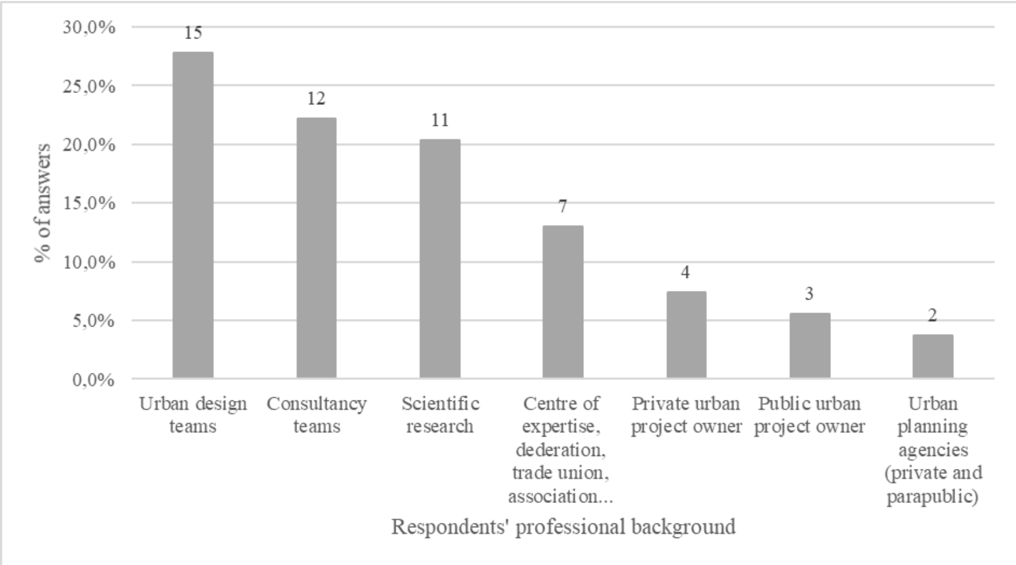

Figure 2 - Survey respondents' professional background

3.2.1. Indicators' operational feasibility

The results regarding the indicators' operational feasibility were organised in four classes: "Positive" (very feasible and feasible), "Neutral", "Negative" (Not feasible at all and not feasible) and "I do not know". Figure 3 presents the percentage distribution for these four classes for each indicator.

We observed that the indicators mainly were perceived as operational, with an average of positive responses of 65,5%. We noted that the top three indicators with positive responses regarding their operational feasibility were, respectively, (1) the pervious surface (96% of positive answers), (2) the food production area (93% of positive answers) and the (3) availability of natural areas (93% of positive answers).

The top three indicators with negative responses were, respectively, (1) the captured air pollutants (28% of negative answers), (2) the average distance from the materials source (20% of negative answers) and the (3) ratio of native fauna (15% of negative answers).

Finally, the top three indicators that presented a lack of awareness and understanding from the respondents were (1) the abiotic resource depletion – fossil fuels (43% of "I do not know" answers), the (2) Shannon diversity index of habitat (41% of "I do not know" answers) and the (3) captured air pollutants (31% of "I do not know" answers).

Figure 3 presents the perceived feasibility of the indicators in percentage for the four classes of answers. In order to gather insights from the results, we also classed the answers in quartiles (Table 3). Quartiles allow us to organise the data and create four groups based on the distribution of observations for each strategy. Quartile 4 represents the strategies that have been more observed within that class of answers, and Quartile 1 represents the less observed strategies in the category.

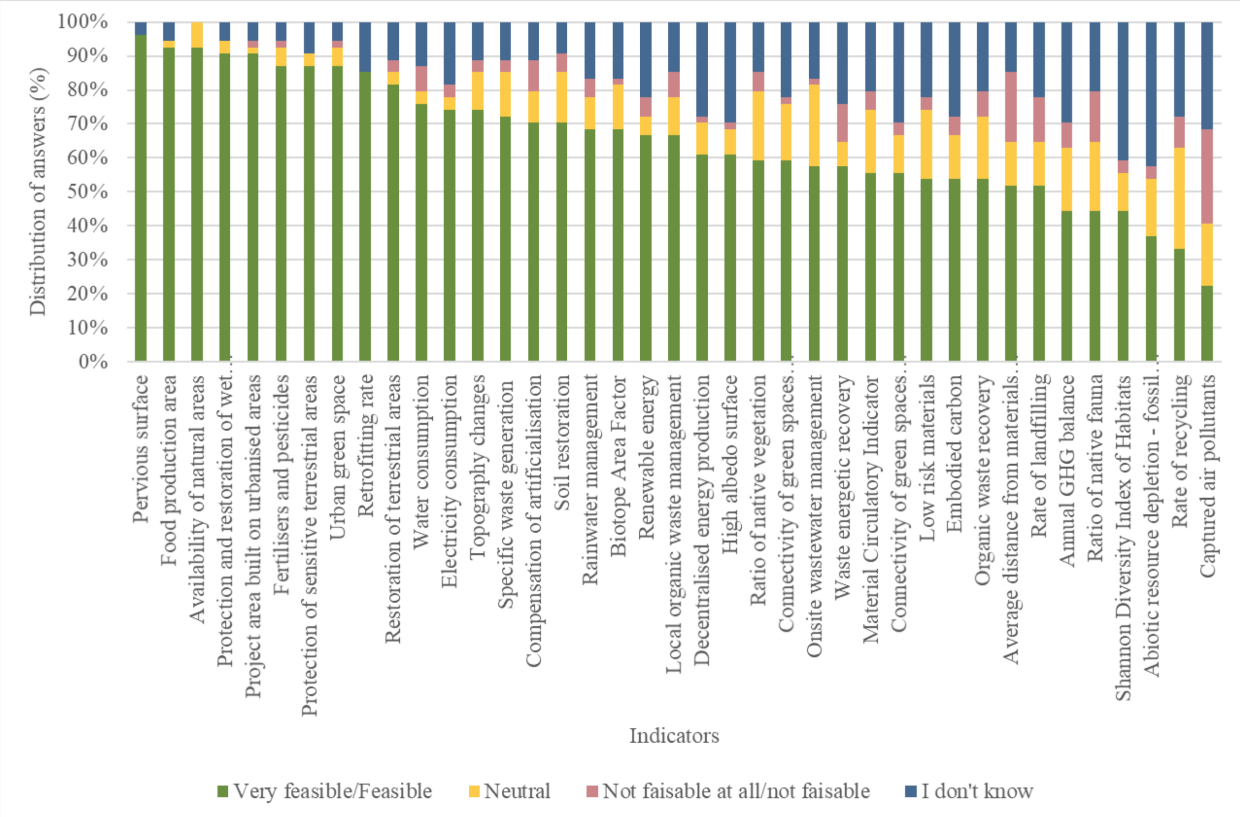

Figure 3 - Distributions of answers regarding the operational feasibility of the indicators

Analysing this data it is possible to draw a few insights. At first, indicators that have more complex calculations methods and require more complex data, such as LCA based indicators (namely the Abiotic resource depletion – fossil fuels and the Embodied carbon), are perceived as less operational by the respondents. Furthermore, indicators requiring extensive ecological inventories, such as native fauna and flora ratios, also present discouraging results. Several factors can influence these results, such as their innovative aspects, the lack of available data, and the cost and time required to implement them, which usually does not fit the market-based urban design process. Moreover, indicators related to waste management in the use phase (like the rates of recycling and landfilling) also present less favourable results. As specified by the respondents, this is much related to the difficulty to obtain data in France due to municipal waste management without segmented data.

Finally, indicators that the respondents mainly well perceived seemed to be those based on surface ratios. Those can be easily calculated without extra data or expertise, even in the early urban design phase.

Table 2 – Survey answers distribution in quartiles

#	Indicators short name	Quartiles			
		Positive	Neutral	Negative	I don't know
1	Renewable energy	Q2	Q1	Q3	Q3
2	Decentralised energy production	Q2	Q1	Q2	Q3
3	Abiotic resource depletion - fossil fuels	Q1	Q2	Q1	Q4
4	Electricity consumption	Q3	Q1	Q3	Q2
5	High albedo surface	Q2	Q2	Q3	Q2
6	Water consumption	Q3	Q1	Q1	Q1
7	Rainwater management	Q3	Q4	Q1	Q2
8	Pervious surface	Q4	Q4	Q3	Q3
9	Onsite wastewater management	Q2	Q1	Q1	Q2
10	Material Circulatory Indicator	Q2	Q4	Q2	Q3
11	Retrofitting rate	Q4	Q3	Q3	Q4
12	Low risk materials	Q1	Q1	Q1	Q1
13	Average distance from materials source	Q1	Q1	Q1	Q1
14	Embodied carbon	Q1	Q4	Q3	Q3
15	Annual GHG balance	Q1	Q1	Q1	Q1
16	Food production area	Q4	Q1	Q2	Q1
17	Fertilisers and pesticides	Q4	Q1	Q1	Q1
18	Specific waste generation	Q3	Q2	Q4	Q1
19	Organic waste recovery	Q1	Q2	Q2	Q1
20	Local organic waste management	Q2	Q3	Q3	Q1
21	Waste energetic recovery	Q2	Q1	Q1	Q1
22	Rate of landfilling	Q1	Q3	Q1	Q2
23	Rate of recycling	Q1	Q2	Q2	Q4
24	Protection and restoration of wet ecosystems	Q4	Q1	Q3	Q3
25	Protection of sensitive terrestrial areas	Q4	Q1	Q2	Q3
26	Restoration of terrestrial areas	Q4	Q2	Q1	Q4
27	Project area built on urbanised areas	Q4	Q1	Q3	Q2
28	Compensation of artificialisation	Q3	Q2	Q3	Q2
29	Topography changes	Q3	Q1	Q1	Q1
30	Soil restoration	Q3	Q4	Q1	Q2
31	Captured air pollutants	Q1	Q4	Q3	Q3
32	Availability of natural areas	Q4	Q1	Q1	Q2
33	Urban green space	Q4	Q4	Q2	Q3
34	Ratio of native vegetation	Q2	Q3	Q3	Q4
35	Ratio of native fauna	Q1	Q1	Q1	Q1
36	Biotope Area Factor	Q3	Q1	Q1	Q1
37	Connectivity of green spaces (within the plot)	Q2	Q4	Q3	Q3
38	Connectivity of green spaces (outside the plot)	Q2	Q1	Q1	Q1
39	Shannon Diversity Index of Habitats	Q1	Q1	Q2	Q1

3.2.2. Hypothesis test: Surface ratio indicators

Among the 39 indicators, we had indicators requiring different types of data and different analytical modes, such as indicators based on surface ratios, estimated consumption data, ecological inventories, and life-cycle assessments. Nevertheless, those based on surface ratios were the majority, accounting for 18 indicators (see appendix 5 for the different classifications).

In this context, we verified the hypothesis that the urban design stakeholders perceived the surface ratio indicators as more operational and feasible. Using a bilateral t-test, we analysed the number of positive notes (very feasible/feasible) received by the surface ratio indicators (18 indicators) and the remaining (21 indicators). The bilateral t-test returned an average of 42 positive answers for the surface ratio indicators against 30 to the other indicators, with a p=0,000025, validating our hypothesis.

Such results converge with previous studies highlighting the demand for design tools and indicators that the design teams themselves could easily assess. It means indicators that rely on existing data and does not require external expertise or third-party inputs and analyses (Blanco et al., 2022).

3.2.3. Pertinence of a design tool

We observed positive feedback regarding the pertinence of a design tool using a selection of the presented indicators in facilitating the design of urban projects that produce mutual benefits for society and ecosystems. Around 80% of the respondents indicated it as very pertinent or pertinent.

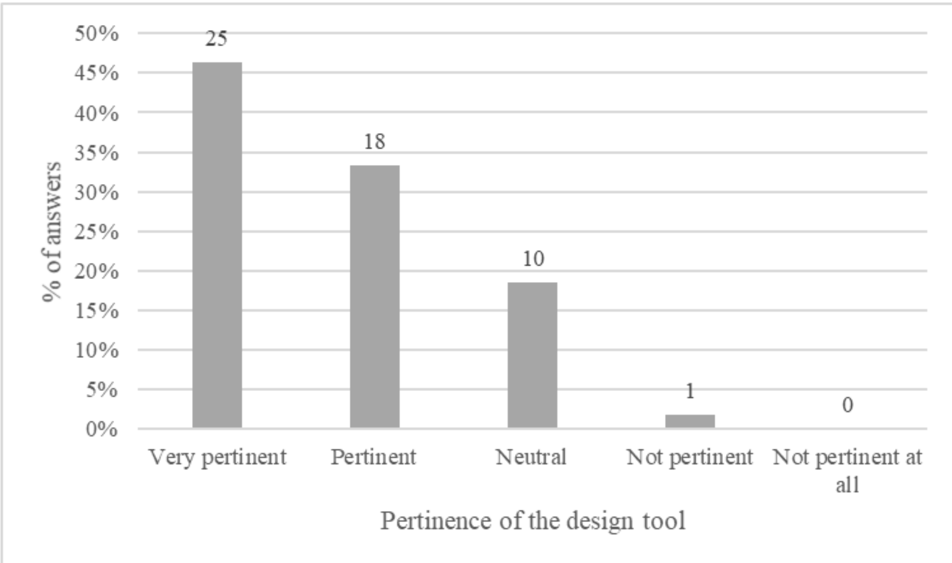

Figure 4 - Pertinence of a design tool based on the analysed indicators

3.2.4. Proposed indicator set

Relying on the survey results, we selected a smaller set of indicators to compose an operational indicator set for the French context. To make this selection, we based on the quartile distribution of the indicators, giving priority to indicators with better positive evaluations and lesser negative or lack of comprehension evaluations. We also considered possible redundancies among the indicators, minimizing them. Finally, we also integrated feedback from the respondents on the evaluated indicators. Their feedback allowed us to promote a few adjustments, improving their clarity and aligning them with indicators proposed by french regulations.

We aim in this work to propose a set of indicators that can be easily and quickly adopted by the operational stakeholders (mainly the French ones), so our selection finds support in their evaluation. Due to this fact, interesting and innovative indicators may stay out of our selection, but they remain exciting opportunities and are an option for further evolutions of this indicator set, namely those highlighted as optional ones in our results.

Table 4 presents the indicators considered as non-operational and removed from the final indicator set and the respective justifications. Table 5 presents the final proposed indicator set to assess regenerative urban projects, integrating the insights gathered during the survey and the respective justifications.

In the ecosystem services cascade and the PSR causal model perspective, the selected indicators relate to three main elements affecting ecosystem services production: the pressures, the state, and the responses. The majority of the selected indicators assess the human responses to manage the ecosystem state (increasing it) and the pressures over it (reducing it). Despite assessing the responses, they remain not too prescriptive, which is positive for neighbourhood design tools (Abusaada & Elshater, 2021; Grazieschi, Asdrubali, & Guattari, 2020). They left space for design teams to find the appropriate solutions according to the site context. Examples of the response indicators are the rainwater management indicator, which encourages the use of low impact techniques to manage rainwater at the plot level; the retrofitting rate indicator, which proposes to reduce new constructions and rely on existing infrastructure; and the material circularity indicator, encouraging circular approach for the construction materials. Following, a few indicators assess the ecosystem state, such as the biotope area factor, the pervious surface and the regional connectivity indicators. Finally, a few others asses direct human pressures over the ecosystems, such as the embodied carbon and the energy and water consumption.

As the ecosystem services production is highly related to the ecosystem state and the pressures over these structures, improving these indicators between the initial and the final situation implies enhancing the potential production of ecosystem services (Kandziora et al., 2013; Puppim de Oliveira et al., 2011). Thus this indicator set can be considered as an operational opportunity to engage in the production of different ecosystem services without using direct ecosystem services assessment methods, such as modelling and ecological inventories, that may not be operational at the neighbourhood scale and during the urban design process (Pandeya et al., 2016).

Finally, the indicators presented in table 4 could also be helpful for particular contexts, despite being considered less operational and pertinent for our objective. We draw attention to those pointed out as optional, namely indicators #15, #21, #22 and #23. Specifically, regarding #15, the annual GHG balance indicator, in the perspective of climate change and designing neighbourhoods that promote less carbon-intensive lifestyles, it could have an excellent opportunity to inform the design and redesign of urban neighbourhoods. Furthermore, indicators in table 4 could hold a clue of topics that deserve to be the target of training and skill upgrades for design teams.

Table 3 - Indicators considered non-operational

#	Short name	Justification
2	Decentralised energy production	The survey highlighted a lack of clarity about the indicator and only average positive feedback. Furthermore, the indicator is slightly redundant with indicator #1 Renewable energy and #14 Embodied carbon. As local production is not always better from the life cycle perspective, indicators #1 and #14 can guide towards this objective when relevant.
3	Abiotic resource depletion - fossil fuels	The results showed a high lack of clarity concerning this indicator and few positive feedback. From a life cycle perspective, indicator #14 Embodied carbon, cover the objective, reducing the redundancies.
13	Average distance from materials source	The indicator had an important negative perception, despite a high understanding. Furthermore, it is also redundant with indicator #14 Embodied carbon.
15	Annual GHG balance	The indicator presented a high lack of understanding. Furthermore, it assesses performance on the "use phase", being less adapted to inform design. We removed it from the final set, but we propose to keep it as an optional indicator on projects with a focus on GHG emissions.
18	Specific waste generation	Despite a high acceptance and understanding rate, respondents pointed out that waste indicators are hard to follow in France because the management is done at larger scales, lacking data at the neighbourhood level. Furthermore, the indicator is focused on the "use phase", being less adapted to inform the design and is more lifestyle-related than urban design related.
19	Organic waste recovery	The survey highlighted that the indicator is not well accepted and has a high lack of understanding. Furthermore, similar to indicator #18, data is hard to collect in the French context, and it is related to the "use phase". Finally, it presents some redundancy with indicator #20, related to local organic waste management.
21	Waste energetic recovery	Same as indicator #19. Nevertheless, this indicator can be impacted by waste management solutions proposed in the design phase. This way, we propose to keep it as an optional indicator.
22	Rate of landfilling	Same as indicator #19. Nevertheless, this indicator can be impacted by waste management solutions proposed in the design phase. This way, we propose to keep it as an optional indicator.
23	Rate of recycling	Same as indicator #19. Nevertheless, this indicator can be impacted by waste management solutions proposed in the design phase. This way, we propose to keep it as an optional indicator.
24	Protection and restoration of wet ecosystems	Although the indicator was well accepted and well understood, it is redundant with indicator #25, analysing terrestrial ecosystems. Furthermore, it does not apply to every project. We merged aquatic and terrestrial indicators for protection and restoration in indicator #25.
31	Captured air pollutants	The indicator had more negative answers and a high lack of understanding. It is also more related to the "use phase" being less adapted to inform design.
32	Availability of natural areas	Even though this indicator was very well accepted and understood, we removed it because it can be redundant with indicator #33 Urban green space, which was well noted. Moreover, indicator #33 is not dependent on population data and may create less confusion when analysing data over time.
34	Ratio of native vegetation	The results highlighted that the indicator was not well accepted. Moreover, the data necessary seems complicated to collect in the early design phases.
35	Ratio of native fauna	Same as #34.
37	Connectivity of green spaces (within the plot)	The survey showed that this indicator was very well accepted and understood. Furthermore, respondents highlighted that this indicator should give better insights at larger scales, so we decided to keep only indicator #38, assessing the connectivity within the surroundings.
39	Shannon Diversity Index of Habitats	The indicator had a high lack of understanding and low positive perception. Furthermore, on its objective, it has some level of redundancy with indicator #36 Biotope Area Factor, that have been selected.

Table 4 - Proposed indicators set

#	Indicator description	Justification and survey inputs
1	Renewable energy: The share of total annual energy consumption derived from renewable sources (non-combustion only) - (%).	On average, the indicator was well accepted and understood by stakeholders. Furthermore, a new french regulation (RE2020) imposes a similar indicator.
4	Electricity consumption: The total annual consumption per capita - (Kwh/m2.an)	Same as #1. We adapted the indicator unit to align with RE2020 regulation.
5	High albedo surface: The share of the project area covered by high albedo materials (>0.75) - (%).	On average, the indicator was well accepted, even with a relevant rate of stakeholders who are not aware of the notion.
6	Water consumption: The daily water consumption per capita (L/m2.day).	The indicator was well accepted and understood. We adapted the unit, making it related to the project surface and not inhabitants, following respondents' feedback.
7	Rainwater management: The proportion of annual stormwater managed at the site level (reused, infiltered, evapotranspired…) - (%).	The indicator was well accepted and understood. We just added examples of on-site management to enhance clarity.
8	Pervious surface: The share of permeable surface in relation to the total project surface - (%).	This indicator was the most well-accepted on the sample. It was also well understood.
9	Onsite wastewater management: The share of total annual wastewater generated that is managed on-site with low impact techniques - (%).	The indicator was relatively well accepted and understood.
10	Material Circulatory Indicator: The indicator measures the degree of circularity of a system, with a value from 0 to 1. It is calculated from the estimated amount of virgin, recycled and reused materials used in construction, the amount of waste generated at the end of the life cycle and a factor related to the project's usage rate.	Despite a high lack of knowledge on the topic, this indicator was relatively well accepted. As there is a lack of indicators assessing construction waste management and as this indicator offers a life-cycle perspective, we decided to keep it.
11	Retrofitting rate: The share of the project's floor area targeted for retrofitting, redevelopment or rehabilitation of existing infrastructure- (%).	This indicator was very well accepted and understood.
12	Low-risk materials: The share (in mass) of building materials that avoid toxic chemicals listed in the RED list of the International Living Future Institute.	The answers are scattered, without an agreement, nevertheless presenting low acceptance. As the topic is innovative, there are no other indicators related to materials health, and this data may be partly available for the embodied carbon analysis we decided to keep this indicator.
14	Embodied carbon: The total embodied carbon balance in the construction, accounting for emissions (including energy consumed in construction and material production), sequestrations and offsets ($kgCO_2eq/m^2$).	The indicator was not well accepted and presented a high lack of knowledge. However, the new french RE2020 regulation proposes a similar indicator, so we kept it and adapted the measurement unit.
16	Food production area: The share of the project surface dedicated to different urban agriculture solutions - (%).	The indicator was very well accepted and understood.
17	Fertilisers and pesticides: The share of the project area managed under a zero pesticide, biocide and petrochemical fertiliser policy - (%).	The indicator was very well accepted and understood.
20	Local organic waste management: The share of organic waste collected and recovered on site (composting, anaerobic digestion...) - (%).	The indicator was relatively well accepted and had a good understanding by respondents. We decided to keep this as the only waste indicator as it should be the easiest one to collect data at the neighbourhood scale.
25	Protection of sensitive areas: The share of the project's terrestrial or wet areas designated as protected - (%).	The indicators related to the protection of sensitive areas (terrestrial and wet) were very well accepted and understood. We merged terrestrial and wet zones in one single indicator for simplification.
26	Ecological restoration: The share of project terrestrial or wet areas targeted for ecological restoration - (%).	Same as #26.

27	Project area built on urbanised areas: The share of the project area built on already urbanised areas - (%).	The indicator was well accepted and understood. We removed brownfields from the indicator due to their ecological potential, following respondents' feedback.
28	Compensation of artificialisation: The share of the equivalent project area set aside for protection or restoration (outside the project site) in the form of compensation for artificialisation caused by the project - (%).	The indicator was relatively well accepted and very well understood. Moreover, it could contribute and be aligned with the Net-Zero Land Take french objectives.
29	Topography changes: The proportion of the project area that has undergone topography changes - (%).	This indicator was well accepted and understood.
30	Soil restoration: The share of the project area targeted for restoration of soil structure or quality - (%).	This indicator was well accepted and understood.
33	Urban green space: The share of natural areas in the total project area - (%).	This indicator was well accepted and understood
36	Biotope Area Factor: The amount of area available for nature and vegetation in relation to the total area under consideration, weighted by a specific coefficient for each type of cover, related to its potential for vegetation growth and hosting biodiversity.	This indicator was well accepted and understood.
38	Connectivity of green spaces (outside the plot): Integral connectivity index within the project area, calculated on the basis of the area of habitat plots and links to other paths, ranging from 0 to 1 (calculated on geographic information software or Graphab).	This indicator was not very well accepted and not well understood. Despite it, we believe connectivity with the regional green and blue networks are of significant importance and can be easily calculated. We decided to keep it assuring at least one connectivity indicator on the set.

3.3. Limitations:

This work presents a few limitations that must be acknowledged. At first, we used a data treatment protocol and a RACER evaluation method to reduce a large sample of indicators into a smaller sample possible to be analysed in detail. Despite its interest in this process, it remains a qualitative method, subject to bias associated with the research team's interpretations of the indicators. We relied upon the indicators factsheets on their source document whenever possible in our analysis to reduce this bias. Furthermore, to compensate for this bias, we did a second round of evaluation with external experts through the survey. However, in the pool of 159 indicators evaluated on the RACER analysis, other indicators may be useful and pertinent for different contexts, and they could be a resource for further research.

Furthermore, our final indicator set, with 23 indicators, integrates a field perspective from a French context and could be extrapolated to an European or global north context. Nevertheless, it reflects contextualised topics of concern and debate, and that would probably be different in a global south context, requiring adaptation and attention to their use.

Still, our indicators are exclusively related to environmental topics. Social and economic aspects are fundamental in regenerative design and deserve exploration, even if we choose to concentrate on environmental aspects in this work.

Finally, we considered the neighbourhood scale, which impacted our RACER evaluation, so indicators relate and are sound to this scale. Extrapolating them to larger scales may be easier than applying them to the building scale, even if a few may still be sound. Nevertheless, our initial RACER list with 159 indicators may hold other interesting opportunities for more minor scales.

4. Conclusion

Starting from a large set of established urban sustainability indicators, we were able to evaluate and propose an operational indicator set. These indicators are adapted to assess the performance and assist the design process of a regenerative neighbourhood that aims to enhance the production of ecosystem services.

These indicators are of great interest and are novel development in the field. They fill a lack of operational approaches to regenerative design at the neighbourhood scale and can inform new assessment and design tools. They are an excellent opportunity to bridge the gap between the theory and practice of regenerative design.

Based on our results, urban design practitioners see the pertinence of such a design tool. Still, we argue that this tool does not necessarily need to be in the form of a regenerative neighbourhood label. Previous research on the topic pointed to resistance toward new labels. On the contrary, there seems to be a demand for self-assessment and process tools. Such tools can be used by design teams independently, organising the design process and helping them select urbanisation strategies and solutions. From a theoretical perspective, process-centred tools converge with the holistic aspirations of regenerative design.

The previous regenerative urban design framework proposed by Pedersen Zari (2015) used a comparative approach based on pre-development metrics, assessing indicators for a reference ecosystem and trying to reach these indicators through urban design. We argue that referring to a past ecosystem situation may not be pertinent from an ecological perspective. At first, ecosystems continuously evolve, and selecting the reference situation may be tricky. Secondly, in a context of rapid and growing global ecological and climate changes, taking a past situation as a reference may lead to choices that are not pertinent in future scenarios. Finally, understanding cities as complex socio-ecosystems in co-evolution, the ideal is to compare the initial situation (in the present) with the projected one. Thus, the project should engage in a continuous improvement process and promote the amelioration in the socio-ecosystem's overall context. For this task, our indicators seem to be useful.

The use of indicators on urban design tools or regulations are commonly followed by reference values, indicating minimal expected performances. Nevertheless, establishing these reference values seems contradictory from a regenerative design perspective. Projects depend on the site context, and not every indicator may be relevant to every project. One interesting opportunity to allow comparison is to create a local/regional baseline based on other equivalent sustainable projects. This approach could challenge the project performances beyond the regional standard practice.

Considering a new regenerative design framework, it is important to highlight the need to integrate regenerative design principles that are still undermined in practice, such as the participatory and continuous improvement approaches. Such a design tool could be organised as a toolkit, proposing a phasing to the design process, presenting possible urban strategies, solutions, case benchmarks and the proposed indicators. Finally, the indicators set could also inform existing and established design tools that lack holistic perspectives. Namely, they could be an asset for the LBC framework, which presents lacks regarding ecosystem structures and larger urban scales than the building.

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Appendix:

The Appendix from Chapter 3, section 2, related to the paper *Indicators for Regenerative neighbourhood design: an indicator set definition* are presented on the Appendix B section of this document (page 179). They were moved there to improve the document readability.

Conclusions Chapter 3

Analysing the use of the strategies in a large sample of sustainable neighbourhoods allowed us to identify and validate trends in their selection. For instance, strategies with a life-cycle and circular economy perspective are still lacking in sustainable neighbourhood projects. Thus, we are interested in reinforcing them through our indicator set, selecting indicators that will guide us in this direction. The insights from the survey were fundamental to the selection of indicators and adjusting the taxonomy to its final version.

The neighbourhood survey results were also helpful to confirm governance levers highlighted in chapter two, namely the governance issues between core stakeholders and their stability and the financial viability of the projects.

The survey was also valuable to understand that design teams are eager for new tools, but they prefer process-oriented tools. These tools can be used autonomously, not necessarily being attached to a third-party certification process. The results also highlighted the role of ecological diagnostics in the design process, how they affect projects and their significant lack in practice. It adds valuable insights in delineating the design process framework presented in the discussion section of this document.

Our exercise with the indicators was also enriching. The challenge resides in finding a balance between an indicator framework that 1) is scientifically sound, 2) that can be a proxy to enhancing the production of ecosystem services, 3) that fosters innovation, that leaves an open field for creativity and at the same time 4) are operational and can be quickly adopted by urban design teams.

Our final selection of 23 indicators is a first trial that seems sound and accepted in a French context. They are an essential brick for constituting a design framework that will bridge the gap between theoretical regenerative design and sustainable neighbourhood practice. From an ecosystem services perspective, assessing and enhancing these indicators can promote, through causal relations, the production of ecosystem services and mutual benefits for nature and society from urban projects. Now they need to be tested in the field to assess their pertinence and real-world feasibility.

Conclusions Chapitre 3

L'analyse de l'utilisation des stratégies dans un large échantillon de quartiers durables nous a permis d'identifier et de valider des tendances dans leur sélection. Par exemple, les stratégies axées sur le cycle de vie et l'économie circulaire font encore défaut dans les projets de quartiers durables. Nous souhaitons donc les renforcer à travers notre série d'indicateurs, en sélectionnant des indicateurs qui nous guideront dans cette direction. Les résultats de l'enquête ont été fondamentaux pour la sélection des indicateurs et l'adaptation de la taxonomie à sa version finale.

Les résultats de l'enquête ont également été utiles pour confirmer les leviers de gouvernance mis en évidence au chapitre deux, à savoir les problèmes de gouvernance entre les principales parties prenantes et leur stabilité et la viabilité financière des projets.

L'enquête a également permis de comprendre que les équipes de conception sont avides de nouveaux outils, mais qu'elles préfèrent les outils axés sur les processus de conception. Ces outils peuvent être utilisés de manière autonome, sans être nécessairement rattachés à un processus de certification par une tierce partie. Les résultats ont également mis en évidence le rôle des diagnostics écologiques dans la conception, la manière dont ils affectent les projets et leur manque important dans la pratique. Ces résultats apportent un éclairage précieux pour délimiter le cadre de conception présenté dans la partie discussion de ce document.

Notre exercice avec les indicateurs a également été enrichissant. Le défi réside dans la recherche d'un équilibre entre un cadre d'indicateurs qui 1) est scientifiquement solide, 2) qui peut servir d'indicateur pour améliorer la production de services écosystémiques, 3) qui encourage l'innovation et qui laisse un champ ouvert à la créativité et en même temps 4) qui est opérationnel et peut être rapidement adopté par les équipes de conception urbaine.

Notre sélection finale de 23 indicateurs est un premier essai qui semble solide et accepté dans un contexte français. Ils constituent une brique essentielle pour un cadre de conception qui rapprochera la pratique et la théorie des projets urbains régénératifs. Du point de vue des services écosystémiques, l'évaluation et l'amélioration de ces indicateurs peuvent favoriser, par le biais de relations causales, la production de services écosystémiques et de bénéfices mutuels pour la nature et la société. Il faut maintenant les tester sur le terrain pour évaluer leur pertinence et leur faisabilité dans le monde réel.

Discussion

The different results and knowledge generated in this research contributed to growing the maturity of regenerative design and ecosystem-level biomimicry theories and practices. It helped us understand the trends, needs, and lacks in using such an approach to neighbourhood design. These different learnings are valuable insights to formalise an urban design process and a framework that could help design teams get closer to the ideal of regenerative design, drawing inspiration from natural ecosystems.

This framework could contribute to different steps of the urban design process, enhancing the production of ecosystem services and mutual benefits for nature and society. It would also represent an opportunity to integrate the different regenerative design principles in the urban design process, namely those identified in Chapter 1:

1. A net-positive and mutually beneficial project for nature and society;

2. A co-evolutionary project that promotes a long-term regeneration process, leading the urban system and the ecological system to evolve together over time towards better health and functioning;

3. A design process based on a systemic reading of the site, assuring local anchorage and answering local ecological and social needs;

4. A participatory and community-based process that capitalises on local knowledge and involves actors in the project's design, implementation, and continuity over time;

5. A continuous improvement perspective over time.

In this discussion, we will revisit and build upon our results to formalise an urban design process and framework, discuss from a macro point of view the use of ecosystem-level biomimicry for regenerative design and explore limitations and further research opportunities.

i. Defining an urban design process and framework

i.i. Enhancing the ecosystem services production through urbanisation responses

Through the Lavasa and the Lloyd cases, we observed that urban design approaches based on ecosystem services are indeed an opportunity to promote mutually beneficial positive impacts. Analysing the ecosystem services cascade and the DPSIR framework (Kandziora et al., 2013; Potschin et al., 2018), which formalises a theoretical framework on the production of ecosystem services, we observed two main factors correlated to its production that can be addressed on urban projects: 1) Reducing anthropic pressures over ecosystems, and 2) Regenerating ecosystem structure.

In our current urbanisation process, society relies on the benefits promoted by ecosystems to improve its well-being. Doing this, we create pressures and simplify the ecosystems' structure (Alberti, 2005; Díaz et al., 2015). Such logic reduces the potential to produce ecosystem services, creating a negative feedback loop. Thus, proposing urban solutions and strategies to manage pressures and regenerate ecosystems structures creates a set of responses that are levers to re-equilibrating human relations to ecosystems and enhance ecosystem services production (Figure 7).

We argue that to optimise such benefits, the selection of these responses must be enlightened by the site's socio-ecological reality and project objectives in an informed decision-making process. These responses should take form in different ways on the urban projects, following the site reality. Our cases studies and surveys in Chapters 2 and 3 highlighted various possible strategies and solutions and the trends in their use.

From a broader point of view, a design process informed by socio-ecological information can also contribute to two significant challenges in urban design: 1) to territorialise global environmental urban challenges that still struggle to be translated from international policies to local actions (Bombenger and Larrue, 2014) and, 2) to enhance the use of urban ecology knowledge to coupling social and ecological systems (Barot et al., 2019).

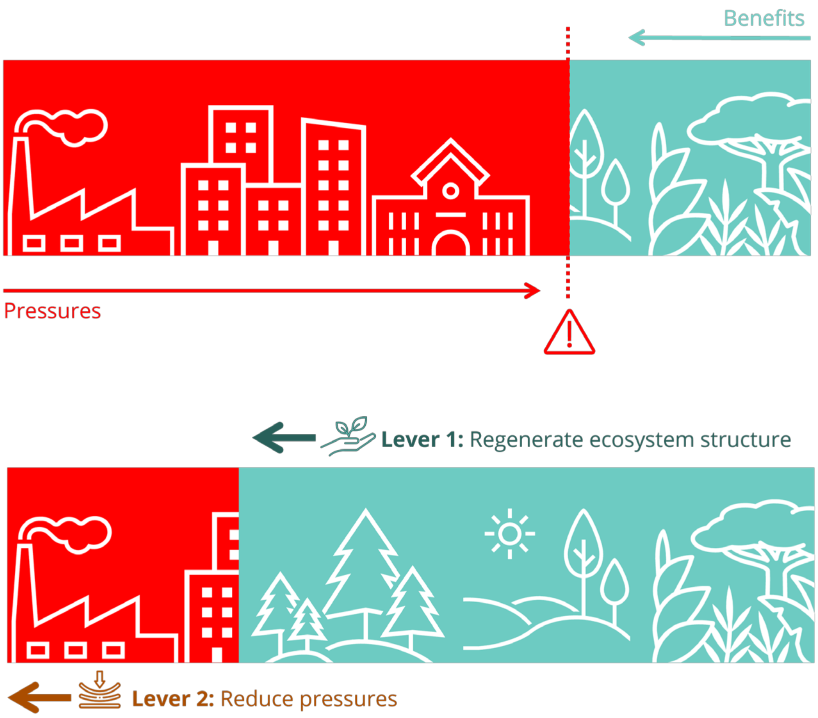

Figure 7: Conceptual framework: levers of action to enhance the production of ecosystem services.

i.ii. Diagnostics informing the decision-making process

In urban design theory and practice, the role of diagnostics has been largely overlooked (Leach, Mulhall, Rogers, & Bryson, 2019). Our results confirmed and highlighted the importance and lack of socio-ecological diagnostics in informing the design of sustainable neighbourhoods. This lack has probably several reasons. At first, it can relate to the shrinkage of "urban programming" practices, in which public stakeholders study and define strategical priorities for urbanisation. Diagnostics had a central place in these studies. However, with outsourcing programming practices from public project owners to private design teams and project developers, diagnostics are fragmented and appear too late in the projects (Zetlaoui-Léger, 2009a, 2009b). A second point is related to the urban design governance, once public stakeholders do not systemically request socio-ecological diagnostics on their request for proposals (Carmona, 2017). The consequence of this is that when diagnostics are done, they only allow to reduce impacts and not strategically inform decision making.

Nevertheless, socio-ecological diagnostics presents several opportunities for a regenerative urban design process. For instance, they can be a lever for selecting relevant strategies and solutions for each project. A formal socio-ecological diagnostic could help identify and prioritise relevant topics to be tackled in an urban project. This approach also allows promoting interdisciplinarity, integrating different disciplines and points of view in the early phases of the decision-making process (Clergeau, 2019). Formalising diagnostics in the design process would contribute to anchoring projects on the site reality, avoiding "one-size fits all" solutions.

Using the diagnostics to enumerate priorities is a way also to tackle the financial viability issues raised in our results. In the context of market-based urban development, choices need to be made and priorities defined. While detailed cost-benefit or life-cycle analysis would be the best tools, a simplified prioritisation of solutions based on diagnostics would avoid generalistic, non-site relevant solutions and greenwash (Gibbons et al., 2018). A simplified prioritisation tool could help designers make realistic compromises. With the delays and expertise constraints in the early design phases, such diagnostics could be done using secondary data. Engaging in early phase diagnostics using secondary data could be even done by public project sponsors, contributing to the reemergence of urban programming approaches and strategic planning that support positive mutual benefits for nature and society.

i.iii. Governance and social participation in regenerative urban design

Our case studies observed an absence of civil society in contributing to project narratives, leading to discourses mainly defined by project owners and design teams. Despite the increasing number of stakeholders engaged in urban design, the different groups do not have the same power and knowledge to defend their interests. However, their participation is key to promoting solid political support (Zepf and Andres, 2012) that can ensure mutual positive impacts on society and nature. Furthermore, the studied NSA frameworks, like the LBC and the LEED-ND, present very few engagements toward social participation in their process.

Despite it, we also observed interesting good practices in our case studies. One example is merging social participation and diagnostics, such as in the Paddock project. The design team invited people interested in the project and living nearby to join a field diagnostic campaign in the early design phase. During three days, the design team with the local stakeholders explored the future project area, identifying natural patterns such as rainwater preferred ways and vegetation and fauna species.

Another example is using participation to address governance questions. The Blatchford project created a stakeholders committee to help adjust the project design and implementation. This kind of committee can help assure the stability of the sustainable and regenerative narratives in the project. This is even more relevant in contexts with complex and evolving stakeholders organisation. This committee could also have a role in the project use phase, assuring the project management and continuous improvement once design teams are no longer present.

i.iv. The Regenerative Design for Neighbourhood (Red'in) process and the indicator framework

Chapter 3 revealed a demand for new tools to help urban design teams to propose projects that can enhance the production of urban ecosystem services. These tools can help advance the knowledge on assessing ecosystem services production in urban areas and informing the design process. Nevertheless, these tools must be operational to facilitate the knowledge transfer from urban ecology to urban design practice (Barot et al., 2019).

The proposed taxonomy in Chapter 3, counting 42 different strategies for urban design that can enhance the production of ecosystem services, is a first formalisation. This taxonomy presents a vast panel of strategies that can inspire and guide design teams to identify opportunities and define priorities on regenerative urban design. However, based on our results, we propose an operational framework (Figure 8). The framework is hierarchically organised, presenting 4 dimensions related to the four main components of ecosystems, 11 urban challenge topics, 18 strategies to enhance the production of urban ecosystem services and 26 indicators. This version presents a more mature and synthetic tool and will be the base for our further developments.

We argue that assessing the responses, the ecosystem state and the pressures over it could be more practical than formally assessing ecosystem services directly. These elements and the selected indicators have a direct causal relation with the ecosystem services production, being a good proxy to assess the desired positive impacts (Figure 9). This represents a significant paradigm shift from the current ecosystem-level biomimicry for regenerative design theories and practice. Until now, the standard has been to assess ecosystems services directly (Pedersen Zari, 2015; Pedersen Zari and Hecht, 2020). Nevertheless, such an approach poses problems in the urban design process, making its adoption difficult. At first, the ecosystem services assessment in small urban scales as the neighbourhood faces a lack of data and inappropriate assessment methods (Pandeya et al., 2016). Secondly, complex socio-ecological processes are involved in ecosystem services production and their perception by society, like scale thresholds and socio-cultural contexts (Andersson et al., 2015) that are hard to grasp in complex socio-ecosystems as cities.

Dimension	Topic	Strategy	Indicators
Energy	Electricity	1.Rely on renewable energy	1. Renewable energy
		2. Reduce energy consumption	2. Electricity consumption
	Heat islands	3. Manage heat islands	3. High albedo surface
Materials	Water ressources	4. Reduce water consumption	4. Water consumption
		5. Manage rainwater locally	5. Rainwater management
			6. Pervious surface
		6. Manage wastewater sustainably	7. Onsite wastewater management
	Building materials	7. Promote con. materials circularity	8. Material Circulatory Indicator
		8. Prioritise retrofit/rehabilitation	9. Retrofitting rate
		9. Use low risk materials	10. Low risk materials
	GHG	10. Reduce embodied carbon	11. Embodied carbon
		11. Promote low carbon life styles	12. Annual GHG Balance
	Food	12. Enhance local food production	13. Food production area
	Pesticides/fertilizers	13. Reduce pesticides and fertilizers	14. Fertilizers and pesticides
	Waste	14. Manage waste sustainably	15. Local organic waste management
			16. Rate of landfilling
			17. Rate of recycling
Abiotic	Physical structure	15. Protect and restore natural and sensible areas	18. Protection of sensitive areas
			19. Ecological restoration
			20. Topography changes
			21. Soil restoration
		16. Reduce landtake	22. Compensation of artificialisation
			23. Project area built on urbanised areas
Biotic	Habitat	17. Provide natural habitat	24. Urban Green Space
			25. Biotope Area Factor
	Ecological network	18. Enhance the ecological network	26. Connectivity of green spaces (outside the plot)

Figure 8: Strategies taxonomy and associated indicators.

Finally, the use of indicators could be seen as reductionist by regenerative design theorists. Nevertheless, we argue that indicators can help move toward operational approaches at the urban neighbourhood scale in a process-centred tool. Moreover, these indicators can follow the project's performance over time, allowing a continuous improvement and adaptative approach. The indicators could also be used in a design governance perspective, allowing to set objectives and compare different design propositions, avoiding irrealistic and barely comparable answers to a project request (Zetlaoui-Léger, 2009a).

The proposed framework also offers an opportunity to advance established regenerative tools that today do not cover the integrality topics and strategies proposed here. For instance, the Living Building has a substantial lack concerning biotic elements.

With the learnings acquired in this research, we propose a design process organised into 6 steps called Regenerative Design for Neighbourhoods (Figure 10). This process should be used in consonance with our final taxonomy and selected indicators, facilitating the regenerative design at the neighbourhood scale. The steps proposed could seem as conventional since they directly relate to standard practices in environmental planning and management like EcoDesign, Environmental Management Systems (ISO 14001) and Strategic Environmental Assessments. Nevertheless, as our results highlighted, sustainable urban design practice does not follow such a structured process. For example, projects do not systemically engage with diagnostics and do not use it to inform decision-making. The different steps proposed are subsequently described and also detailed in Box 1.

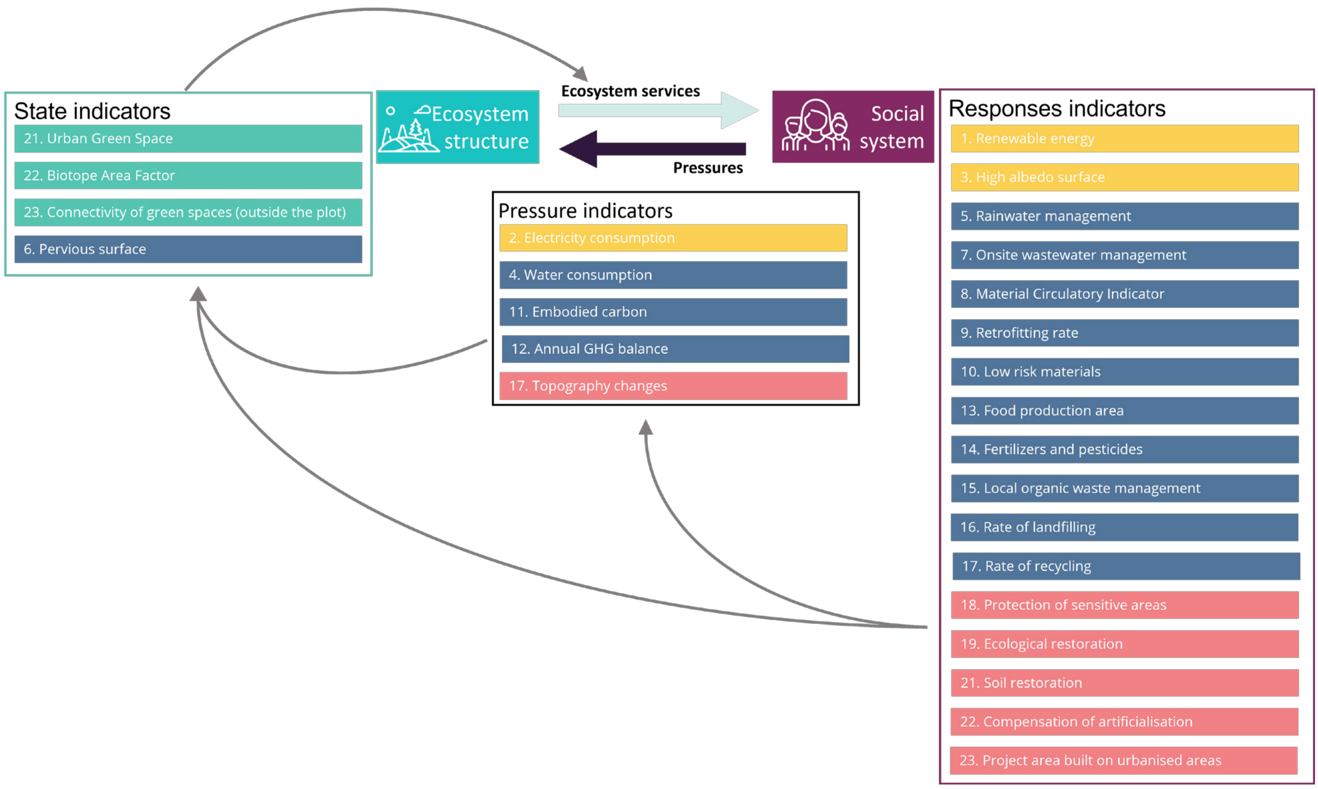

Figure 9: Indicators causal relations to the production of ecosystem services.

The first step is the realisation of the diagnostics. We propose a flexible approach, in which a first diagnostic is done using secondary data. The objective is to raise awareness of the site's reality, covering ecological and social aspects. The diagnostic should be formalised in a document, and a synthesis report should be produced (for example, using a SWOT method). The diagnostic should at least cover the 18 strategies themes but should not be limited to them.

The second step is the definition of the project scope and baselines. Here the objective is to identify among the 18 strategies which are relevant to the site reality and which are not, engaging in a strategic prioritisation and planning process. The scope must be defined using the knowledge acquired during the diagnostic step and present arguments. Once the scope is defined, the relevant indicators will be consequently identified. In the sequence, we recommend building two baselines using the selected indicators. The first baseline should document the site reality at the initial situation. It will allow comparison with different project scenarios and over time. The second baseline should document the regional reality for the same indicators. The regional baseline can be based on average regional secondary data or data from an equivalent project from the same watershed.

The third step is the objective definition. Here, relying upon the diagnostics, scope and baselines, we will define the project objectives. The objectives must be documented, establishing the aimed goal for each indicator.

The fourth step is the design phase. Here urban design teams can use their methods and experience to select, propose and organise solutions that will allow the project to reach the previously defined goals.

The fifth and sixth steps concern the project assessment and its redesign. At first, the project must be assessed before advancing to the implementation phase to confirm that the proposed design meets the defined objectives. If not, it should engage in the redesign. On a second time, the project can be assessed on a fixed time basis (for instance, annually), allowing for adjusting the project if the performances are no longer met or to reengage in the process if there are changes in the site reality and project scope. This reevaluation will allow the adaptative and continuous improvement approach.

Before formalising a request for proposals, steps 1 to 3 can be done by public project sponsors in a programming perspective. It would help to define the project priorities in a strategic planning approach. If project sponsors outsource the whole process to a private actor, all the steps can be done by design/development teams. Furthermore, as a transversal point in the process, we recommend the creation of a stakeholders committee. This committee must focus on engaging a large diversity of stakeholders and build on their inputs and capacities in the whole process.

To facilitate the process and the use of the proposed framework, we developed 18 factsheets presenting the strategies, giving examples of solutions that can contribute to its achievement and describing the associated indicators and their calculation methods. Factsheets are presented in Appendix A.

The proposed framework, composed of a six-step design process and factsheets defining strategies and indicators, could be defined as a process-centred tool aiming to organise and facilitate the design process. As a process-centred tool, it relates more to environmental management tools (such as the strategic environmental assessment or even ISO 14001 standard) than to standard NSA tools (such as LEED-ND and BREEAM). Process-centred tools are less prescriptive and do not focus on specific outcomes, allowing flexibility and creativity for urban design teams. Our framework relates to less conventional frameworks in the urban design field, such as the One Planet Living framework, issued from the BedZed Neighbourhood experience by BioRegional. The One Planet Living framework also organises the process, proposes topics to be addressed through strategic planning, and offers a non-mandatory third-party evaluation to ensure that the steps were correctly followed.

BOX 1: The Red'In design process

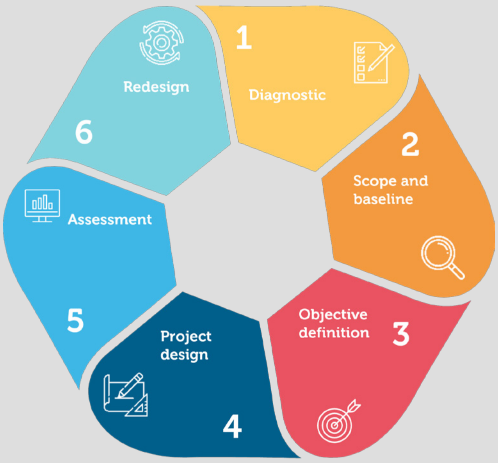

Figure 10: Red'In urban design process.

0. Stakeholder mapping and committee definition: This step aims to identify the project stakeholders and formalise a committee that will follow and enrich the design process. Stakeholders mapping must be documented. We recommend using an interest and power matrix.

1. Diagnostic: This step aims to organise contextual data to create awareness among the design team about the site's socio-ecological context and inform the design process.

Activities and methods:

1.1 Prepare a socio-ecological diagnostic: We propose the development of a socio-ecological diagnostic based on secondary data on early design phases. This diagnostic should gather social and ecological data about the site, such as demographics, economic situation, social inequalities, biodiversity condition and species, the ecological condition of abiotic spaces, pollution, public policies for sustainability etc. The diagnostic should at least promote insights regarding the 18 strategies topic. This ecological diagnostic should be formalised as a diagnostic report shared with the design team and should also rely on civil society participation.

1.2 Synthesis: We propose using a simplified SWOT matrix in a brainstorming session with the whole design team. This session should produce a synthesis of the diagnostic and identify site strengths/potentials and weaknesses/threats.

2. Scope and baseline definition: This step aims to define project priorities, guide the definition of solutions and select indicators based on the site reality. It also aims to create baselines for the selected indicators, allowing comparison and informing the definition of objectives.

Activities and methods:

2.1 Scope definition: Based on the diagnostic, the design team should select topics that will be prioritised in the project. This definition can also be done through a participative workshop with the identified stakeholders. From this definition, the indicators will also be selected. Each of the 18 strategies needs to be opted in or out, with a justification based on the diagnostic.

2.2 Prepare a site baseline: In this step, the design team should build a site baseline, assessing the site indicators at the initial situation;

2.3 Prepare a regional baseline: The design team should draw a regional baseline in this step. The site baseline should reflect the site initial situation, without interventions. The regional baseline should reflect the average practice of the regional projects. It can be done based on an equivalent project on the area (preferably on the same hydrological basin) or using average regional data. The regional baseline must be supported by arguments and justified for each indicator.

3. Objective definition: This step aims to define the project objectives. The design team must propose a goal for each indicator, relying on the diagnostic and the baselines. The goals should promote improvement from the site baseline. Choices need to be justified. All the involved stakeholders must validate the objectives.

4. Project design: This step aims to propose, select and organise the interventions that will compose the final project and that are how the objectives will be reached. In this step, the design teams use their conventional methods, keeping in mind the aimed objectives. The construction of different urbanisation scenario may be helpful. We highlight the opportunity to use participatory approaches to identify possible solutions and select among scenarios.

5. Assessment: This step aims to assess the final project performance. Objectives that were not reached should be justified or, in an iterative process, the project should be redesigned to meet the objectives. Projects can also be assessed on an annual basis to inform adaptative management and redesign.

6. Redesign: This step aims to redesign the project. It can be done in an iterative process to adapt and reselect urban interventions to meet the defined goals. It can also be used in urban adaptative management, in which, based on annual evaluations, we reengage in the process, updating context information, baselines, objectives and proposing new interventions.

ii. From ecosystem-level biomimicry to a bio-inspired framework

The starting point of this research was the ecosystem-level biomimicry theories and their application to urban design. However, with our developments and results, we propose that our framework would be better defined as a design framework inspired by ecosystems and their production of contributions to society.

Following ISO 18458 norm definitions, biomimicry uses nature as a model following precise methodologies, including functional analysis, abstraction and transposition to human technological problems. The same norm defines bio-inspiration as any creative approach based on the observation of biological models (ISO, 2015). The developments using ecosystems as models for urban design did not follow such a structured methodological process until now. Moreover, the complexity of ecosystems, urban socio-ecosystems and the urban design process makes biomimetic methods not fully adapted to the standard urban design practice.

Despite that, the ecosystems-services notion has been used as a proxy and a framework to make it easier to understand ecosystems and transpose generalities about their functioning to promote sustainable and regenerative urban solutions. However, we highlight that ecosystems services are not a biological model. It is a human-made theoretical concept used to help us understand the relations between social and ecological systems and the societal dependency on these last ones. So, from a pragmatical point of view, ecosystem services cannot be used as a model in a biomimetic process.

Nevertheless, we can draw inspiration from this concept from a broader perspective. Notably, understanding the key elements associated with the ecosystem services production and improving its state. This approach, translated into our proposed framework, is relevant for promoting regenerative design. While partially reductionist, it facilitates human comprehension and translates the regenerative design principles into an operational framework.

iii. Limitations and perspectives

First, we would like to highlight that all the research on regenerative design and biomimicry for urban design, including this work, concentrates on projects in the Global North. However, as highlighted by several international reports, by 2050, urbanisation will mostly happen in the Global South (IPBES, 2019). Thus, the Global South holds a much more significant opportunity to impact global ecological trajectories. With different urbanisation processes and patterns, research is still necessary on sustainability and regenerative design in the Global South context (Barot et al., 2019). One opportunity here is to pilot our framework in Global South projects, in an action-research approach, gathering feedback that would help evolve the framework for these particular contexts.

In the perspective of the “avoid, reduce, compensate” sequence, requalifying existing neighbourhoods is the best scenario to minimise pressures and promote mutual positive impacts on nature and society. In the Global North, retrofitting and neighbourhoods requalification will be much more relevant than new urban developments in the following decades. The Net-Zero land takes policies in Europe and France highlight this trend. As the proposed framework has a continuous improvement perspective, it is sound and relevant in this typology of projects.

One more point concerns using such tools in a market-based and competitive urban development context. Such innovative approaches and terms can be shallowly applied by urban stakeholders, leading to the mobilisation of the “regenerative design” and “biomimicry” concepts as empty catchphrases in greenwashing practices (Gibbons et al., 2020). Aiming to reduce these risks, we concentrated on proposing an operational framework focused on the process with a solid base on regenerative design principles. Here an opportunity relies on using “process” certifications, like those proposed for ISO 14001 and 9001 or in the One Planet Living Framework. Piloting the framework and gathering field feedback is essential to advance this objective.

Another important paradigm shift from our research concerns the reference for comparison. By now, comparing project metrics with previous natural ecosystem states as a reference was the primary trend (Hayter, 2005; Pedersen Zari, 2015). Nevertheless, we argue that it contradicts regenerative design and ecosystems theories. Ecosystems and socio-ecosystems are continuously evolving and changing (Kay, 2000). Moreover, in the context of climate change, fixing aims regarding past references is questionable. The regenerative design focuses on creating a mutually beneficial socio-ecosystem that co-evolves, so we aim to improve the initial situation. We argue that using site and regional baselines are more relevant than intangible objectives defined based on a past ecosystem state.

Regarding the governance of regenerative projects, we just started to tackle the question, defining levers, and several opportunities remain. It seems important to understand how the governance mechanisms impact the project narratives and performance. We highlight the opportunity to conjointly analyse project performance using the proposed framework and the project governance, identifying other levers and trends.

A distinct point regards the urban scale. Our framework was designed having in mind the neighbourhood scale. Still, it could also be valuable and transposable to other larger urban scales, like municipal or territorial planning. Nevertheless, such transposition needs to be done carefully, assuring that the strategies and indicators are still sound and relevant.

Another limitation of our framework is its focus on environmental questions. Due to methodological reasons and to set boundaries for this research, we only looked at environmental topics and impacts, implying purely environmental indicators. Our developments could be completed with socio-economic indicators to assess the positive impact on these spheres. A similar indicators selection method would be appropriate .

Finally, systemically integrating this urban design framework into practice would require integrating new competencies and knowledge into the design team. Two complementary ways seem timely. The first is to act on the training and education of future urban design professionals, to assure a long term change in how they tackle projects. A second opportunity stands in design team composition. Integrating ecologists and other professionals in very early design phases become fundamental to realise diagnostics, to help define priorities and draft solutions.

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Conclusion

The production of nature contributions to people in urban ecosystems is highly dependent on anthropic factors and actions. Urban design, specifically at larger scales such as the neighbourhood, holds an opportunity to recouple social and ecological systems. This thesis in urban ecology and urban design proposed a framework that practitioners can easily adopt to facilitate this task.

The presented results can help advance the knowledge on several fronts, bridging a gap between theory and practice. The main contributions relate to 1) the application of regenerative design at the neighbourhood scale, 2) the use of ecosystem-level bio-inspired and biomimetic approaches to urban design, 3) the design process to catalyse the production of urban ecosystems services, and 4) how to assess the positive benefits.

Our design approach, formalised as a process-centred framework, converges with eco-design and other environmental methods like environmental management systems and the strategical environmental assessment. It diverges from other consolidated neighbourhood sustainability assessments that mainly focus on outcomes and checklists.

Our results help move further on the challenging task of integrating benefits for non-humans in urban design. We kept the trend to reduce the negative impacts on our framework, and we added the notion of regeneration and mutually beneficial positive impacts. To cope with regenerative design and the current ecological crisis, we highlight the need to go beyond. Maybe an utterly nature-centred framework could contribute to finding the balance between a people-centred and nature-centred mindset on urban design.

From practical perspectives, our results pointed to the need to associate efforts to reduce human pressure with those to regenerate ecosystems structure. Furthermore, we also noted the importance of associating technology with nature-based solutions to tackle contemporary urban challenges. Finally, it is critical to advance the mobilisation of solutions aiming at the circularity of urban systems and enhancing their biodiversity.

From a governance point of view, we stress the need to assure civil society participation. Participation may be a way to legitimate and assure non-human interests and benefits of project design. Project financial viability is also an important point that still deserves exploration. The notion of the payment for ecosystem services, still experimental and with low operability at the urban level, could be an opportunity to integrate the negative and positive impacts of urban projects on our socio-economical system.

Finally, this research opened several opportunities in urban design practice. Following our findings and formalisations, the proposed framework requires testing and a real-world perspective. It could contribute to consolidating and disseminating a regenerative urban design philosophy and practice worldwide.

Conclusion générale

La production de contributions de la nature aux personnes dans les écosystèmes urbains dépend fortement de facteurs et d'actions anthropiques. La conception du projet urbain, en particulier à des échelles plus grandes comme le quartier, offre une opportunité de recoupler les systèmes sociaux et écologiques. Cette thèse en écologie urbaine et aménagement a proposé un cadre que les praticiens peuvent facilement adopter pour faciliter cette tâche.

Les résultats présentés peuvent contribuer à faire progresser les connaissances sur plusieurs fronts, en comblant l'écart existant entre la théorie et la pratique. Les principales contributions concernent 1) l'application du design régénératif à l'échelle du quartier, 2) l'utilisation d'approches bio-inspirées et biomimétiques des écosystèmes pour la conception urbaine, 3) le processus de conception pour catalyser la production de services écosystémiques urbains, et 4) la manière d'évaluer les bénéfices positifs ciblés.

Notre approche de conception, formalisée sous la forme d'un cadre centré sur le processus, converge avec l'écoconception et d'autres méthodes environnementales telles que les systèmes de gestion environnementale et l'évaluation environnementale stratégique. Elle s'écarte des autres systèmes d'évaluations de la durabilité des quartiers consolidés, qui se concentrent principalement sur les résultats et sur des prescriptions de conception.

Nos résultats permettent d'avancer dans la tâche difficile de l'intégration des avantages pour les non-humains dans la conception urbaine. Nous avons conservé la tendance observée de réduire les impacts négatifs dans notre cadre, et nous avons ajouté la notion de régénération et d'impacts positifs mutuellement bénéfiques. Pour mettre en place le design régénératif et faire face à la crise écologique actuelle, nous soulignons la nécessité d'aller au-delà. Peut-être qu'un cadre entièrement centré sur la nature pourrait contribuer à trouver l'équilibre entre les approches centrées et ceux centrés sur la nature.

D'un point de vue pratique, nos résultats soulignent la nécessité d'associer les efforts visant à réduire la pression humaine à ceux visant à régénérer la structure des écosystèmes. En outre, nous avons également noté l'importance d'associer la technologie aux solutions fondées sur la nature pour relever les défis urbains contemporains. Enfin, il est essentiel de faire progresser la mobilisation des solutions visant à la circularité des systèmes urbains et à l'amélioration de l'intégration de la biodiversité.

Du point de vue de la gouvernance, nous soulignons la nécessité d'assurer la participation de la société civile. La participation peut être un moyen de légitimer et de garantir les intérêts et les avantages pour les non humains dans la conception du projet. La viabilité financière des projets est également un point important qui mérite encore d'être exploré. La notion de paiement des services écosystémiques, encore expérimentale et peu opérationnelle au niveau urbain, pourrait être une opportunité pour internaliser les impacts négatifs et positifs des projets urbains.

Enfin, cette recherche a ouvert plusieurs opportunités dans la pratique du design urbain. Suite à nos conclusions et formalisations, le cadre proposé nécessite d'être testé et mis en perspective dans le monde réel. Il pourrait contribuer à la consolidation et à la diffusion d'une philosophie et d'une pratique du design urbain régénératif en France et dans le monde.

Appendix

A. Strategies and indicators factsheets

To facilitate the design process and the use of the proposed framework, containing 4 dimensions related to the four main components of ecosystems, 11 urban challenge topics, 18 strategies to enhance the production of urban ecosystem services and 26 indicators, we developed 18 factsheets. The factsheets present the 18 strategies in detail, giving examples of solutions that can contribute to its achievement and describing the associated 26 indicators and their calculation methods. These factsheets can be used in training for urban design teams and as a facilitation tool in urban design workshops to implement the proposed regenerative design framework.

#1 Rely on renewable energies

Objective:

Encourage non-combustible renewable energy production and use.

Attention points:

The use of decentralised and distributed local renewable energy production is positive but must be evaluated based on local site potentialities, global life cycle assessment, and project embodied carbon. Decision-makers and designers must keep a life cycle perspective in mind, avoiding only displacing impacts over the life cycle. The best global solution must be evaluated for each project, aiming to reduce overall socio-ecological impacts and emissions from a global perspective. We recommend using Life Cycle Analysis and simplified carbon footprint tools. Special attention must be given to the energy mix diversification for resilience and solutions that hold opportunities for mutualisation and economy of scale.

Examples of urban solutions:

Geothermal; Wind energy; Solar Energy; Waves energy.

Related Sustainable Development Goals:

Related indicators :

1 - Renewable energy: The share of total annual energy consumption derived from renewable sources (non-combustion only) - (%).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Total renewable energy consumption; Total energy consumption.

Calculation: (Total renewable energy consumption/Total energy consumption)x100.
Interpretation and benchmark: An improving trend and higher values are considered positive.

#2 Reduce energy consumption

Objective:

Reduce total energy consumption in the neighbourhood.

Attention points:

The neighbourhood should encourage a less energy-intensive lifestyle. The solutions should go beyond only technical features.

Examples of urban solutions:

Better fixtures; Bioclimatic design and solar massing; Use of natural lighting; Educational solutions; Cost savings programs; Energy sharing systems; Public lighting correct dimensioning; Energy recovery systems.

Related Sustainable Development Goals:

7 AFFORDABLE AND CLEAN ENERGY

11 SUSTAINABLE CITIES AND COMMUNITIES

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

Related indicators :

2 - Electricity consumption: The total annual consumption per capita - (Kwh/m2.year)

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Total consumption of electricity (kWh/year); Total project surface.

Calculation: Total consumption of electricity (kWh/year)/Total project surface.

Interpretation and benchmark: A declining trend and lower values are considered positive. The RE 2020 regulation sets 85kWhep/(m2/an) as the maximum average for collective housing projects.

#3 Manage heat islands

Objective:

Minimise the creation of urban heat islands and manage its impacts on society and biodiversity, contributing to the local climate regulation.

Attention points:

Nature-based solutions should be the priority to manage heat islands.

Examples of urban solutions:

Urban greening; Wetlands for evapotranspiration; Use of high albedo materials; Solar massing, and heat island modelling in the design phase.

Related Sustainable Development Goals:

Related indicators :

3 - High albedo surface: The share of the project area covered by high albedo materials (>0.75) - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Area covered with high albedo materials (superior to 0,75); Total project surface.

Calculation: (Area covered with high albedo materials (superior to 0,75)/Total project surface)x100.

Interpretation and benchmark: Higher values are considered positive for the same project surface. Despite it, the indicator should not encourage higher artificialisation. The use of Nature-based solutions can decrease the indicator but fight heat islands through other mechanisms (like evapotranspiration).

#4 Reduce water consumption

Objective:

Reduce the total water consumption in the project area, diversify potable water sources, optimise availability and rely on locally available resources.

Attention points:

The neighbourhood should encourage a less water-intensive lifestyle. The solutions should go beyond only technical features.

Examples of urban solutions:

Fixtures upgrade; Education; Rainwater reuse.

Related Sustainable Development Goals:

Related indicators :

4 - Water consumption: The daily water consumption per capita (L/m2.day).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Total amount of water consumption (ℓ /day); Total project surface.

Calculation: Total amount of water consumption (ℓ /day)/Total project surface.

Interpretation and benchmark: A declining trend and lower values are considered positive. Typically, people in developed countries' cities use 272 litres per day, while the average in Africa is 53 litres per day.

#5 Manage rainwater locally

Objective:

Manages rainwater locally through reuse, infiltration, evaporation and other low impact techniques. The project must also ensure rainwater quality.

Attention points:

Low impact techniques and Nature-based solutions must be the priority.

Examples of urban solutions:

Wetlands systems; Phytoepuration; Infiltration pounds; Bioswales, Rainwater reuse.

Related Sustainable Development Goals:

6 CLEAN WATER AND SANITATION

11 SUSTAINABLE CITIES AND COMMUNITIES

14 LIFE BELOW WATER

Related indicators :

5 - Rainwater management: The proportion of annual stormwater managed (reused, infiltered, evapotranspired...) at the site level - (%).

Method: Spreadsheets or hydrological modelling software.

Required data: Total rainwater; Rainwater managed locally.

Calculation: (Total rainwater/Rainwater managed locally)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

6 - Pervious surface: The share of permeable surface in relation to the total project surface - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Permeable surface; Total project surface.

Calculation: (Permeable surface/Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#6 Manage wastewater sustainably

Objective:

Reduce wastewater production and sustainably manage it. Whenever possible systemic and local solutions must be employed. Otherwise, the wastewater must be direct towards a mutualised shared treatment facility.

Attention points:

Economy of scale: Even if local solutions are possible and relevant, it is necessary to think from an economy of scale perspective and use existing collective infrastructure with remaining capacity, avoiding extra embodied carbon.

Examples of urban solutions:

Fixtures upgrade; Phytoepuration systems; Bioreactors.

Related Sustainable Development Goals:

Related indicators :

7 - On-site wastewater management: The share of total annual wastewater generated that is managed on-site with low impact techniques - (%).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Annual wastewater generated; Annual wastewater generated that is managed on site used low impact techniques.

Calculation: (Annual wastewater generated that is managed on-site using low impact techniques/Annual wastewater generated)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#7 Promote construction materials circularity

Objective:

Encourage a circular economy approach for the constructions materials. It must reduce the total materials needs, reduce construction waste generation and maximise the use of demolition, salvaged, reused and recycled materials.

Attention points:

The project should also explore how to design for disassembly, reuse and retrofitting, to face climate and context changes.

Examples of urban solutions:

Reused and salvaged materials; Reduced materials need; Design for disassembly.

Related Sustainable Development Goals:

Related indicators :

8 - Material Circulatory Indicator: The indicator measures the degree of circularity of a system, with a value from 0 to 1. It is calculated from the estimated amount of virgin, recycled and reused materials used in construction, the amount of waste generated at the end of the life cycle and a factor related to the project's usage rate.

Method: LCA, BIM or spreadsheets.

Required data: Data on the estimated amount of virgin, recycled and reused materials used in construction, the amount of waste generated at the end of the life cycle and a factor related to the project's usage rate.

Calculation: For a detailed method and data requirements refer to Circularity Indicators An approach to measuring circularity - Methodology (Ellen MacArthur Foundation).

Interpretation and benchmark: An improving trend and higher values are considered positive. The indicator goes from 0 to 1, and it should be the closest to 1 as possible. This indicator is still experimental, and adaptations may be necessary for a built space context.

#8 Prioritise retroffiting and rehabilitation

Objective:

Minimise new construction to reduce pressure and impacts on ecosystems. The focus should be given to rehabilitation/renovation and retrofitting of existing buildings, public spaces, and infrastructures.

Attention points:

The best option to reduce impacts may be in not building and relying on existing structures. Design teams must seriously explore available options.

Examples of urban solutions:

GRettroffiting; Reduce new infrastructure; Redesign; Urban requalification and renewal.

Related Sustainable Development Goals:

Related indicators :

9 - Retrofitting rate: The share of the project's floor area targeted for retrofitting, redevelopment or rehabilitation of existing infrastructure- (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Renovation, retrofitting and rehabilitation total floor surface; Total project floor surface.

Calculation: (Renovation, retrofitting and rehabilitation total floor surface/ Total project floor surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

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#9 Use low risk materials

Objective:

Prioritise building materials with low impact on human and ecosystem health to ensure healthy lives and ecosystems.

Attention points:

Low-risk materials can be applied on several scales, from public space to interior design. Bio-sourced and biomimetic materials hold a high opportunity to fulfil this requirement.

Examples of urban solutions:

Bio-sourced and biomimetic materials; ILFI DECLARE products; ILFI Red List materials.

Related Sustainable Development Goals:

- 3 GOOD HEALTH AND WELL-BEING
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 14 LIFE BELOW WATER
- 15 LIFE ON LAND

Related indicators :

10 - Low-risk materials: The share (in mass) of building materials that avoid toxic chemicals from the International Living Future Institute RED List.

Method: LCA, BIM or spreadsheets.

Required data: Total mass of new building materials; Total mass of new building materials that avoid ILFI RED List.

Calculation: (Total mas of new building materials that avoid ILFI RED List/Total mass of new building materials)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#10 Reduce embodied carbon

Objective:

Seek embodied carbon neutrality. The project must minimise its carbon print and maximise sequestration and offset for the built infrastructure.

Attention points:

Decision-makers and designers must keep in mind a life cycle perspective, avoiding only displacing impacts and acting in the whole life cycle of the building construction. The best global solution for each project must be evaluated, aiming to reduce impacts and emissions from a global perspective, using Life Cycle Analysis and simplified carbon footprint tools.

Examples of urban solutions:

Use biomaterials; Source materials locally; Reduce materials need; New construction techniques such as 3D printing; Carbon sequestration; Carbon compensation.

Related Sustainable Development Goals:

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION

Related indicators :

11 - Embodied carbon: The total embodied carbon balance in the construction, accounting for emissions (including energy consumed in construction and material production), sequestrations and offsets ($kgCO2eq/m^2$).

Method: LCA.

Required data: Total embodied carbon emissions; Carbon sequestered on the project; Carbon emissions offset after construction; Total project surface.

Calculation: (Total embodied carbon emissions - Carbon sequestered on the project - Carbon emissions offset after construction)/Total project surface.

Interpretation and benchmark: A declining trend and lower values are considered positive. The RE 2020 regulation sets as 490 $kgCO2eq/m^2$) the maximum average for Total embodied carbon emissions in collective housing projects for 2031.

#11 Promote low carbon life styles

Objective:

Design a project that actively reduces the overall carbon emissions during its use phase. The project makes it possible to inhabitants to have a less carbon-intensive lifestyle and has solutions to sequester and offset remaining emissions.

Attention points:

Sequestering and offsetting should be taclked with lower priorities than reducing emissions.

Examples of urban solutions:

Transit oriented design (TOD); Densification; Mixed-use; Shared vehicles; Cycling infrastructure.

Related Sustainable Development Goals:

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION

Related indicators :

12 - Annual GHG balance: Annual GHG footprint (in project use phase), accounting for emissions, sequestration and offsets on a per capita basis - (kgCO2eq/m²).

Method: Spreadsheets using exploitation data or doing a modelled forecast; Carbon balance software.

Required data: Total annual carbon emissions; Annual carbon sequestration; Annual carbon emissions offsetted; Total project surface.

Calculation: (Total annual carbon emissions - Annual carbon sequestration - Annual carbon emissions offsetted)/Total project surface.

Interpretation and benchmark: A declining trend and lower values are considered positive.

#12 Enhance local food production

Objective:

Encourage local food production to improve food security and resilience.

Attention points:

Food production must aim for diversity and be adapted to local culture and biome. It is also essential to prioritise low impact techniques such as agroforestry systems and organic productions.

Examples of urban solutions:

Collective gardens; Private gardens; Agroforestry.

Related Sustainable Development Goals:

Related indicators :

13 - Food production area: The share of the project surface dedicated to different urban agriculture solutions - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Surface of areas designated for urban agriculture; Total project surface.

Calculation: (Surface of areas designated for urban agriculture/Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#13 Minimise pesticides and fertilisers

Objective:

Reduce the use of pesticides, biocides and petrochemical fertilisers in green area management. Priority must be given to alternative strategies contributing to the ecosystem and human health.

Attention points:

Increasing urban agriculture solutions must be done in consonance with this strategy.

Examples of urban solutions:

Adaptative management of green spaces;

Related Sustainable Development Goals:

Related indicators:

14 - Fertilisers and pesticides: The share of the project area managed under a zero pesticide, biocide and petrochemical fertiliser policy - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Total surface managed without the use of pesticides, biocides and petrochemical fertilisers; Total project surface.

Calculation: (Total surface managed without the use of pesticides, biocides and petrochemical fertilisers/Total project surface)x100

Interpretation and benchmark: An improving trend and higher values are considered positive.

#14 Manage waste sustainably

Objective:

Encourage the reduction of waste production and sustainably manage and valorise the remaining production, diverting the total amount that must go to landfills. When possible, local, sustainable solutions must be the priority.

Attention points:

It is necessary to think from an economy of scale perspective and use existing collective infrastructure with remaining capacity, avoiding extra embodied carbon for building new infrastructures. Energetic valorisation should be used with less priority than reuse and recycling strategies.

Examples of urban solutions:

Composting; Bioprocessing; Recycling; Reuse.

Related Sustainable Development Goals:

Related indicators :

15 - Local organic waste management: The share of organic waste collected and recovered on site (composting, anaerobic digestion...) - (%).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: The annual total collected organic waste recovered on site; The annual total produced organic waste.

Calculation: (The annual total collected organic waste recovered on-site/The annual total produced organic waste)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#14 Manage waste sustainably

16 - Rate of landfilling: The share of total annual waste collected that is landfilled - (%).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Total annual amount of waste landfilled; Total annual amount of waste managed.

Calculation: (Total annual amount of waste landfilled/Total annual amount of waste managed)x100.

Interpretation and benchmark: When the total amount of the generated waste is dully managed, a declining trend and lower values are considered positive

17- Rate of recycling: The share of total annual waste collected that is recycled - (%).

Method: Spreadsheets using exploitation data or doing a modelled forecast.

Required data: Total annual amount of waste recycled; Total annual amount of waste managed.

Calculation: (Total annual amount of waste recycled/Total annual amount of waste managed)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#15 Protect and restore natural and sensible areas

Objective:

Protect and restore natural/sensible/health areas on the project site.

Attention points:

Particular attention should be given to protecting existing natural areas, keeping unsealed soil, conserving natural topography, protecting wet ecosystems, and restoring contaminated or degraded soils.

Examples of urban solutions:

Soil restoration; Wet ecosystem rehabilitation; Protection of sensible areas.

Related Sustainable Development Goals:

Related indicators :

18 - Protection of sensitive areas: The share of the project's terrestrial or wet areas designated as protected - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: The share of the project's terrestrial or wet areas designated as protected; Total project surface.

Calculation: (The share of the project's terrestrial or wet areas designated as protected/ Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#15 Protect and restore natural and sensible areas

19 - Ecological restoration: The share of project terrestrial or wet areas targeted for ecological restoration - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: The share of project terrestrial or wet areas targeted for ecological restoration; Total project surface.

Calculation: (The share of project terrestrial or wet areas targeted for ecological restoration/ Total project surface)x100

Interpretation and benchmark: An improving trend and higher values are considered positive.

20 - Topography changes: The proportion of the project area that has undergone topography changes - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: The area of the project that has undergone topography changes; Total project surface.

Calculation: (The area of the project that has undergone topography changes/ Total project surface)x100.

Interpretation and benchmark: A declining trend and lower values are considered positive.

21 - Soil restoration: The share of the project area targeted for restoration of soil structure or quality - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Project area targeted for restoration of soil structure or quality; Total project surface.

Calculation: (Project area targeted for restoration of soil structure or quality/ Total project surface)x100).

Interpretation and benchmark: An improving trend and higher values are considered positive.

#16 Reduce land take

Objective:

Reduce land take and avoid urban sprawling. The project should prioritise already urbanised areas and compensate for any new land taken.

Attention points:

Compensation should, in priority, be done inside the same watershed.

Examples of urban solutions:

Densification; Reforestation.

Related Sustainable Development Goals:

Related indicators :

22 - Project area built on urbanised areas: The share of the project area built on already urbanised areas - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: The share of the project area built on already urbanised areas; Total project surface.

Calculation: (The share of the project area built on already urbanised areas; Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#16 Reduce land take

23 - Compensation of artificialisation: The share of the equivalent project area set aside for protection or restoration (outside the project site) in the form of compensation for artificialisation caused by the project - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Project area set aside for protection or restoration (outside the project site) in the form of compensation for artificialisation caused by the project; Total project surface.

Calculation: (Project area set aside for protection or restoration (outside the project site) in the form of compensation for artificialisation caused by the project/ Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.

#17 Provide natural habitat

Objective:

Provide natural habitat diversity to host endemic species and support biodiversity.

Attention points:

Even if artificial habitats are welcome (as nests and other structures), focus should be given to the natural habitat potential.

Examples of urban solutions:

Enhance the diversity of natural habitats for local relevant specie; Increase vegetated surface; Use Nature-based solutions; Use of complex and site-adapted vegetation schemes; Invasive species management; Artificial habitats.

Related Sustainable Development Goals:

11 SUSTAINABLE CITIES AND COMMUNITIES

14 LIFE BELOW WATER

15 LIFE ON LAND

Related indicators :

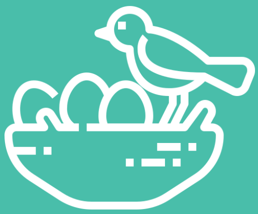
24 - Urban green space: The share of natural areas in the total project surface - (%).

Method: Spreadsheets or GIS using project surface data.

Required data: Natural areas surface; Total project surface;

Calculation: (Natural areas surface/Total project surface)x100.

Interpretation and benchmark: An improving trend and higher values are considered positive.



#17 Provide natural habitat

25 - Biotope Area Factor: The amount of area available for nature and vegetation in relation to the total project surface, weighted by a specific coefficient for each type of cover, related to its potential for vegetation growth and hosting biodiversity, ranging from 0 to 1.

Method: Spreadsheets or GIS using project surface data.

Required data: Different ecological surface areas per type; Total project surface; Coefficients.

Calculation: ((surface area type A x coef. A) + (surface area type B x coef. B) + ... + (surface area type N x coef. N))/total project surface.

Interpretation and benchmark: An improving trend and higher values are considered positive. For the coeficients value we advise using the Clergeau et Provendier (2017, Plante&Cité) grid. For instance, Berlin enforces a BAF between 0,3 and 0,6. CSTB is developing a new methodology that must be used once published.

#18 Enhance the ecological network

Objective:

Promote ecological connectivity, creating green and blue networks.

Attention points:

Connectivity must happen inside the plot, creating connectivity between habitat patches and outside the plot, promoting connectivity with the surroundings' green and blue networks.

Examples of urban solutions:

Geothermal; Wind energy; Solar Energy; Waves energy...

Related Sustainable Development Goals:

Related indicators :

26 - Connectivity of green spaces (outside the plot): Integral connectivity index within the project area, calculated based on the area of habitat plots and links to other paths, ranging from 0 to 1.

Method: Graphab/GIS using project surface data.

Required data: Land use data inside and around the project.

Calculation: Graphab/GIS using project surface data.

Interpretation and benchmark: An improving trend and higher values are considered positive. For detailed method consult Saura and Pascual-Hortal (2007).

B. Appendix from section 3.2

This section presents the different appendix from Chapter 3, section 2, related to the paper *Indicators for Regenerative neighbourhood design: an indicator set definition*. They were moved here to improve the document readability.

Appendix 1 – Taxonomy of urban strategies contributing to the production of ecosystems services at the neighbourhood scale from Blanco et al. (2022).

Dimension	Topic	Strategies
Energy flows	Electricity	Uses and/or produces renewable energy
		Has solutions to reduce the energy consumption in the neighbourhood
		Has a local energy storage infrastructure
	Heat and light	It was designed to optimise the solar input on blocks and buildings
		Has solutions to share heat and energy between blocks and buildings
		Minimises light and noise impacts
Material flows	Water resources	Reduces the total water consumption in the neighbourhood
		Manages rainwater locally (reuse, infiltration, evaporation…)
		Manages wastewater/greywater locally
	Building materials	Uses demolition, salvaged and recycled materials for building construction
		Retrofitted existing buildings and infrastructures
		Prioritises the use of building materials with low impact on human and ecosystem health
		Sourced building materials locally
		It was designed to reduce the need for building materials
		It was designed to be adaptable, retrofitted, reused and/or deconstructed
		Sought embodied carbon neutrality
	Carbon	Sequestered/compensated carbon emissions from use phase
		The urban form was designed to reduce carbon emissions (high density, mixed-use…)
		Has sustainable urban mobility strategies to reduce carbon emissions
	Food	Produces food locally
	Chemical products	Restricts the use of phytosanitary products on its management
	Waste	Manages organic waste locally
		Recycles and sustainably manages domestic waste
		Has solutions to reduce the local waste production
Abiotic Structure	Water bodies	Restored water bodies/wet ecosystems
		Limited the development over aquatic ecosystems/wet zones
	Soil	Avoided soil sealing/unsealed soil
		Avoided topography changes
		Limited the development over natural, healthy or sensible areas (as greenlands, farmlands, flood areas, special interest areas...)
		Compensated the urbanised area protecting other natural areas
		Has solutions to improve the soil quality and fertility
	Air	Has solutions to improve the neighbourhood air quality
Biotic structure	Flora	Has solutions to increase the amount and diversity of vegetated spaces
		Connects to the local ecological network
		Uses complex and site-appropriated vegetation schemes
		Reintroduces indigenous flora species
		Manages invasive flora species
	Fauna	Provides natural habitat diversity to host indigenous species
		Reintroduces indigenous fauna species
		Design artificial abiotic habitat structures for fauna
		Avoid the fragmentation of exiting natural habitat
		Manages invasive fauna species

Appendix 2 - Survey questionnaire (in French)

Indicateurs des projets urbains régénératifs

Cette enquête s'inscrit dans le cadre d'une recherche doctorale en collaboration avec le Muséum National d'Histoire Naturelle. Elle vise à évaluer l'opérationnalité et faisabilité d'un jeu de 39 indicateurs ex-ante et ex-post liés aux performances environnementales et écologiques des projets urbains, pour intégrer un outil d'aide à la décision. Nous ciblons des réponses par des acteurs français de la pratique et de la recherche de l'écologie urbaine, du développement durable et de l'urbanisme.

Chaque indicateur doit être évalué selon leur facilité d'usage par des acteurs opérationnels dans la phase de CONCEPTION des projets urbains. C'est-à-dire, la faisabilité de la collecte de données, de calcul et de la surveillance à un cout raisonnable.

Il vous faudra environ 10 minutes pour répondre ce questionnaire.

Évaluation des indicateurs

Évaluez les indicateurs selon leur facilité opérationnelle: la faisabilité de la collecte de données, de calcul et de la surveillance, à un cout et effort raisonnable.
Parmi les indicateurs, vous trouverez des indicateurs ex-ante, que peuvent être calculés dans les phases de conception avec des donnés du projet, et des indicateurs ex-post, plutôt liés à la performance du projet en phase d'exploitation. Dans le cas des indicateurs ex-post (comme les consommations d'eau, d'énergie et la production des déchets), gardez en tête qu'une première évaluation pendant la phase de conception du projet peut être réalisée basé sur les engagements et estimations du projet, avec une validation à postériori dans la phase d'exploitation.
Si vous ne vous sentez pas légitime à opiner sur quelques indicateurs, vous pouvez utiliser l'option "Je ne sais pas".

1. Energie et chaleur
*

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Énergies renouvelables : La part de la consommation annuelle totale d'énergie dérivée de sources renouvelables (uniquement non combustibles) - (%).	○	○	○	○	○	○
Production décentralisée d'énergie : La part de l'énergie totale annuelle qui provient de systèmes de production décentralisés ou sur site - (%).	○	○	○	○	○	○
Épuisement des ressources - combustibles fossiles : L'épuisement des ressources énergétiques fossiles promues par le projet – (calculé via méthode d'analyse de cycle de vie, MJ equivalent).	○	○	○	○	○	○
Consommation d'électricité : La consommation annuelle totale par habitant – (kWh/année /habitant)	○	○	○	○	○	○
Surface à fort albédo : La part de la surface du projet couverte par des matériaux à albédo élevé (>0,75) - (%).	○	○	○	○	○	○

2. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

3. Gestion de l'eau
*

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Consommation d'eau : La consommation quotidienne d'eau par habitant (L/jour /habitant).	○	○	○	○	○	○
Gestion des eaux pluviales : La part de l'eau pluviale annuelle gérée à l'échelle du site - (%).	○	○	○	○	○	○
Surface perméable : La part de la surface perméable par rapport à la surface totale du projet - (%).	○	○	○	○	○	○
Gestion des eaux usées : La part du total annuel des eaux usées produites qu'est gérée sur le site avec des techniques à faible impact - (%).	○	○	○	○	○	○

4. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

5. Construction *

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Circularité des matériaux : L'indicateur mesure le degré de circularité d'un système, avec une valeur de 0 à 1. Il est calculé à partir de l'estimation de la quantité de matériaux vierges, recyclés et réutilisés employés dans la construction, la quantité de déchets générés à la fin du cycle de vie et d'un facteur lié au taux d'utilisation du projet.	○	○	○	○	○	○
Taux de rénovation: La part de la surface de plancher du projet cible de rénovation, de réaménagement ou de réhabilitation d'infrastructures existantes- (%).	○	○	○	○	○	○
Matériaux à faible risque pour la santé globale : La part (en masse) des matériaux de construction qui évitent les produits chimiques toxiques figurant sur la RED list de l'«International Living Future Institute» (LBC).	○	○	○	○	○	○
Distance moyenne de la source des matériaux : La moyenne pondérée (en masse) de la distance entre la source des matériaux de construction et le site du projet.	○	○	○	○	○	○

6. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

7. Gaz à effet de serre

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Carbone incorporé : Le bilan total de carbone incorporé dans la construction, en comptabilisant les émissions (y compris l'énergie consommée pour la construction et pour la production des matériaux), les séquestrations et les compensations (tonnes eq. CO2).	○	○	○	○	○	○
Bilan carbone annuel: Bilan annuel de GES (phase d'exploitation du projet), comptabilisant les émissions, la séquestration et la compensation par habitant - (tonnes eq. CO2/habitant).	○	○	○	○	○	○

8. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

9. Production alimentaire
*

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Production alimentaire : La part de la surface du projet consacrée aux différentes solutions de l'agriculture urbaine - (%).	○	○	○	○	○	○
Engrais et pesticides: La part de la surface du projet gérée dans le cadre d'une politique zéro pesticide, biocide et engrais pétrochimique - (%).	○	○	○	○	○	○

10. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

11. Gestion des déchets
*
(en phase d’exploitation du projet)

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Production de déchets : La production annuelle de déchets solides par habitant (kg/année /habitant).	○	○	○	○	○	○
Déchets organiques valorisés : La part du total des déchets organiques collectés qu'est valorisé (compostage, méthanisation...) - (%).	○	○	○	○	○	○
Gestion locale des déchets organiques : La part des déchets organiques collectés et valorisés sur site (compostage, méthanisation...) - (%).	○	○	○	○	○	○
Valorisation énergétique des déchets : La part du total des déchets collectés qu’est valorisé énergétiquement - (%).	○	○	○	○	○	○
Mise en décharge des déchets : La part du total des déchets annuels collectés qu’est mise en décharge - (%).	○	○	○	○	○	○
Recyclage des déchets : La part du total des déchets annuels collectés qu’est recyclée- (%).	○	○	○	○	○	○

12. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

13. Air, sol et milieux humides
*

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Protection et restauration des écosystèmes humides et aquatiques : La part des zones humides du projet protégées ou cibles de restauration écologique - (%).	○	○	○	○	○	○
Protection des zone terrestres sensibles : La part des zones terrestres du projet désignées comme protégées - (%).	○	○	○	○	○	○
Restauration des zones terrestres: La part des zones terrestres du projet cibles de restauration écologique - (%).	○	○	○	○	○	○
Surface du projet construite sur des zones urbanisés : La part de la surface du projet construite sur des friches et zones déjà urbanisées - (%).	○	○	○	○	○	○
Compensation de l'artificialisation : La part de la surface équivalente du projet mise de côté sous protection ou restaurée (en dehors du site de projet) en forme de compensation de l'artificialisation mené par le projet - (%).	○	○	○	○	○	○
Topographie : La part de la surface du projet qu'a subi des modifications de relief - (%).	○	○	○	○	○	○
Restauration du sol : La part de la surface du projet cible de restauration de la structure ou de la qualité du sol - (%).	○	○	○	○	○	○
Polluants atmosphériques capturés : Quantité annuelle de polluants capturés par la végétation ou par d'autres techniques de traitement - (kg/ha/année).	○	○	○	○	○	○

14. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

____

15. Espaces verts
*

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Disponibilité d'espaces naturels : La surface d'espaces verts par habitant - (m2/habitants).	○	○	○	○	○	○
Espace vert urbain : La part des zones à caractère naturel sur la surface totale du projet - (%).	○	○	○	○	○	○

16. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

17. Biodiversité *

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Végétation indigène : Le rapport entre le nombre d'espèces végétales indigènes et la richesse totale végétale (nombre total d'espèces) du site de projet - (%).	○	○	○	○	○	○
Faune indigène: Le rapport entre le nombre d'espèces de faune indigène et la richesse totale de faune (nombre total d'espèces) du site de projet - (%).	○	○	○	○	○	○
Coefficient de biotope : La quantité de surface disponible pour la nature et la végétation par rapport à la surface totale considérée, pondérée par un coefficient spécifique pour chaque type de couverture, lié à son potentiel de croissance végétale et d'accueil de la biodiversité.	○	○	○	○	○	○

	Très faisable	Faisable	Neutre	Pas faisable	Pas du tout faisable	Je ne sais pas
Connectivité des espaces verts (à l'intérieur de la parcelle) : Indice intégral de connectivité à l'intérieur de la zone du projet, calculé sur la base de la surface des parcelles d'habitat et des liens avec d'autres sentiers, allant de 0 à 1 (calculé sur des logiciels d'information géographique ou Graphab).	○	○	○	○	○	○
Connectivité des espaces verts (à l'extérieur de la parcelle): Indice intégral de connectivité dans la zone d'influence du projet, calculé sur la base de la surface des parcelles d'habitat et des liens avec d'autres chemins, compris entre 0 et 1 (calculé sur des logiciels d'information géographique ou Graphab).	○	○	○	○	○	○
Diversité de Shannon des habitats : Calculé sur la base de la présence et de l'abondance des différents types de biotopes sur la zone du projet. Il indique la complexité de la structure de la végétation et le potentiel de la biodiversité (idéalement calculé sur des logiciels d'information géographique).	○	○	○	○	○	○

18. Avez-vous d'autres pistes d'indicateurs que vous trouvez pertinents pour la thématique présentée ci-dessus ou de commentaires génériques sur les indicateurs présentés?

Informations additionnelles

19. Pensez-vous qu'u outil d'aide à la décision, appuyé sur une sélection des indicateurs ici présentés, est pertinent pour faciliter la conception de projets urbains vertueux et producteurs de bénéfices mutuels à la société et aux écosystèmes?
 *

 Cet outil vise à faciliter la définition d'objectifs, engagements, stratégies et solutions d'aménagement pour réduire la pression du projet sur les écosystèmes, promouvoir la régénération de la structure de ces derniers et par conséquent augmenter le potentiel de production de services écosystémiques urbains du projet. L'outil en question sera compose par: 1) Des fiches qui présenteront de stratégies d'aménagement et pistes de solutions techniques, et 2) Par un jeu d'indicateurs accompagné des fiches descriptives, avec l'objectif de l'indicateur, la méthode de calcul et des benchmarks.

	Tres pertinent	Pertinent	Neutre	Pas pertinent	Pas du tout pertinent
Pertinence de l'outil	○	○	○	○	○

20. A quelle typologie d'acteurs appartenez-vous ? *

 ○ Maîtrise d'ouvrage publique

 ○ Maîtrise d'ouvrage privée

 ○ Maîtrise d'œuvre

 ○ Bureau d'études environnement

 ○ Recherche scientifique

 ○ Fédération, syndicat, association, centre d'expertise...

 ○ [ ] Other

21. Y a-t-il des commentaires supplémentaires que vous souhaiteriez nous communiquer ?

22. Si vous voulez suivre les résultats de cette recherche, merci de renseigner votre adresse e-mail.

Appendix 3 – Identified indicators (733 indicators)

#	Indicator	Source
1	Production of food	REGREEN
2	Soil infiltration capacity;	REGREEN
3	% sealed relative to permeable surface (ha);	REGREEN
4	Leaf Area Index;	REGREEN
5	Temperature decrease by tree cover×m2 of plot trees cover ;	REGREEN
6	Leaf area (m2) and distance to roads (m);	REGREEN
7	Noise reduction dB(A)/ vegetation unit (m);	REGREEN
8	O3,SO2,NO2, CO, and PM10 µm removal (tons yr−1) multiplied by tree cover (m2);	REGREEN
9	Cover density of vegetation barriers separating built areas from the sea;	REGREEN
10	P, K, Mg and Ca in mgkg−1 compared to given soil/water quality standards;	REGREEN
11	CO2 sequestration by trees (carbon multiplied by 3.67 to convert to CO2);	REGREEN
12	Species diversity and abundance of birds and bumble bees;	REGREEN
13	Surface of green public spaces (ha)/inhabitant (or every 1000 inhabitants);	REGREEN
14	Abundance of birds, butterflies and other animals valued for their aesthetic attributes;	REGREEN
15	Reduction of premature deaths and hospital admissions	REGREEN
16	Reduction of human deaths	REGREEN
17	Number of persons with change from annoyed to not annoyed	REGREEN
18	dB(A) change per person/household per year	REGREEN
19	Reduction of number and frequency of combined sewage overflow	REGREEN
20	Reduction of localised flooding	REGREEN
21	Total number of people and number of vulnerable people exposed to the cooling effect of urban green infrastructure	REGREEN
22	Reduction in cumulative population-risk weighted exceedance heat index	REGREEN
23	Monetary benefits based on avoided externalities	REGREEN
24	Return on investment of tree planting (beneficiaries*mitigation/cost)	REGREEN
25	Monetary value based on estimated marginal social costs of carbon	REGREEN
26	Monetary value based on carbon market prices	REGREEN
27	Replacement cost of engineering structures	REGREEN
28	Economic value of noise reduction based on hedonic pricing	REGREEN
29	Avoided damage based on the total value of properties protected	REGREEN
30	Avoided damage based on specific depth-damage functions for different	REGREEN
31	Replacement cost of manmade	REGREEN
32	Savings based on replacement cost	REGREEN
33	Average Carbon storage	REGREEN
34	Community gardens/allotments for food self-consumption per inhabitant	REGREEN
35	Share of water surface	REGREEN
36	Shares of wetlands for water regulation	REGREEN
37	Vegetation areas alongside with watercourses for water regulation	REGREEN
38	Share of green areas in municipal districts in danger of floods	REGREEN
39	Share areas of municipal districts potentially exposed to urban flooding	REGREEN
40	Cooling effects of GI compared to sealed surfaces	REGREEN
41	Recreation spaces per inhabitant	REGREEN
42	Total areas of urban alluvial forests for habitat, species and genetic diversity	REGREEN
43	Areas exposed to extreme flood risk	REGREEN
44	Share of areas exposed to flooding	REGREEN

45	Share of population exposed to flood risk	REGREEN
46	Population without urban green spaces in their neighbourhood	REGREEN
47	Increased physical activities in GI areas	REGREEN
48	Employment in directly GI related sectors (agriculture, forestry, and fisherie)	REGREEN
49	Residential land and property increment value (1 km from green areas)	REGREEN
50	Total number of visits specially related to education or for cultural reasons	REGREEN
51	Economic benefit of reduction of stormwater to be treated in public sewerage system	REGREEN
52	Reduced energy demand for heating and cooling	REGREEN
53	Jobs created	REGREEN
54	Nutrient abatement, abatement of pollutants	REGREEN
55	Reduced energy demand for heating and cooling	REGREEN
56	Net carbon sequestration by urban forests (including GHG emissions from maintenance activities)	REGREEN
57	Annual amount of pollutants captured and removed by vegetation	REGREEN
58	Increased evapotranspiration	REGREEN
59	Temperature reduction in urban areas	REGREEN
60	Heatwave risks	REGREEN
61	Temperature	REGREEN
62	Infiltration capacities	REGREEN
63	User values attached to green/blue areas	REGREEN
64	Index of biodiversity	REGREEN
65	Number of users and public awareness	REGREEN
66	% of accessible public green space per capita	REGREEN
67	% of citizens living within a given distance from accessible public green space	REGREEN
68	The availability and distribution of different types of parks and/or ecosystem services with respect to specific individual or household socioeconomic profiles and landscape design	REGREEN
69	Security against violent assault, including indicators of crime by time of day	REGREEN
70	Being able to participate effectively in political choices that govern one's life, including indicators on level and quality of public participation in environmental management	REGREEN
71	Structural aspects - family and friendship ties	REGREEN
72	Chronic stress and stress-related diseases as shown in cortisol levels	REGREEN
73	Increase in number and percentage of people being physically active (min. 30 min 3 times/week)	REGREEN
74	Reduced percentage of obese people and children	REGREEN
75	Reduction in overall mortality and increased lifespan	REGREEN
76	Reduction in number of cardiovascular morbidity and mortality events	REGREEN
77	Land annually taken for built-up areas/person	REGREEN
78	Soil sealing	REGREEN
79	Number of combined tropical nights (above 20 °C) and hot days (above 35 °C)	REGREEN
80	Emissions of NO_2, PM_{10}, $PM_{2.5}$	REGREEN
81	Number of annual occurrences of maximum daily 8 hour mean of $O_3 > 120$ µg/m3	REGREEN
82	Number of annual occurrences of 24 hour mean of $PM_{10} > 50$ µg/m3	REGREEN
83	Number of annual occurrences of hourly mean of $NO_2 > 200$ µg/m3	REGREEN
84	Number of annual occurrences of (traffic noise at levels exceeding 55 db(A) during the day and 50 db(A) during the nights (possibly broken down over the source of noise)	REGREEN
85	Number of annual introductions of invasive alien species*	REGREEN
86	Urban temperature	REGREEN
87	Noise level	REGREEN

88	Percentage of population exposed to road noise within urban areas above 55 dB during the day and above 50 dB during the night	REGREEN
89	Percentage of population exposed to air pollution above the standards	REGREEN
90	Concentration of air pollutants NO_2, PM10, PM2.5, O_3	REGREEN
91	Concentration of nutrients and biological oxygen demand in surface water	REGREEN
92	Bathing water quality	REGREEN
93	Percentage of population connected to urban waste water collection and treatment plants	REGREEN
94	Number of inhabitants per area	REGREEN
95	Artificial area per inhabitant (m2/person)	REGREEN
96	Length of the road network per area	REGREEN
97	Percentage of built-up area	REGREEN
98	Weighted Urban Proliferation	REGREEN
99	Imperviousness	REGREEN
100	Sites with contaminated soil	REGREEN
101	Percentage of urban green space	REGREEN
102	Percentage of natural area	REGREEN
103	Percentage of agricultural area	REGREEN
104	Percentage of abandoned area	REGREEN
105	Canopy coverage	REGREEN
106	Foliage damage crown dieback	REGREEN
107	Connectivity of urban green spaces	REGREEN
108	Fragmentation of urban green space	REGREEN
109	Number and abundance of bird species	REGREEN
110	Number of lichen species	REGREEN
111	Number of invasive alien species	REGREEN
112	Percentage of urban ecosystems covered by Natura 2000 area	REGREEN
113	Bulk density	REGREEN
114	Soil organic carbon (SOC)	REGREEN
115	Soil biodiversity	REGREEN
116	Earthworms	REGREEN
117	Available water capacity	REGREEN
118	Annual carbon sequestration	Nature4Cities
119	Avoided GHG emissions	Nature4Cities
120	Air temperature	Nature4Cities
121	Adaptive Comfort (indoor)	Nature4Cities
122	Thermal Comfort Score (outdoor)	Nature4Cities
123	Physiological equiv. temperature	Nature4Cities
124	Peak flow variation	Nature4Cities
125	Stormwater quality	Nature4Cities
126	Total rainfall volume	Nature4Cities
127	Water Detention Time	Nature4Cities
128	Common Air Quality Index	Nature4Cities
129	Exceedance of air quality limit value – Local scale	Nature4Cities
130	Urban Green Space Proportion	Nature4Cities
131	Shannon Diversity Index of Habitats	Nature4Cities
132	Biotope Area Factor	Nature4Cities
133	Connectivity of green spaces	Nature4Cities

134	Normalized Difference Vegetation Index	Nature4Cities
135	Sustainable Practices Index	Nature4Cities
136	Soil biological activity	Nature4Cities
137	Soil classification Factor	Nature4Cities
138	Energy Security	Nature4Cities
139	Per Capita Food Production Variability	Nature4Cities
140	Buildings Energy needs	Nature4Cities
141	Cumulative Energy Demand	Nature4Cities
142	Water scarcity	Nature4Cities
143	Raw Material Efficiency	Nature4Cities
144	Specific waste generation	Nature4Cities
145	Efficiency of valorisation as a result of recycling processes	Nature4Cities
146	Day-evening-night noise level	Nature4Cities
147	Effects of night noise on health	Nature4Cities
148	Quality of life	Nature4Cities
149	Perceived health	Nature4Cities
150	Heat induced mortality	Nature4Cities
151	Air quality indicators: short term health effects	Nature4Cities
152	Air quality indicators: long term health effects	Nature4Cities
153	Recognition	Nature4Cities
154	Procedural justice	Nature4Cities
155	Distributional justice	Nature4Cities
156	Capabilities	Nature4Cities
157	Responsibility	Nature4Cities
158	Social capital	Nature4Cities
159	Accessibility	Nature4Cities
160	Segregation Index	Nature4Cities
161	Percentage of gender violence	Nature4Cities
162	Percentage of victimization	Nature4Cities
163	Domestic Property Insurance Claims	Nature4Cities
164	Number of deaths and missing people	Nature4Cities
165	Construction and demolition waste	Nature4Cities
166	Material Circulatory Indicator	Nature4Cities
167	Gross Value Added in the local Environmental Good & Services sector	Nature4Cities
168	Adjusted Net Saving	Nature4Cities
169	House Pricing Index	Nature4Cities
170	Household Internet Access	U4SSC
171	Fixed Broadband Subscriptions	U4SSC
172	Wireless Broadband Subscriptions	U4SSC
173	Wireless Broadband Coverage	U4SSC
174	Availability of WIFI in Public Areas	U4SSC
175	Smart Water Meters	U4SSC
176	Water Supply ICT Monitoring	U4SSC
177	Drainage / Storm Water System ICT Monitoring	U4SSC
178	Smart Electricity Meters	U4SSC
179	Electricity Supply ICT Monitoring	U4SSC
180	Demand Response Penetration	U4SSC
181	Dynamic Public Transport Information	U4SSC

182	Traffic Monitoring	U4SSC
183	Intersection Control	U4SSC
184	Open Data	U4SSC
185	e-Government	U4SSC
186	Public Sector e-Procurement	U4SSC
187	R&D Expenditure	U4SSC
188	Patents	U4SSC
189	Small and Medium-Sized Enterprises	U4SSC
190	Unemployment Rate	U4SSC
191	Youth Unemployment Rate	U4SSC
192	Tourism Industry Employment	U4SSC
193	ICT Sector Employment	U4SSC
194	Basic Water Supply	U4SSC
195	Potable Water Supply	U4SSC
196	Water Supply Loss	U4SSC
197	Wastewater Collection	U4SSC
198	Household Sanitation	U4SSC
199	Solid Waste Collection	U4SSC
200	Electricity System Outage Frequency	U4SSC
201	Electricity System Outage Time	U4SSC
202	Access to Electricity	U4SSC
203	Public Transport Network	U4SSC
204	Public Transport Network Convenience	U4SSC
205	Bicycle Network	U4SSC
206	Transportation Mode Share	U4SSC
207	Travel Time Index	U4SSC
208	Shared Bicycles	U4SSC
209	Shared Vehicles	U4SSC
210	Low-Carbon Emission Passenger Vehicles	U4SSC
211	Public Building Sustainability	U4SSC
212	Integrated Building Management Systems in Public Buildings	U4SSC
213	Pedestrian infrastructure	U4SSC
214	Urban Development and Spatial Planning	U4SSC
215	Air Pollution	U4SSC
216	GHG Emissions	U4SSC
217	Drinking Water Quality	U4SSC
218	Water Consumption	U4SSC
219	Freshwater Consumption	U4SSC
220	Wastewater Treatment	U4SSC
221	Solid Waste Treatment	U4SSC
222	EMF Exposure	U4SSC
223	Noise Exposure	U4SSC
224	Green Areas	U4SSC
225	Green Area Accessibility	U4SSC
226	Protected Natural Areas	U4SSC
227	Recreational Facilities	U4SSC
228	Renewable Energy Consumption	U4SSC
229	Electricity Consumption	U4SSC

230	Residential Thermal Energy Consumption	U4SSC
231	Public Building Energy Consumption	U4SSC
232	Student ICT Access	U4SSC
233	School Enrolment	U4SSC
234	Higher Education Degrees	U4SSC
235	Adult Literacy	U4SSC
236	Electronic Health Records	U4SSC
237	Life Expectancy	U4SSC
238	Maternal Mortality Rate	U4SSC
239	Physicians	U4SSC
240	In-Patient Hospital Beds	U4SSC
241	Health Insurance/Public Health Coverage	U4SSC
242	Cultural Expenditure	U4SSC
243	Cultural Infrastructure	U4SSC
244	Informal Settlements	U4SSC
245	Expenditure on Housing	U4SSC
246	Gender Income Equality	U4SSC
247	Gini Coefficient	U4SSC
248	Poverty Share	U4SSC
249	Voter Participation	U4SSC
250	Child Care Availability	U4SSC
251	Natural Disaster Related Deaths	U4SSC
252	Disaster Related Economic Losses	U4SSC
253	Resilience Plans	U4SSC
254	Population Living in Disaster Prone Areas	U4SSC
255	Emergency Service Response Time	U4SSC
256	Police Service	U4SSC
257	Fire Service	U4SSC
258	Violent Crime Rate	U4SSC
259	Traffic Fatalities	U4SSC
260	Local Food Production	U4SSC
261	Connaissance des espèces	Plante&Cité
262	Identification des espaces à enjeux	Plante&Cité
263	Composition et structure végétale	Plante&Cité
264	Trame Verte et Bleue et connectivité des espaces verts	Plante&Cité
265	Niveau de connaissance et d'usages des sols	Plante&Cité
266	Coefficient de biotope par surface	Plante&Cité
267	Influence de la végétation et des zones d'eau sur le climat	Plante&Cité
268	Gestion des eaux pluviales	Plante&Cité
269	Diversité des formes d'agriculture urbaine	Plante&Cité
270	Disponibilité en espaces à caractère naturel en ville	Plante&Cité
271	Dégradation dans les espaces à caractère naturel	Plante&Cité
272	Plans de gestion des espaces verts	Plante&Cité
273	Minimisation des intrants utilisés	Plante&Cité
274	Gestion différenciée	Plante&Cité
275	Diversification des habitats faune / flore	Plante&Cité
276	Plans d'actions et dispositifs intégrant la biodiversité	Plante&Cité
277	Labellisations, chartes et démarches	Plante&Cité

278	Diversité et fonctionnement des partenariats	Plante&Cité
279	Formation et sensibilisation des agents et des élus	Plante&Cité
280	Actions de sensibilisation et de mobilisation	Plante&Cité
281	Perception de la nature en ville	Plante&Cité
282	Superficie du projet (Ha) (dont Ha d'espaces publics et espaces verts)	EcoQuartier
283	Densité bâtie brute et nette (Nombre d'équivalent logement/ha avec 1 équivalent logement pour	EcoQuartier
284	70 m2 SDP)(densité nette : hors espaces verts publics)	EcoQuartier
285	Coût total HT du projet / Ha aménagé (dont part foncier et part travaux)	EcoQuartier
286	Coût de fonctionnement HT du quartier (éclairage, espaces verts) / Ha aménagé	EcoQuartier
287	Participations publiques HT / m2 SDP (produite ou réhabilitée)(logement + autre bâti)	EcoQuartier
288	Description de l'offre de logement (répartition des logements selon typologie (T1, T2, T3, T4, T5) et financement (libre, aidée, social)	EcoQuartier
289	Qualité de l'offre de mobilité (pourcentage de logements et locaux d'activités distants de : moins de 500 m d'une station de tramway, de moins de 300 m d'une station de bus ou de voiture partagée ou moins de 3 km d'une gare ou d'une aire de co-voiturage (en zone non urbaine)	EcoQuartier
290	Desserte communication (% de bâtiments reliés au haut débit/à la fibre)	EcoQuartier
291	Part du quartier située dans une zone à risque naturel ou technologique (en précisant le niveau d'aléa)	EcoQuartier
292	Coefficient d'imperméabilisation (somme des surfaces imperméables/surface totale du secteur)	EcoQuartier
293	Satisfaction des habitants vis-à-vis de leur quartier et de leur logement	EcoQuartier
294	Attractivité résidentielle	EcoQuartier
295	Pratiques respectueuses de l'environnement	EcoQuartier
296	Surfaces urbanisées évitées	EcoQuartier
297	Impact sur les documents de planification	EcoQuartier
298	Impact sur les pratiques locales	EcoQuartier
299	Identification et valorisation des ressources et des potentiels mobilisés dans le projet	EcoQuartier
300	Typologie et diversité des acteurs impliqués dès l'amont et à chaque stade du projet (y compris en phase de gestion)	EcoQuartier
301	Approche en coût global	EcoQuartier
302	Qualité d'usage des espaces neufs et reconfigurés	EcoQuartier
303	Amélioration continue	EcoQuartier
304	Part d'espaces libres (non bâtis)	EcoQuartier
305	Projets collectifs	EcoQuartier
306	Adéquation des logements produits aux revenus des ménages et aux objectifs	EcoQuartier
307	Part des logements impactés par des nuisances	EcoQuartier
308	Sentiment de sécurité	EcoQuartier
309	Perméabilité du quartier	EcoQuartier
310	Valorisation du patrimoine	EcoQuartier
311	Identité locale et sentiment d'attachement des habitants et usagers à leur cadre de vie	EcoQuartier
312	Taux d'occupation des activités et commerces	EcoQuartier
313	Proximité des services de base	EcoQuartier
314	Circuits courts	EcoQuartier
315	Part des ménages utilisant un mode alternatif à la voiture pour le trajet domicile-travail, dont le co-voiturage	EcoQuartier
316	Offre alternative de services de partage ou de location de voiture ou autre véhicule	EcoQuartier
317	Services numériques	EcoQuartier

318	Ilots de chaleur urbain	EcoQuartier
319	Consommation énergétique des bâtiments	EcoQuartier
320	Déchets collectés	EcoQuartier
321	Consommation moyenne d’eau potable	EcoQuartier
322	Coefficient de biotopes biodiversité	EcoQuartier
323	Fréquence des réunions d’associations avec les riverains, usagers et habitants, à toutes les phases du projet, et notamment après la livraison du quartier.	EcoQuartier
324	Prise en compte et valorisation des apports des habitants dans l’élaboration des contenus du projet.	EcoQuartier
325	Dynamique d’implication des habitants dans la vie du quartier.	EcoQuartier
326	Coût des travaux/Ha aménagé.	EcoQuartier
327	Retour fiscal : durée de retour sur investissement pour la collectivité.	EcoQuartier
328	Existence d’un budget d’aménagement correctif post-livraison.	EcoQuartier
329	Qualification des modes de gestion au regard du respect des ressources environnementales (gestion différenciée des espaces verts, gestion de la ressource en eau, préservation de la biodiversité, gestion de l’éclairage, gestion des déchets et de la propreté urbaine…).	EcoQuartier
330	Degré de satisfaction des services techniques en charge de la propreté et de la sécurité vis-à-vis de la facilité d’intervention au sein du quartier et de ses équipements.	EcoQuartier
331	Capitalisation des retours d’expérience issus de l’ÉcoQuartier: remontée et enrichissement des projets urbains, prescriptions urbaines, et architecturales, services aux habitants et usagers…	EcoQuartier
332	Nombre et périmètre des évaluations.	EcoQuartier
333	% de l’EcoQuartier en extension urbaine	EcoQuartier
334	Densité perçue par les habitants et usagers/densité perçue par les autres (dont les riverains).	EcoQuartier
335	% de surface des espaces privés à usage public (ou collectifs) par habitant.	EcoQuartier
336	Fréquentation des espaces publics	EcoQuartier
337	% de logement en investissement locatif	EcoQuartier
338	Cohésion sociale et bien-vivre ensemble (fonctionnement socio-urbain du quartier).	EcoQuartier
339	Caractéristiques des rez-de-chaussée (nombre de mètre linéaire par type d’ouvertures (vitrines, mur aveugle, transparence…) au rez-de-chaussée des bâtiments sur les voies principales)	EcoQuartier
340	Part de logements NF certifiés	EcoQuartier
341	Nombre de « malfaçons » ou de « plaintes » concernant les logements et le fonctionnement du quartier.	EcoQuartier
342	Sentiment de prise en compte de l’histoire locale.	EcoQuartier
343	Nombre de m² d’activités créés par type d’activités représentées (bureaux, industrie et commerces (commerces à détailler)	EcoQuartier
344	Nombre d’heures d’insertion réalisées dans le cadre du chantier et de la vie de quartier.	EcoQuartier
345	Nombre d’établissements/d’emplois relevant de l’ESS	EcoQuartier
346	Rapport entre le nombre de logements et le nombre d’emploi	EcoQuartier
347	Contribution de l’ÉcoQuartier au développement économique local (en complémentarité avec l’économie existante).	EcoQuartier
348	Diversité de l’offre commerciale dans le quartier : poids des commerces de première nécessité parmi l’ensemble des activités	EcoQuartier
349	Volume total de matériaux recyclés (chantier)/volume total de matériaux	EcoQuartier
350	Pourcentage de bâtiments labellisés «Bâtiment Biosourcé ».	EcoQuartier
351	Pourcentage en surface des voiries dédiées aux liaisons douces par rapport aux voiries créées tous modes.	EcoQuartier

352	Nombre de places de stationnement avec recharge pour voiture électrique/bâtiments.	EcoQuartier
353	Part des locaux de stationnement vélo équipés avec branchement électrique	EcoQuartier
354	Quantité de places de stationnement automobile par type de stationnement (mutualisé, privatif, sur voirie)	EcoQuartier
355	Accessibilité et confort des itinéraires modes actifs.	EcoQuartier
356	Impact visuel de la voiture.	EcoQuartier
357	Ressenti et réalité quant à la modération des vitesses	EcoQuartier
358	Couverture mobile	EcoQuartier
359	Existence d'un outil numérique permettant de faciliter l'exploitation des espaces publics.	EcoQuartier
360	Pourcentage de logements équipés de capteurs intelligents.	EcoQuartier
361	Bilan radiatif : albédo du quartier (0<valeur<1).	EcoQuartier
362	Prise en compte et satisfaction du confort d'été	EcoQuartier
363	Contribution à la réduction des émissions de gaz à effet de serre du quartier	EcoQuartier
364	Impact du quartier sur l'aggravation des risques (notamment inondations).	EcoQuartier
365	Nombre de m^2 bâtis pour lesquels la performance énergétique est supérieure aux seuils réglementaires minimum (RT2012 pour le neuf).	EcoQuartier
366	Production de chaleur renouvelable et/ou de récupération sur l'ÉcoQuartier	EcoQuartier
367	Consommation énergétique de l'éclairage public.	EcoQuartier
368	Distance maximale à un point de dépôt comportant un dispositif de tri.	EcoQuartier
369	Taux d'équipements des ménages en composteurs individuels ou collectifs.	EcoQuartier
370	% des déchets verts valorisés	EcoQuartier
371	Réutilisation, recyclage ou valorisation des déchets de chantier (% en masse).	EcoQuartier
372	Pourcentage de terres issues de terrassements utilisées sur place ou à proximité.	EcoQuartier
373	Taux de raccordement des bâtiments à des sources alternatives à l'eau potable.	EcoQuartier
374	Pourcentage de surface plancher construite ou réhabilitée disposant de systèmes de récupération des eaux pluviales.	EcoQuartier
375	Pourcentage des eaux de ruissellement récupérées et valorisées (citernes, bassins d'arrosage…).	EcoQuartier
376	Evolution (maintien du nombre d'espèces végétales avant et après projet).	EcoQuartier
377	Nombre de nouvelles espèces (sur la base de l'inventaire exhaustif).	EcoQuartier
378	Dispositifs proposés pour inciter des pratiques d' « éco-habitant » : éco-mobilité (covoiturage, auto-partage, circulations douces etc.), collecte sélective, recyclage et valorisation des déchets et encombrants, circuits courts de consommation, etc.	EcoQuartier
379	Part de logements produits dans l'ÉcoQuartier par rapport à l'ensemble des logements programmés dans le PLH sur la même période.	EcoQuartier
380	Part de l'emploi créé dans le secteur de la construction.	EcoQuartier
381	Variation du taux d'effort des ménages dans le territoire avant et après la mise en oeuvre des ÉcoQuartier.	EcoQuartier
382	TLO - Thermal load of outstreaming body	Nature4Cities
383	UTCI - Universal thermal climate index	Nature4Cities
384	MRT - Mean radiant temperature	Nature4Cities
385	MRT - Mean radiant temperature	Nature4Cities
386	PMV - Predicted mean vote	Nature4Cities
387	β - Bowen ratio	Nature4Cities
388	EPTvar - Evapotranspiration variation	Nature4Cities
389	SWS - Soil water storage	Nature4Cities
390	TROvol - Total runoff volume	Nature4Cities

391	RRR - Total runoff/Total rainfall ratio	Nature4Cities
392	FAV - Variation of flooded area	Nature4Cities
393	EAQLVcity - Exceedance of air quality limit value – City scale	Nature4Cities
394	AAPCV - Annual amount of pollutants captured by vegetation	Nature4Cities
395	IAS - Number of invasive alien species	Nature4Cities
396	PALHB - Potential of areas likely to host biodiversity	Nature4Cities
397	RNPS - Ratio of Native Plant Species	Nature4Cities
398	PSL - Land Use and associated impacts on biodiversity	Nature4Cities
399	LUsom – Land use related to Soil organic matter changes	Nature4Cities
400	Cfer - Chemical fertility of soil	Nature4Cities
401	EcoF - Ecotoxicology factor	Nature4Cities
402	SWI - Soil water infiltration	Nature4Cities
403	SCr - Soil Crusting	Nature4Cities
404	Sct - Soil contamination	Nature4Cities
405	SMP - Soil macro porosity	Nature4Cities
406	SOM - Soil Organic Matter	Nature4Cities
407	SR - Soil respiration	Nature4Cities
408	SWR - Soil water reservoir for plants	Nature4Cities
409	Energy Efficiency	Nature4Cities
410	Energy Intensity of Water Supply	Nature4Cities
411	Energy Use in Agriculture	Nature4Cities
412	Per Capita Food Supply Variability	Nature4Cities
413	Water security	Nature4Cities
414	Agricultural water withdrawal	Nature4Cities
415	Absolute water comsumption	Nature4Cities
416	Water Efficiency	Nature4Cities
417	Water intensity	Nature4Cities
418	Abiotic resource depletion - Fossil fuels	Nature4Cities
419	Abiotic resource depletion - Metal and mineral	Nature4Cities
420	Rate of landfilling	Nature4Cities
421	Rate of recycling	Nature4Cities
422	Night noise level	Nature4Cities
423	Population Annoyance Index	Nature4Cities
424	Place attachment	Nature4Cities
425	Bodily integrity	Nature4Cities
426	Availability ES	Nature4Cities
427	Gentrification	Nature4Cities
428	Areal Sprawl	Nature4Cities
429	Betweenness	Nature4Cities
430	Annual Budget of Natural Assets	Nature4Cities
431	Crime counts	Nature4Cities
432	Perceived crime	Nature4Cities
433	Percentage of citiznes feeling safe	Nature4Cities
434	Number of people injured, relocated and evacuated	Nature4Cities
435	Recycling rate of municipal waste	Nature4Cities
436	Labour producvtivity of bioeconomy	Nature4Cities
437	Number of VAT registered bioeconomy business	Nature4Cities
438	Direct and indirect public spending on bioeconomy	Nature4Cities

439	Private investment on bioeconomy	Nature4Cities
440	City’s unemployment rate (core indicator)	ISO 37120:2018
441	Percentage of persons in full-time employment (supporting indicator)	ISO 37120:2018
442	Youth unemployment rate (supporting indicator)	ISO 37120:2018
443	Number of businesses per 100 000 population (supporting indicator)	ISO 37120:2018
444	Number of new patents per 100 000 population per year (supporting indicator)	ISO 37120:2018
445	Annual number of visitor stays (overnight) per 100 000 population (supporting indicator)	ISO 37120:2018
446	Commercial air connectivity (number of non-stop commercial air destinations) (supporting indicator)	ISO 37120:2018
447	Average household income (USD) (profile indicator)	ISO 37120:2018
448	Annual inflation rate based on the average of the past five years (profile indicator)	ISO 37120:2018
449	City product per capita (USD) (profile indicator)	ISO 37120:2018
450	Percentage of female school-aged population enrolled in schools (core indicator)	ISO 37120:2018
451	Percentage of students completing secondary education: survival rate (core indicator)	ISO 37120:2018
452	Primary education student–teacher ratio (core indicator)	ISO 37120:2018
453	Percentage of school-aged population enrolled in schools (supporting indicator)	ISO 37120:2018
454	Number of higher education degrees per 100 000 population (supporting indicator)	ISO 37120:2018
455	Total end-use energy consumption per capita (GJ/year) (core indicator)	ISO 37120:2018
456	Percentage of total end-use energy derived from renewable sources (core indicator)	ISO 37120:2018
457	Percentage of city population with authorized electrical service (residential) (core indicator)	ISO 37120:2018
458	Number of gas distribution service connections per 100 000 population (residential) (core indicator)	ISO 37120:2018
459	Final energy consumption of public buildings per year (GJ/m2) (core indicator)	ISO 37120:2018
460	Electricity consumption of public street lighting per kilometre of lighted street (kWh/year) (supporting indicator)	ISO 37120:2018
461	Average annual hours of electrical service interruptions per household (supporting indicator)	ISO 37120:2018
462	Heating degree days (profile indicator)	ISO 37120:2018
463	Cooling degree days (profile indicator)	ISO 37120:2018
464	Fine particulate matter (PM2.5) concentration (core indicator)	ISO 37120:2018
465	Fine particulate matter (PM10) concentration (core indicator)	ISO 37120:2018
466	Greenhouse gas emissions measured in tonnes per capita (core indicator)	ISO 37120:2018
467	Percentage of areas designated for natural protection (supporting indicator)	ISO 37120:2018
468	NO2 (nitrogen dioxide) concentration (supporting indicator)	ISO 37120:2018
469	SO2 (sulfur dioxide) concentration (supporting indicator)	ISO 37120:2018
470	O3 (ozone) concentration (supporting indicator)	ISO 37120:2018
471	Noise pollution (supporting indicator)	ISO 37120:2018
472	Percentage change in number of native species (supporting indicator)	ISO 37120:2018
473	Debt service ratio (debt service expenditure as a percentage of a city's own-source revenue) (core indicator)	ISO 37120:2018
474	Capital spending as a percentage of total expenditures (core indicator)	ISO 37120:2018
475	Own-source revenue as a percentage of total revenues (supporting indicator)	ISO 37120:2018
476	Tax collected as a percentage of tax billed (supporting indicator)	ISO 37120:2018
477	Gross operating budget per capita (USD) (profile indicator)	ISO 37120:2018
478	Gross operating budget per capita (USD) (profile indicator)	ISO 37120:2018

479	Women as a percentage of total elected to city-level office (core indicator)	ISO 37120:2018
480	Number of convictions for corruption and/or bribery by city officials per 100 000 population (supporting indicator)	ISO 37120:2018
481	Number of registered voters as a percentage of the voting age population (supporting indicator)	ISO 37120:2018
482	Voter participation in last municipal election (as a percentage of registered voters) (supporting indicator)	ISO 37120:2018
483	Average life expectancy (core indicator)	ISO 37120:2018
484	Number of in-patient hospital beds per 100 000 population (core indicator)	ISO 37120:2018
485	Number of physicians per 100 000 population (core indicator)	ISO 37120:2018
486	Under age five mortality per 1 000 live births (core indicator)	ISO 37120:2018
487	Number of nursing and midwifery personnel per 100 000 population (supporting indicator)	ISO 37120:2018
488	Suicide rate per 100 000 population (supporting indicator)	ISO 37120:2018
489	Percentage of city population living in inadequate housing (core indicator)	ISO 37120:2018
490	Percentage of population living in affordable housing (core indicator)	ISO 37120:2018
491	Number of homeless per 100 000 population (supporting indicator)	ISO 37120:2018
492	Percentage of households that exist without registered legal titles (supporting indicator)	ISO 37120:2018
493	Total number of households (profile indicator)	ISO 37120:2018
494	Persons per unit (profile indicator)	ISO 37120:2018
495	Vacancy rate (residential) (profile indicator)	ISO 37120:2018
496	Living space (square metres) per person (profile indicator)	ISO 37120:2018
497	Secondary residence rate (profile indicator)	ISO 37120:2018
498	Residential rental dwelling units as a percentage of total dwelling units (profile indicator)	ISO 37120:2018
499	Percentage of city population living below the international poverty line (core indicator)	ISO 37120:2018
500	Percentage of city population living below the national poverty line (supporting indicator)	ISO 37120:2018
501	Gini coefficient of inequality (supporting indicator)	ISO 37120:2018
502	Annual population change (profile indicator)	ISO 37120:2018
503	Percentage of population that are foreign born (profile indicator)	ISO 37120:2018
504	Population demographics (profile indicator)	ISO 37120:2018
505	Percentage of population that are new immigrants (profile indicator)	ISO 37120:2018
506	Percentage of city population that are non-citizens (profile indicator)	ISO 37120:2018
507	Number of university students per 100 000 population (profile indicator)	ISO 37120:2018
508	Square metres of public indoor recreation space per capita (supporting indicator)	ISO 37120:2018
509	Square metres of public outdoor recreation space per capita (supporting indicator)	ISO 37120:2018
510	Number of firefighters per 100 000 population (core indicator)	ISO 37120:2018
511	Number of fire-related deaths per 100 000 population (core indicator)	ISO 37120:2018
512	Number of natural-hazard-related deaths per 100 000 population (core indicator)	ISO 37120:2018
513	Number of police officers per 100 000 population (core indicator)	ISO 37120:2018
514	Number of homicides per 100 000 population (core indicator)	ISO 37120:2018
515	Number of volunteer and part-time firefighters per 100 000 population	ISO 37120:2018
516	Response time for emergency response services from initial call (supporting indicator)	ISO 37120:2018
517	Crimes against property per 100 000 population (supporting indicator)	ISO 37120:2018
518	Number of deaths caused by industrial accidents per 100 000 population	ISO 37120:2018

519	Number of violent crimes against women per 100 000 population (supporting indicator)	ISO 37120:2018
520	Percentage of city population with regular solid waste collection (residential) (core indicator)	ISO 37120:2018
521	Total collected municipal solid waste per capita (core indicator)	ISO 37120:2018
522	Percentage of the city's solid waste that is recycled (core indicator)	ISO 37120:2018
523	Percentage of the city's solid waste that is disposed of in a sanitary landfill (core indicator)	ISO 37120:2018
524	Percentage of the city's solid waste that is treated in energy-from-waste plants (core indicator)	ISO 37120:2018
525	Percentage of the city's solid waste that is biologically treated and used as compost or biogas (supporting indicator)	ISO 37120:2018
526	Percentage of the city's solid waste that is disposed of in an open dump (supporting indicator)	ISO 37120:2018
527	Percentage of the city's solid waste that is disposed of by other means (supporting indicator	ISO 37120:2018
528	Hazardous waste generation per capita (tonnes) (supporting indicator)	ISO 37120:2018
529	Percentage of the city's hazardous waste that is recycled (supporting indicator)	ISO 37120:2018
530	Number of cultural institutions and sporting facilities per 100 000 population (core indicator)	ISO 37120:2018
531	Percentage of municipal budget allocated to cultural and sporting facilities (supporting indicator)	ISO 37120:2018
532	Annual number of cultural events per 100 000 population (e.g. exhibitions, festivals, concerts) (supporting indicator)	ISO 37120:2018
533	Number of internet connections per 100 000 population (supporting indicator)	ISO 37120:2018
534	Number of mobile phone connections per 100 000 population (supporting indicator)	ISO 37120:2018
535	Kilometres of public transport system per 100 000 population (core indicator)	ISO 37120:2018
536	Annual number of public transport trips per capita (core indicator)	ISO 37120:2018
537	Percentage of commuters using a travel mode to work other than a personal vehicle (supporting indicator)	ISO 37120:2018
538	Kilometres of bicycle paths and lanes per 100 000 population (supporting indicator)	ISO 37120:2018
539	Transportation deaths per 100 000 population (supporting indicator)	ISO 37120:2018
540	Percentage of population living within 0,5 km of public transit running at least every 20 min during peak periods (supporting indicator)	ISO 37120:2018
541	Average commute time (supporting indicator)	ISO 37120:2018
542	Number of personal automobiles per capita (profile indicator)	ISO 37120:2018
543	Number of two-wheeled motorized vehicles per capita (profile indicator)	ISO 37120:2018
544	Total urban agricultural area per 100 000 population (core indicator)	ISO 37120:2018
545	Amount of food produced locally as a percentage of total food supplied to the city (supporting indicator)	ISO 37120:2018
546	Percentage of city population undernourished (supporting indicator)	ISO 37120:2018
547	Percentage of city population that is overweight or obese — Body Mass Index (BMI) (supporting indicator)	ISO 37120:2018
548	Green area (hectares) per 100 000 population (core indicator)	ISO 37120:2018
549	Areal size of informal settlements as a percentage of city area (supporting indicator)	ISO 37120:2018
550	Jobs–housing ratio (supporting indicator)	ISO 37120:2018
551	Basic service proximity (supporting indicator)	ISO 37120:2018
552	Population density (per square kilometre) (profile indicator)	ISO 37120:2018

553	Number of trees per 100 000 population (profile indicator)	ISO 37120:2018
554	Built-up density (profile indicator)	ISO 37120:2018
555	Percentage of city population served by wastewater collection (core indicator)	ISO 37120:2018
556	Percentage of city's wastewater receiving centralized treatment (core indicator)	ISO 37120:2018
557	Percentage of population with access to improved sanitation (core indicator)	ISO 37120:2018
558	Compliance rate of wastewater treatment (supporting indicator)	ISO 37120:2018
559	Percentage of city population with potable water supply service (core indicator)	ISO 37120:2018
560	Percentage of city population with sustainable access to an improved water source (core indicator)	ISO 37120:2018
561	Total domestic water consumption per capita (litres/day) (core indicator)	ISO 37120:2018
562	Compliance rate of drinking water quality (core indicator)	ISO 37120:2018
563	Total water consumption per capita (litres/day) (supporting indicator)	ISO 37120:2018
564	Average annual hours of water service interruptions per household (supporting indicator)	ISO 37120:2018
565	Percentage of water loss (unaccounted for water) (supporting indicator)	ISO 37120:2018
566	Percentage of service contracts providing city services which contain an open data policy	ISO 37122:2019
567	Percentage of the labour force employed in occupations in the information and communications technology (ICT) sector	ISO 37122:2019
568	Percentage of the labour force employed in occupations in the education and research and development sectors	ISO 37122:2019
569	Percentage of city population with professional proficiency in more than one language	ISO 37122:2019
570	Number of computers, laptops, tablets or other digital learning devices available per 1 000 students	ISO 37122:2019
571	Number of science, technology, engineering and mathematics (STEM) higher education degrees per 100 000 population	ISO 37122:2019
572	Percentage of electrical and thermal energy produced from wastewater treatment, solid waste and other liquid waste treatment and other waste heat resources, as a share of the city's total energy mix for a given year	ISO 37122:2019
573	Electrical and thermal energy (GJ) produced from wastewater treatment per capita per year	ISO 37122:2019
574	Electrical and thermal energy (GJ) produced from solid waste or other liquid waste treatment per capita per year	ISO 37122:2019
575	Percentage of the city's electricity that is produced using decentralised electricity production systems	ISO 37122:2019
576	Storage capacity of the city's energy grid per total city energy consumption	ISO 37122:2019
577	Percentage of street lighting managed by a light performance management system	ISO 37122:2019
578	Percentage of street lighting that has been refurbished and newly installed	ISO 37122:2019
579	Percentage of public buildings requiring renovation/refurbishment	ISO 37122:2019
580	Percentage of buildings in the city with smart energy meters	ISO 37122:2019
581	Number of electric vehicle charging stations per registered electric vehicle	ISO 37122:2019
582	Percentage of buildings built or refurbished within the last 5 years in conformity with green building principles	ISO 37122:2019
583	Number of real-time remote air quality monitoring stations per square kilometre (km2)	ISO 37122:2019
584	Percentage of public buildings equipped for monitoring indoor air quality	ISO 37122:2019
585	Annual amount of revenues collected from the sharing economy as a percentage of own-source revenue	ISO 37122:2019

586	Percentage of payments to the city that are paid electronically based on electronic invoices	ISO 37122:2019
587	Annual number of online visits to the municipal open data portal per 100 000 population	ISO 37122:2019
588	Percentage of city services accessible and that can be requested online	ISO 37122:2019
589	Average response time to inquiries made through the city's non-emergency inquiry system (days)	ISO 37122:2019
590	Average downtime of the city's IT infrastructure	ISO 37122:2019
591	Percentage of the city's population with an online unified health file accessible to health care providers	ISO 37122:2019
592	Annual number of medical appointments conducted remotely per 100 000 population	ISO 37122:2019
593	Percentage of the city population with access to real-time public alert systems for air and water quality advisories	ISO 37122:2019
594	Percentage of households with smart energy meters	ISO 37122:2019
595	Percentage of households with smart water meters	ISO 37122:2019
596	Percentage of public buildings that are accessible by persons with special needs	ISO 37122:2019
597	Percentage of municipal budget allocated for the provision of mobility aids, devices and assistive technologies to citizens with special needs	ISO 37122:2019
598	Percentage of marked pedestrian crossings equipped with accessible pedestrian	ISO 37122:2019
599	Percentage of municipal budget allocated for provision of programmes designated for bridging the digital divide	ISO 37122:2019
600	Percentage of public recreation services that can be booked online	ISO 37122:2019
601	Percentage of the city area covered by digital surveillance cameras	ISO 37122:2019
602	Percentage of waste drop-off centres (containers) equipped with telemetering	ISO 37122:2019
603	Percentage of the city population that has a door-to-door garbage collection with an individual monitoring of household waste quantities	ISO 37122:2019
604	Percentage of total amount of waste in the city that is used to generate energy	ISO 37122:2019
605	Percentage of total amount of plastic waste recycled in the city	ISO 37122:2019
606	Percentage of public garbage bins that are sensor-enabled public garbage bins	ISO 37122:2019
607	Percentage of the city's electrical and electronic waste that is recycled .	ISO 37122:2019
608	Number of online bookings for cultural facilities per 100 000 population	ISO 37122:2019
609	Percentage of the city's cultural records that have been digitised	ISO 37122:2019
610	Number of public library book and e-book titles per 100 000 population	ISO 37122:2019
611	Percentage of city population that are active public library users	ISO 37122:2019
612	Percentage of the city population with access to sufficiently fast broadband	ISO 37122:2019
613	Percentage of city area under a white zone/dead spot/not covered by telecommunication connectivity	ISO 37122:2019
614	Percentage of the city area covered by municipally provided Internet connectivity	ISO 37122:2019
615	Percentage of city streets and thoroughfares covered by real-time online traffic alerts and information	ISO 37122:2019
616	Number of users of sharing economy transportation per 100 000 population	ISO 37122:2019
617	Percentage of vehicles registered in the city that are low-emission vehicles	ISO 37122:2019
618	Number of bicycles available through municipally provided bicycle-sharing services per 100 000 population	ISO 37122:2019
619	Percentage of public transport lines equipped with a publicly accessible real-time system	ISO 37122:2019
620	Percentage of the city's public transport services covered by a unified payment system	ISO 37122:2019
621	Percentage of public parking spaces equipped with e-payment systems	ISO 37122:2019

622	Percentage of public parking spaces equipped with real-time availability systems	ISO 37122:2019
623	Percentage of traffic lights that are intelligent/smart	ISO 37122:2019
624	City area mapped by real-time interactive street maps as a percentage of the city's total land area	ISO 37122:2019
625	Percentage of vehicles registered in the city that are autonomous vehicles	ISO 37122:2019
626	Percentage of public transport routes with municipally provided and/or managed Internet connectivity for commuters	ISO 37122:2019
627	Percentage of roads conforming with autonomous driving systems	ISO 37122:2019
628	Percentage of the city's bus fleet that is motor-driven	ISO 37122:2019
629	Annual percentage of municipal budget spent on urban agriculture initiatives	ISO 37122:2019
630	Annual total collected municipal food waste sent to a processing facility for composting per capita (in tonnes)	ISO 37122:2019
631	Percentage of the city's land area covered by an online food-supplier mapping system	ISO 37122:2019
632	Annual number of citizens engaged in the planning process per 100 000 population	ISO 37122:2019
633	Percentage of building permits submitted through an electronic submission system	ISO 37122:2019
634	Average time for building permit approval (days).	ISO 37122:2019
635	Percentage of the city population living in medium-to-high population densities	ISO 37122:2019
636	Percentage of treated wastewater being reused	ISO 37122:2019
637	Percentage of biosolids that are reused (dry matter mass)	ISO 37122:2019
638	Energy derived from wastewater as a percentage of total energy consumption of the city	ISO 37122:2019
639	Percentage of total amount of wastewater in the city that is used to generate energy	ISO 37122:2019
640	Percentage of the wastewater pipeline network monitored by a real-time datatracking sensor system	ISO 37122:2019
641	Percentage of drinking water tracked by real-time, water quality monitoring station	ISO 37122:2019
642	Number of real-time environmental water quality monitoring stations per 100 000 population	ISO 37122:2019
643	Percentage of the city's water distribution network monitored by a smart water system	ISO 37122:2019
644	Percentage of buildings in the city with smart water meters	ISO 37122:2019
645	Historical disaster losses as a percentage of city product	ISO 37123:2019
646	Average annual disaster loss as a percentage of city product	ISO 37123:2019
647	Percentage of properties with insurance coverage for high-risk hazards	ISO 37123:2019
648	Percentage of total insured value to total value at risk within the city	ISO 37123:2019
649	Employment concentration	ISO 37123:2019
650	Percentage of the workforce in informal employment	ISO 37123:2019
651	Average household disposable income	ISO 37123:2019
652	Percentage of schools that teach emergency preparedness and disaster risk reduction	ISO 37123:2019
653	Percentage of population trained in emergency preparedness and disaster risk reduction	ISO 37123:2019
654	Percentage of emergency preparedness publications provided in alternative languages	ISO 37123:2019
655	Educational disruption	ISO 37123:2019
656	Number of different electricity sources providing at least 5 % of total energy supply capacity	ISO 37123:2019
657	Electricity supply capacity as a percentage of peak electricity demand	ISO 37123:2019
658	Percentage of critical facilities served by off-grid energy services	ISO 37123:2019
659	Magnitude of urban heat island effects (atmospheric)	ISO 37123:2019
660	Percentage of natural areas within the city that have undergone ecological evaluation for their protective services	ISO 37123:2019
661	Territory undergoing ecosystem restoration as a percentage of total city area	ISO 37123:2019

662	Annual frequency of extreme rainfall events	ISO 37123:2019
663	Annual frequency of extreme heat events	ISO 37123:2019
664	Annual frequency of extreme cold events	ISO 37123:2019
665	Annual frequency of flood events	ISO 37123:2019
666	Percentage of city land area covered by tree canopy	ISO 37123:2019
667	Percentage of city surface area covered with high-albedo materials contributing to the mitigation of urban heat islands	ISO 37123:2019
668	Annual expenditure on upgrades and maintenance of city service assets as a percentage of total city budget	ISO 37123:2019
669	Annual expenditure on upgrades and maintenance of storm water infrastructure as a percentage of total city budget	ISO 37123:2019
670	Annual expenditure allocated to ecosystem restoration in the city's territory as a percentage of total city budget	ISO 37123:2019
671	Annual expenditure on green and blue infrastructure as a percentage of total city budget	ISO 37123:2019
672	Annual expenditure on emergency management planning as a percentage of total city budget	ISO 37123:2019
673	Annual expenditure on social and community services as a percentage of total city budget	ISO 37123:2019
674	Total allocation of disaster reserve funds as a percentage of total city budget	ISO 37123:2019
675	Frequency with which disaster-management plans are updated	ISO 37123:2019
676	Percentage of essential city services covered by a documented continuity plan	ISO 37123:2019
677	Percentage of city electronic data with secure and remote back-up storage	ISO 37123:2019
678	Percentage of public meetings dedicated to resilience in the city	ISO 37123:2019
679	Number of intergovernmental agreements dedicated to planning for shocks as percentage of total intergovernmental agreements	ISO 37123:2019
680	Percentage of essential service providers that have a documented business continuity plan	ISO 37123:2019
681	Percentage of hospitals equipped with back-up electricity supply	ISO 37123:2019
682	Percentage of population with basic health insurance	ISO 37123:2019
683	Percentage of population that is fully immunized	ISO 37123:2019
684	Number of infectious disease outbreaks per year	ISO 37123:2019
685	Capacity of designated emergency shelters per 100 000 population	ISO 37123:2019
686	Percentage of buildings structurally vulnerable to high-risk hazards.	ISO 37123:2019
687	Percentage of residential buildings not in conformity with building codes and standards	ISO 37123:2019
688	Percentage of damaged infrastructure that was "built back better" after a disaster	ISO 37123:2019
689	Annual number of residential properties flooded as a percentage of total residential properties in the city	ISO 37123:2019
690	Percentage of residential properties located in high-risk zones	ISO 37123:2019
691	Vulnerable population as a percentage of city population	ISO 37123:2019
692	Percentage of population enrolled in social assistance programmes	ISO 37123:2019
693	Percentage of population at high risk from natural hazards	ISO 37123:2019
694	Percentage of neighbourhoods with regular and open neighbourhood association meetings	ISO 37123:2019
695	Annual percentage of the city population directly affected by natural hazards	ISO 37123:2019
696	Percentage of city population covered by multi-hazard early warning system	ISO 37123:2019
697	Percentage of emergency responders who have received disaster response training	ISO 37123:2019

698	Percentage of local hazard warnings issued by national agencies annually that are received in a timely fashion by the city	ISO 37123:2019
699	Number of hospital beds in the city destroyed or damaged by natural hazards per 100 000 population	ISO 37123:2019
700	Number of active and temporary waste management sites available for debris and rubble per square kilometre	ISO 37123:2019
701	Percentage of emergency responders in the city equipped with specialized communication technologies able to operate reliably during a disaster event	ISO 37123:2019
702	Number of evacuation routes available per 100 000 population	ISO 37123:2019
703	Percentage of city population that can be served by city food reserves for 72 hours in an emergency	ISO 37123:2019
704	Percentage of the city's population living within one kilometre of a grocery store	ISO 37123:2019
705	Percentage of city area covered by publicly available hazard maps	ISO 37123:2019
706	Pervious land areas and public space and pavement built with porous, draining materials as a percentage of city land area	ISO 37123:2019
707	Percentage of city land area in high-risk zones where risk-reduction measures have been implemented	ISO 37123:2019
708	Percentage of city departments and utility services that conduct risk assessment in their planning and investment	ISO 37123:2019
709	Annual number of critical infrastructures flooded as a percentage of critical infrastructure in the city	ISO 37123:2019
710	Annual expenditure on water retention measures as a percentage of city prevention measures budget	ISO 37123:2019
711	Number of different sources providing at least 5 % of total water supply capacity	ISO 37123:2019
712	Percentage of city population that can be supplied with drinking water by alternative methods for 72 hours	ISO 37123:2019
713	Percent of total project area for Agriculture	LBC 4.0
714	Area of protected land set aside (away from project site)	LBC 4.0
715	EV charging stations/parking station	LBC 4.0
716	% of impervious parking surface	LBC 4.0
717	% of Single-occupancy vehicle trips	LBC 4.0
718	% of fuel based trips	LBC 4.0
719	Reduction on water needs based on a regional baseline	LBC 4.0
720	Stormwater managed on site	LBC 4.0
721	Natural an local closed loop water systems	LBC 4.0
722	Wastewater treated on site	LBC 4.0
723	Ennergy needs reduction from an equivalent building baseline	LBC 4.0
724	Embodied carbon reduction from an equivalent building baseline	LBC 4.0
725	On site renewable energy production	LBC 4.0
726	Embodied carbon offset (or sequestration)	LBC 4.0
727	Energy autonomy	LBC 4.0
728	Views and daylight ratio	LBC 4.0
729	Indor Air Quality	LBC 4.0
730	Percentage of material sources from from 500 Km, 1000 Km and 5000 Km radius	LBC 4.0
731	Waste diverted from landfill	LBC 4.0
732	Percentage of building materials that avoid the red list	LBC 4.0
733	Percentage of reused, salvaged and certfied sustainable wood building materials	LBC 4.0

Appendix 4 – RACER Evaluation (159 indicators)

#	Indicator	Relevant	Acceptable	Credible	Easy to monitor	Robust	RACER note
1	Percentage of total end-use energy derived from renewable sources	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
2	Share of renewable energy localy produced based on site potentialities	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
3	Percentage of electrical and thermal energy produced from wastewater treatment, solid waste and other liquid waste treatment and other waste heat resources, as a share of the city's total energy mix for a given year	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	12
4	Percentage of the city's electricity that is produced using decentralised electricity production systems	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
5	Renewable Energy Consumption	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
6	Energy Efficiency	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
7	Energy Security	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
8	Abiotic resource depletion - Fossil fuels	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
9	Buildings Energy needs	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
10	Cumulative Energy Demand	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
11	Electricity Consumption	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
12	Number of m² built for which the energy performance is higher than the minimum regulatory thresholds (RT2012 for new buildings)	1 - Not fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	10
13	Reduced energy demand for heating and cooling	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
14	Energy needs reduction (%) from an equivalent project baseline	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	10

15	Adaptive comfort	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
16	Air temperature	1 - Not fulfilled	3 - Completely fulfilled	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	11
17	Radiation balance: albedo of the neighbourhood (0<value<1)	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
18	Magnitude of urban heat island effects (atmospheric)	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	1 - Not fulfilled	3 - Completely fulfilled	12
19	Day-evening-night noise level	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
20	Physiological equiv. Temperature	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
21	PMV - Predicted mean vote	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
22	Population Annoyance Index	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
23	Thermal Comfort Score (outdoor)	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
24	UTCI - Universal thermal climate index	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
25	Percentage of city surface area covered with high-albedo materials contributing to the mitigation of urban heat islands	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	12
26	β - Bowen ratio	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
27	Freshwater Consumption	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
28	Percentage of city population with potable water supply service (core indicator)	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
29	Potable Water Supply	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
30	Rate of connection of buildings to alternative sources of drinking water	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
31	Total water consumption per capita (litres/day) (supporting indicator)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
32	Water Efficiency	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11

33	Water intensity	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	11
34	Water security	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
35	Water Supply Loss	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
36	Reduction on water needs based on a regional baseline on same types	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	13
37	EPTvar - Evapotranspiration variation	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
38	FAV - Variation of flooded area	1 - Not fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
39	Pervious land areas and public space and pavement built with porous, draining materials as a percentage of city land area	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
40	Percentage of built or rehabilitated floor area with rainwater harvesting systems	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
41	Percentage of rainwater water recovered and reused (cisterns, watering basins, etc.)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	13
42	RRR - Total runoff/Total rainfall ratio	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
43	Shares of wetlands for water regulation	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	10
44	Stormwater quality	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
45	SWS - Soil water storage	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
46	Total rainfall volume	1 - Not fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
47	TROvol - Total runoff volume	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
48	Water Detention Time	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
49	Infiltration capacities	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
50	SWI - Soil water infiltration	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10

51	Household Sanitation	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
52	Percentage of population connected to urban waste water collection and treatment plants	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
53	Percentage of total amount of wastewater in the city that is used to generate energy	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
54	Percentage of treated wastewater being reused	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
55	Percentage of wastewater treated on site	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
56	Material Circulatory Indicator	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
57	Pourcentage de terres issues de terrassements utilisées sur place ou à proximité.	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	12
58	Raw Material Efficiency	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
59	Percentage of materials from reused, salvaged or recycled sources	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	12
60	Ratio of retrofited/rehabilated project surface/total project surface	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	13
61	Percentage of building materials that avoid the ILFI Red List	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
62	Percentage of materials from a specified distance to the project site	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	10
63	Average distance from materials source	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	12
64	Total materials need (mass)	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
65	Abiotic resource depletion - Metal and mineral	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
66	Total embodied carbon	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
67	Total cabon sequestered on the construction	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
68	Total embodied carbon offseted	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12

69	Average Carbon storage	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
70	Annual carbon sequestration	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	14
71	Greenhouse gas emissions measured in tonnes per capita (core indicator)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	14
72	Offsetd/compensated GHG emissions (use phase)	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	13
73	Avoided GHG emissions	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
74	Amount of food produced locally as a percentage of total food supplied to the city (supporting indicator)	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
75	Diversity of forms of urban agriculture	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	13
76	Local Food Production	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
77	Per Capita Food Production Variability	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
78	Per Capita Food Supply Variability	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
79	Percentage of agricultural area	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
80	Minimisation of inputs used on green area management	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	11
81	Percentage of organic waste processed locally	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
82	Annual total collected municipal food waste sent to a processing facility for composting per capita (in tonnes)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
83	Percentage of green waste recovered	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	13
84	Construction and demolition waste	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
85	Efficiency of valorisation as a result of recycling processes	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
86	Percentage of biosolids that are reused (dry matter mass)	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12

87	Percentage of city population with regular solid waste collection (residential) (core indicator)	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
88	Percentage of the city's solid waste that is biologically treated and used as compost or biogas (supporting indicator)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
89	Percentage of total amount of plastic waste recycled in the city	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	13
90	Percentage of total amount of waste in the city that is used to generate energy	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
91	Rate of landfilling	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
92	Rate of recycling	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
93	Reuse, recycling or recovery of construction waste (% by mass)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
94	Percentage of the city's solid waste that is treated in energy-from-waste plants (core indicator)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
95	Percentage of waste diverted from landfill	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
96	Specific waste generation	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
97	Total collected municipal solid waste per capita (core indicator)	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
98	Concentration of nutrients and biological oxygen demand in surface water	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
99	Share of water surface	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	11
100	Percentage of original aquatic/wet zones converted(or protected)	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
101	Percentage sealed relative to permeable surface (ha);	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
102	Artificial area per inhabitant (m2/person)	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
103	Percentage of altered topography surface	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14

104	Total volume of topography alterations	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
105	Percentage of areas designated for natural protection (supporting indicator)	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
106	Percentage of natural areas	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13
107	Areal Sprawl	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
108	Avoided urbanised areas	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	11
109	Weighted urban proliferation	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
110	Percentage of project built on urbanised areas or brownfields	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
111	Territory undergoing ecosystem restoration as a percentage of total city area	1 - Not fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	12
112	Area of protected land set aside (away from project site)	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
113	P, K, Mg and Ca in mgkg−1 compared to given soil/water quality standards;	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	13
114	SCr - Soil Crusting	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
115	Bulk density	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	11
116	Cfer - Chemical fertility of soil	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
117	EcoF - Ecotoxicology factor	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
118	LUsom – Land use related to Soil organic matter changes	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
119	Sct - Soil contamination	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
120	Sites with contaminated soil	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	13
121	SMP - Soil macro porosity	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10

122	Soil biological activity	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
123	Soil organic carbon (SOC)	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
124	SOM - Soil Organic Matter	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
125	SR - Soil respiration	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
126	AAPCV - Annual amount of pollutants captured by vegetation	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
127	Common Air Quality Index	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
128	Emissions of NO2, PM10, PM2.5	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
129	Exceedance of air quality limit value – Local scale	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
130	Canopy coverage	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	13
131	Plant composition and structure	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	9
132	Availability of natural spaces in the city	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
133	Evolution (maintenance of the number of plant species before and after the project).	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	12
134	Green Areas	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
135	Index of biodiversity	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
136	Leaf Area Index;	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
137	Normalized Difference Vegetation Index	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
138	Percentage of natural area	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
139	Fragmentation of urban green space	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
140	Percentage of urban green space	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14

141	Urban Green Space Proportion	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	14
142	Number of new species (based on the comprehensive inventory).	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
143	Number of lichen species	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
144	RNPS - Ratio of Native Plant Species	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
145	Shannon Diversity Index of Habitats	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	12
146	Biotope Area Factor	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	15
147	Diversification of fauna/flora habitats	3 - Completely fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	13
148	PALHB - Potential of areas likely to host biodiversity	3 - Completely fulfilled	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	11
149	Abundance of birds, butterflies and other animals valued for their aesthetic attributes;	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
150	Species diversity and abundance of birds and bumble bees;	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
151	Earthworms	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	10
152	IAS - Number of invasive alien species	3 - Completely fulfilled	3 - Completely fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	11
153	Number of annual introductions of invasive alien species	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
154	Percentage change in number of native species (supporting indicator)	3 - Completely fulfilled	1 - Not fulfilled	1 - Not fulfilled	1 - Not fulfilled	3 - Completely fulfilled	9
155	Soil biodiversity	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	1 - Not fulfilled	3 - Completely fulfilled	10
156	Connectivity of green spaces	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	12
157	PSL - Land Use and associated impacts on biodiversity	1 - Not fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	10
158	Betweenness	2 - Partly fulfilled	1 - Not fulfilled	1 - Not fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	9
159	Project area undergoing soil quality and structure restoration	3 - Completely fulfilled	2 - Partly fulfilled	2 - Partly fulfilled	3 - Completely fulfilled	3 - Completely fulfilled	13

Appendix 5 – Indicator classification (39 indicators)

#	Short name	Indicator type
1	Renewable energy	Exploitation data or estimation
2	Decentralised energy production	Exploitation data or estimation
3	Abiotic resource depletion - fossil fuels	LCA
4	Electricity consumption	Exploitation data or estimation
5	High albedo surface	Surface ratio
6	Water consumption	Exploitation data or estimation
7	Rainwater management	Modeling
8	Pervious surface	Surface ratio
9	Onsite wastewater management	Exploitation data or estimation
10	Material Circulatory Indicator	LCA/BIM/Spreadsheets
11	Retrofitting rate	Surface ratio
12	Low risk materials	LCA/BIM/Spreadsheets
13	Average distance from materials source	LCA/BIM/Spreadsheets
14	Embodied carbon	LCA
15	Annual GHG balance	Exploitation data or estimation
16	Food production area	Surface ratio
17	Fertilisers and pesticides	Surface ratio
18	Specific waste generation	Exploitation data or estimation
19	Organic waste recovery	Exploitation data or estimation
20	Local organic waste management	Exploitation data or estimation
21	Waste energetic recovery	Exploitation data or estimation
22	Rate of landfilling	Exploitation data or estimation
23	Rate of recycling	Exploitation data or estimation
24	Protection and restoration of wet ecosystems	Surface ratio
25	Protection of sensitive areas	Surface ratio
26	Ecological restoration	Surface ratio
27	Project area built on urbanised areas	Surface ratio
28	Compensation of artificialisation	Surface ratio
29	Topography changes	Surface ratio
30	Soil restoration	Surface ratio
31	Captured air pollutants	Modeling
32	Availability of natural areas	Surface ratio
33	Urban green space	Surface ratio
34	Ratio of native vegetation	Exploitation data or estimation
35	Ratio of native fauna	Exploitation data or estimation
36	Biotope Area Factor	Surface ratio
37	Connectivity of green spaces (within the plot)	Surface ratio
38	Connectivity of green spaces (outside the plot)	Surface ratio
39	Shannon Diversity Index of Habitats	Surface ratio

C. Other relevant peer-reviewed publications authored during the PhD.

1. Blanco E, Cruz E, Lequette C, et al. (2021) Biomimicry in french urban projects: Trends and perspectives from the practice. Biomimetics 6(2): 1–16. DOI: 10.3390/biomimetics6020027.

2. Uchiyama Y, Blanco E and Kohsaka R (2020) Application of biomimetics to architectural and urban design: A review across scales. Sustainability (Switzerland) 12(23): 1–15. DOI: 10.3390/su12239813.

biomimetics

Communication

Biomimicry in French Urban Projects: Trends and Perspectives from the Practice

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Abstract: Biomimicry is a design framework with growing interests in sustainable architectural and urban design practice. Nevertheless, there is a significant lack of studies and knowledge regarding its practical application. In 2020, a French workgroup called Biomim'City Lab published a document identifying and describing 16 urban projects designed by French teams integrating biomimicry at various levels. Our research is an opportunistic study analyzing this data, aiming to identify trends and challenges in the French market. We analyzed the projects using a mixed-method approach, through quantitative typological analysis and qualitative narrative analysis. This sample of French projects indicates a trend of increasing interest in biomimicry on built space projects in France. Biomimicry was primarily applied at the façade/roof/soil systems, mostly using macroscopic models as ecosystems, plants, and animals. Designers declared to aim diverse objectives with the biomimetic approach; still, thermal comfort is the most recurrent in the sample. We also identified that challenges remain to foster the field application, as the lack of awareness of the urban fabric stakeholders on the topic and the gaps between research and design practice.

Keywords: biomimicry; architecture; urban design; French urban projects

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1. Introduction

Biomimicry draws upon emulation of, and knowledge transfer from, living organisms and whole ecosystems to find solutions to human problems [1]. In the built environment sciences, it is a growing topic [2–4], with an application that mainly aims for sustainable innovation [3,5]. Biomimicry offers an opportunity to operationalize sustainability and regenerative development on architectural and urban projects [2,6].

The practice of biomimetic architecture faced the first increase throughout the nineties, within the beginning of a global context of energy transition, giving birth to iconic biomimetic projects like the Eastgate building (1996) [2,5]. With the simultaneous development of biomimetic architecture in research, education, and architectural practice, the last two decades presented a surge of interest in the topic [7].

In Europe, biomimicry has been highlighted by the European Commission as an opportunity for research and innovation, with potential contributions to tackle climate change adaptation and mitigation [8]. Furthermore, some European research institutions focus on advancing the theory and practice of biomimicry in architectural and urban design. In Germany, the Universities of Stuttgart, Freiburg, and Tübingen have jointly dedicated efforts to develop and test biomimicry applications through the trans-regional Collaborative Research Center "Biological Design and Integrative Structures" SFB-TRR 141 [9]. In France, the French National History Museum created in 2019 the Bioinspire-Museum project to coordinate and promote bioinspiration throughout its activities, highlighting architectural and urban design applications of their biological and ecological knowledge [10]. In the

Netherlands TU Delft has specialized teaching in the topic and hosted relevant research regarding biomimetic architectural design [11].

In France, biomimicry is a growing field of innovation. Since 2015 local stakeholders organize a national congress on biomimicry (Biomim'Expo), to showcase national emerging projects and research on the topic. In architecture and urban design, a collaborative workgroup of biomimicry practitioners was launched in 2019, called Biomim'City Lab. This collective, animated by Ceebios (a not-for-profit French network and center of expertise on biomimicry), integrates ten different French stakeholders of the urban fabric, as architects, real estate developers, consulting companies, and research institutions (in alphabetical order: Bechu & Associés, Ceebios, Eiffage, Elan, Icade, In Situ Architecture, New Corp Conseil, Nobatek/INEF 4, Renault, and Tangam Architectes). They all have experimented at some level biomimicry in their projects, aiming at sustainable development. This workgroup focus on increasing skills, co-developing new tools, and sharing expertise within the French context.

In 2020, one year after its creation, the Biomim'City Lab published an online report called "*Projets urbains bio-inspirés: un état des lieux des projets français*" (Bio-inspired urban projects: an inventory of French projects, available only in French in the Supplementary Materials). This report documented, in standard factsheets, sixteen French projects that have integrated biomimicry and bio-inspired approaches at different levels on urban projects dating from 2007 to 2019. The report presents the collected data, results, and feedback from the design teams from a sample of bio-inspired projects in architecture and urban design in France. The report is a communication and awareness-raising tool for practitioners to enhance biomimicry development in France [12].

The report is different from any other previous scientific and non-scientific publications regarding its objectives and data. Previously published thematic reports had only a few projects briefly presented [13]. In the academic field, few studies documented and explored the practice of biomimicry [11,14,15]. Hayes et al. (2019) realized one of the few available cases studies, focusing on six system-level biomimicry urban projects, but none of them from a European context. Furthermore, the analyzed projects in their study were not identified either deeply described.

The sixteen documented projects from the "Bio-inspired urban projects: an inventory of French projects" report were selected by the BiomimCity'Lab stakeholders, following each stakeholder own preferences. The only criteria among all projects were that they had to integrate at some level a biomimetic approach and be situated in France or be designed by French teams. As a result, the analyzed projects vary in form, size, objective, status, and biomimicry application level. Furthermore, the report is not an exhaustive study of the French biomimetic urban projects, but it constituted an unprecedented sample worth analyzing. Several documented projects are proposals for architectural and urban design competitions, and the report includes projects that were not successful in the process.

As a significant lack of studies and knowledge regarding biomimicry's design practice applied to architectural and urban designs remains [16], our research carried out an opportunistic analysis of this French biomimetic practice sample, relying on all of the sixteen projects factsheets produced by the Biomim'City Lab. This study is an opportunity to through lights on the contemporary trends in the practice and challenges that design teams face integrating biomimicry.

In this context, the research questions we have explored are:

- What types of urban biomimetic projects did French teams design?
- How was the biomimetic approach expressed in these projects in terms of goals, biological models and integration level?
- What challenges did the design teams face on the design process?

2. Materials and Methods

2.1. Data Collection

As an opportunistic study, this research did not produced data, but data from the sixteen biomimetic French urban projects presented in the source document ("Projets urbains bio-inspirés: un état des lieux des projets français", Biomim'City Lab, Paris, France, Document S1) were extracted and analyzed. All the French case studies document by the Biomim'City Lab report are here analyzed. Table 1 presents context information about these projects. Table S1 presents all the collected data. They have different understandings in terms of sustainability, comprehension, and abstraction of living systems, not evaluated in this study. However, they all derived from a creative approach based on the observation of biological systems.

Table 1. Analyzed projects.

Project Name	Project Location	Design Year
Alguesens	Paris, France	2016
Bangkok I'm Fashion Hub	Bangkok, Thailand	2015
Biolum_Reef	Marseille, France	2017
CIRC Lyon	Lyon, France	2018
Quartier de Gally (Cité Fertile—Terres de Versailles)	Versailles, France	2018
Ecoquartier Smartseille	Marseille, France	2013
Ecotone	Arcueil, France	2017
Eglise de Nianing	Nianing, Senegal	2014
Estran	Biarritz, France	2019
Groupe Scolaire des Sciences et de la biodiversité	Boulogne-Billancourt, France	2010
Osez Joséphine	Rueil Malmaison, France	2019
Parramata	Parramata, Australia	2013
Pôle d'Excellence sur le Biomimétisme Marin	Biarritz, France	2019
Residence solaire d'Ordener	Senlis, France	2018
Skolkovo Innovation Center	Skolkovo, Russia	2012
Tour D2	Paris, France	2007

Table 2 provides an overview of the variables and classification options used in the study, extracted from each project factsheet and compiled on a Microsoft Office Excel 365 database (Microsoft Corporation, Redmond, WA, USA). To make data scientifically sound with our research questions, we merged some of the original classes from the fact-sheets for the variables "project status", "project type", "integration level of the biomimetic approach", and "biological model". Document S2 explains each of the classification variables and options.

2.2. Analysis

Results were analyzed with a mixed-method approach, using quantitative and qualitative perspectives. At first, we use correlational research, relying on a quantitative typological analysis [17], to explore the sample trends. Following, we used a qualitative narrative and content analysis of text excerpts from the report [17,18]. This step aimed to explore lessons and barriers from the designing team perspective. Both approaches are detailed in the sequence:

2.2.1. Typological Analysis

The typological analysis aims to identify significant trends in the sample, such as their chronological evolution, project types, aimed objectives, level of integration and types of biological models. After data collection, we quantitively analyzed data on Microsoft Office Excel 365 (Microsoft Corporation, Redmond, WA, USA), using frequency and chronological analysis.

Table 2. Collected data from the original factsheets with the classification options used in the study.

Variables	Classification Options
Year of design	-
Project Status	Accepted and constructed or under construction | Accepted but not constructed | Not Accepted.
Type of project	Housing | Equipment | Office | Mixed-use.
Renovation	Partial renovation on the project | No renovation
Aimed objectives with the biomimetic approach	Thermal comfort | Visual/lighting comfort | Acoustic comfort | Indoor air quality | Outdoor air quality | Resistance to mechanical stress | Indoor water management | Outdoor water management | Biodiversity hosting | Adaptation to climate change | Lightening of the structure | Waste management | Others
Integration level of the biomimetic approach	Materials | Technology | Façade/roof/floor system | Building | Plot/Neighborhood.
Type of biological model	Eukaryote—Animal | Eukaryote—Plant | Eukaryote—Fungi | Archaea/Bacteria | Ecosystem
Aimed labels and certifications families	Batiment passif | BDM | BiodiverCity | BREEAM | Cradle to Cradle | E+C- | Effinergie | HQE | LBC | LEED | Matériaux biosourcés | Nature-Art-Education | NF Habitat | RT2012 | WELL
Lessons learned and challenges	Text excerpts (Document S3)

2.2.2. Content Analysis

Content and narrative pattern analysis have been done using text excerpts of the original report. Each project factsheet concluded with a section named "Lessons learned" (*Leçons à retenir*), in which designing and editorial teams highlighted main challenges, levers and barriers to the realization of a biomimetic urban project. We extracted these full excerpts from each factsheet and composed a unique textual corpus for analysis.

The textual corpus (Document S2) was then imported to MaxQDA Analytics Pro 2020 (VERBI GmbH, Berlin, Germany). We first used the word cloud function on this software to identify recurrent terms in the corpus. Afterwards, we used the interactive word tree function to explore phrases and narratives around the most frequent word, understand the context, and draw insights from this data.

2.3. Methodological Limits

This research is an opportunistic study, and some of its limits reflect the limits of the original data source. Notably, the French report does not document all biomimetic urban projects designed in France, but some of them. Nevertheless, we consider it a representative sample that allows us to infer trends in practice, once it is the most updated information available. Furthermore, this research does not aim to evaluate the pertinence and the environmental performance of the projects and their biomimetic design approach.

3. Results

3.1. Project Status and Types

We identified that 44% (n = 7) of the projects have been accepted by the project owners and are built or under construction. Examples in this category are the Nianing Church, a concluded project located in Senegal (Figure 1). This project finds inspiration in the termite mounds model aiming at passive thermal regulation, a well-described biological model successfully applied in previous projects as the CH2 and the Eastgate Center [5]. Another example is the Quartier de Gally project, a neighborhood under construction that aims at natural ecosystems as models to promote a neighborhood that better integrate urban spaces and nature.

Figure 1. Nianing Churc, Sénégal (© Régis L'Hostis/IN SITU Architecture).

A quarter of the projects (n = 4) have been accepted but are not constructed and not under construction. It includes conceptual projects, as the Biolum_Reef, a project that aims to create autonomous human habitat in the sea, presenting bioluminescent bio-inspired technologies and contributing to ocean decontamination and natural habitat provision (Figure 2). This category includes also projects accepted by the client and further abandoned, as the Residence Solaire d'Ordener, a project in which the building orientations were calculated using a solar phyllotaxis algorithm to optimize sunlight exposition, and, finally, projects still in executive design, as the Ecotone project that finds inspiration in transition ecosystems recreating ecosystems services in the urban space.

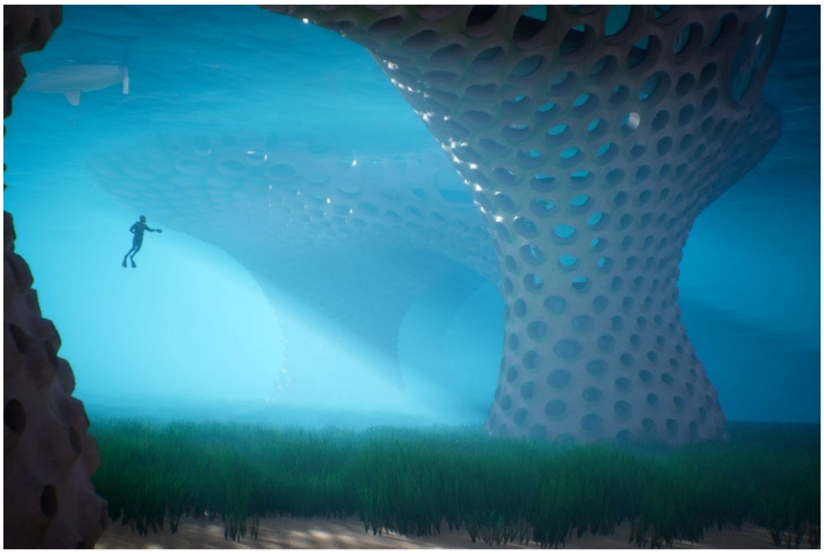

Figure 2. Biolum_Reef (© Treex/Tangram Architectes).

Furthermore, 31% (n = 6) of the projects were not accepted by the project owners. One example is the Osez Josephine project, a mixed-use project that finds inspiration in French forests, aiming for diverse vegetation strategies, more circular water and waste cycles and bioclimatic and evolutive buildings.

Office projects are the most represented (37%), followed by equipment projects (25%), as schools and churches (Figure 3). Housing and mixed-use projects are the less represented types (19% each). Office projects mostly implemented biomimetic approaches, but they also represents the project type with more issues to reach implementation phases (Figure 3). One successful office example is the Tour D2 project, which uses the periosteum structure (membrane covering the bones) as model for its exo-structure, which allowed to reduce the total building mass (Figure 4). An example that did not reach the implementation phase is the Parramatta project, which uses a local eel species model for a passive thermal regulation system.

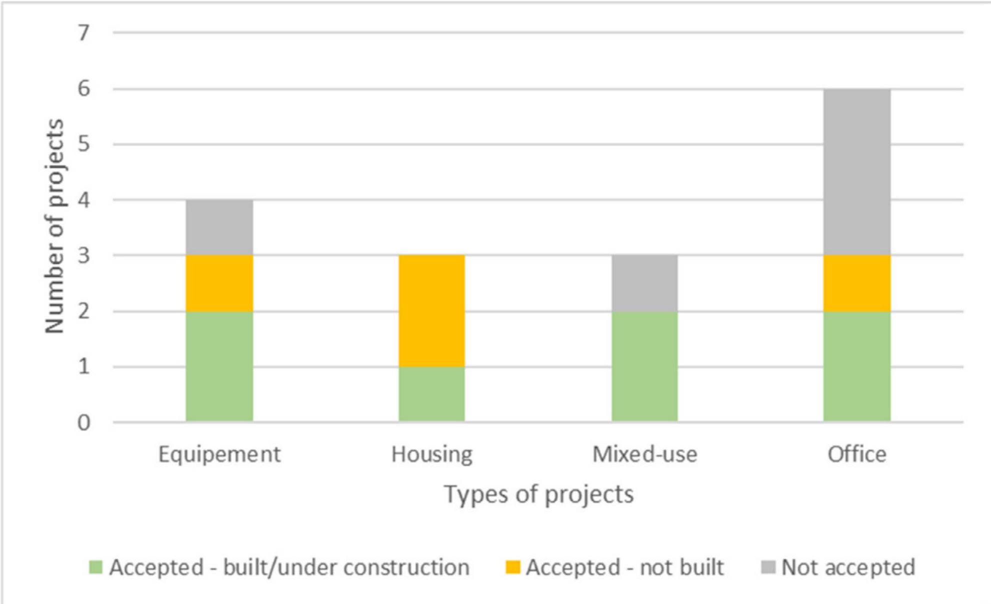

Figure 3. Distribution of projects status according to their types.

Figure 4. Tour D2, La Défense, Paris (© Pierre Elie de Pibrac/Bechu & Associés).

Very few of them addressed the retrofit of existing infrastructures. Only 13% (*n* = 2) integrate some renovation. They are the Osez Josephine and the Quartier de Gally projects. In both, renovations were partial, on some selected pre-existing buildings.

3.2. Chronological Evolution of Projects

Figure 5 outlines this sample distribution over time and according to their design year and status. The oldest documented project in the report was designed in 2007. Between 2012 and 2016, the report presents at least one biomimetic project designed per year. Then, the number increases from 2017 to 2019. Nevertheless, since 2013, we also observe an increasing number of projects that did not reach implementation (not built or not accepted).

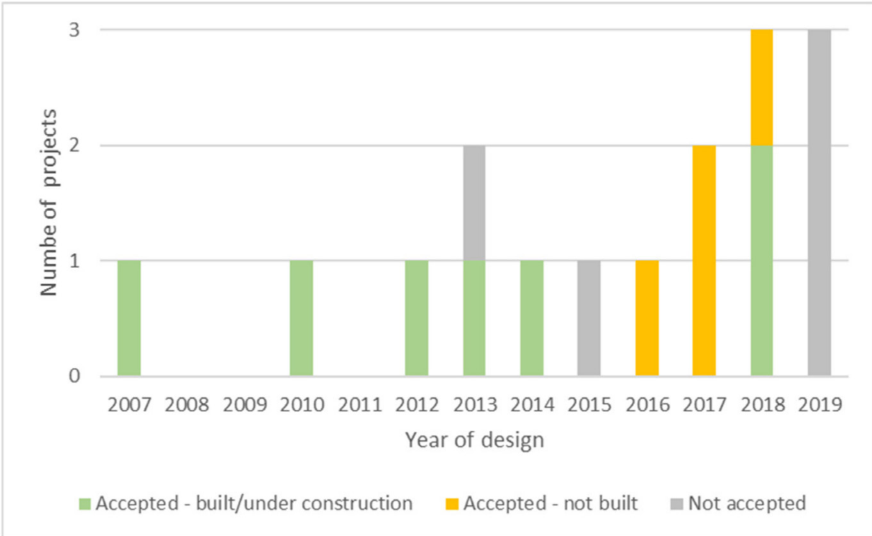

Figure 5. Distribution of the analyzed biomimetic urban projects according to their status and design date.

3.3. Objectives

Figure 6 presents the frequency of declared objectives of the projects with their biomimetic approach. We can observe that six objectives were present in more than ten projects (62.5% of the sample): climate change adaptation, biodiversity hosting, outdoor water management, indoor air quality, visual and lighting comfort, and thermal comfort.

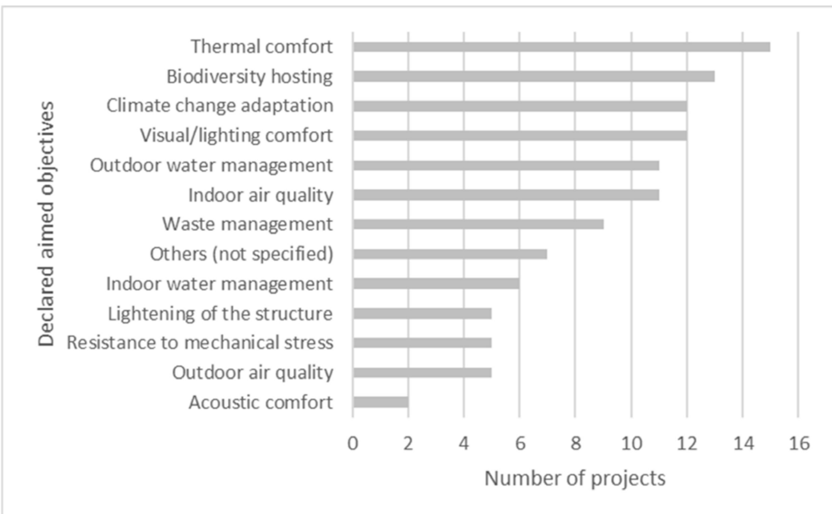

Figure 6. Aimed objectives.

Most of the projects declared to seek several objectives with their biomimetic approach. The average number of objectives aimed per project was 7. The project with a narrower focus is the CIRC, a project that uses bio-inspired adaptative solar protections made of metal with shape memory, aiming for visual and light comfort, and thermal comfort (Figure 7). The projects with a wider focus in the sample, aiming twelve different objectives are the Biolum_Reef, Osez Joséphine and the Pôle d'excellence sur le biomimétisme marin.

Figure 7. CIRC adaptative solar protections (© Art&Build).

We observe that accepted and built or under construction projects in the sample tend to have a narrow focus on their objectives (Figure 8).

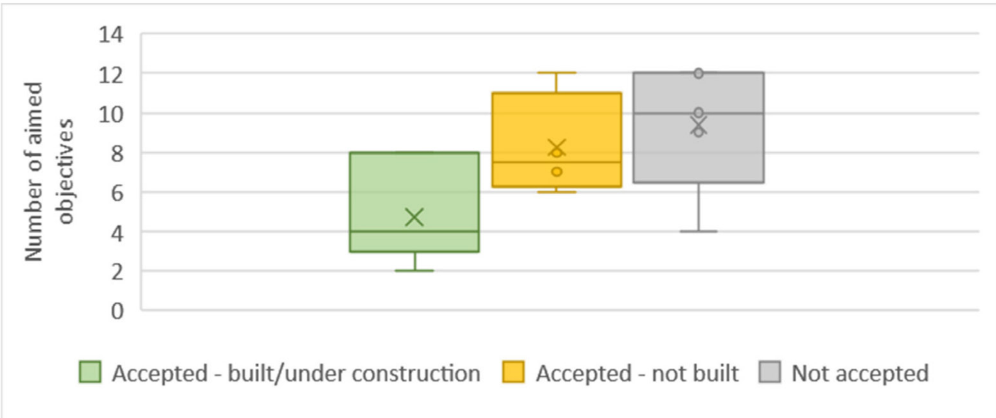

Figure 8. Distribution of the total number of aimed objective in the projects per project status.

3.4. *Level of Integration*

The projects' most recurrent integration level of the biomimetic approach is at the façade/roof/floor systems (Figure 9). Ten projects applied some level of biomimicry at this level. Examples are the Tour D2 project with its exo-structure, the CIRC with its adaptative solar protections and the Alguesens project, which proposes a bio-façade with algae bioreactors, ensuring building thermal regulation and CO_2 sequestration.

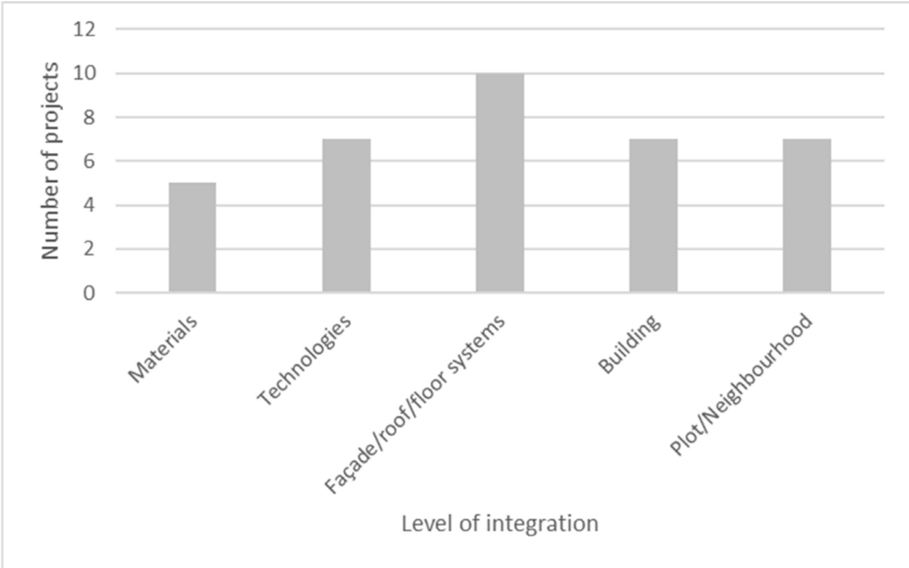

Figure 9. Integration level of the biomimetic approach.

Moreover, the less explored level is building materials (Figure 9). One example is the Bangkok I'm Fashion Hub, which explored a minimal structural surface in local woven bamboo, inspired by spider webs, associated with a bio-inspired membrane ensuring waterproofing and passive ventilation.

At the technology level, one example is the Smartseille project (Figure 10a), which tested a mycelium-based technology to remediate soil pollution on the project site. At the building level, one example is the Estran project, which replicates a foreshore ecosystem in the building, integrating a wetland to serve as a reservoir for rainwater, water treatment system and habitat for biodiversity. Finally, at the plot/neighborhood level, examples are the Quartier de Gally (Figure 10b) and the Ecotone projects.

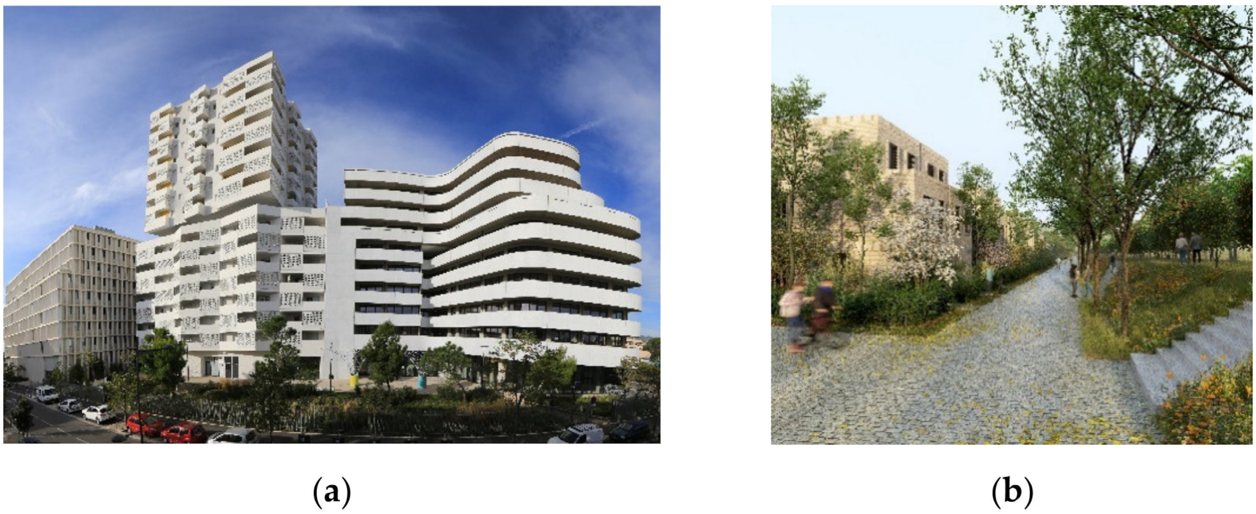

Figure 10. (**a**) Smartseille (© Action Photo Video Thierry Lavernos/Eiffage); (**b**) Quartier de Gally (© ICADE).

On average, projects explore two different levels of integration. Three projects explored just one level (CIRC, Nianing Church and Tour D2), and only one project explored all the dimensions (Pôle d'Excellence sur le Biomimétisme Marin).

3.5. Type of Biological Models

Ecosystems are the most recurrent models, cited in 10 projects, followed by Eukaryotes models as plants and animals. Fungi and Archaea/Bacteria models are the less explored models in our sample (Figure 11).

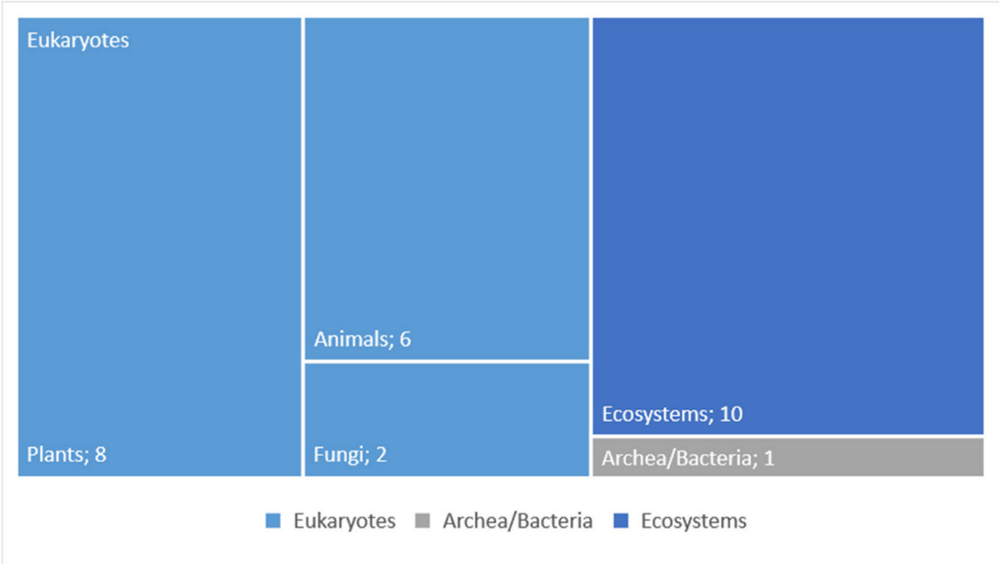

Figure 11. Occurrence of the different types of biological models (*n* = number of observations).

3.6. Green Labels

To give visibility to their sustainable engagements and performances, ten projects from the sample (62.5%) highlighted labels that the projects aimed for or obtained. Fifteen different labels families have been cited, but only six have been cited more than once (Figure 12). We can find a higher presence of standard French market label families as HQE, E+C- and BiodiverCity. Nevertheless, innovative labels, not yet fully adopted by the French market, have been observed, as the LBC.

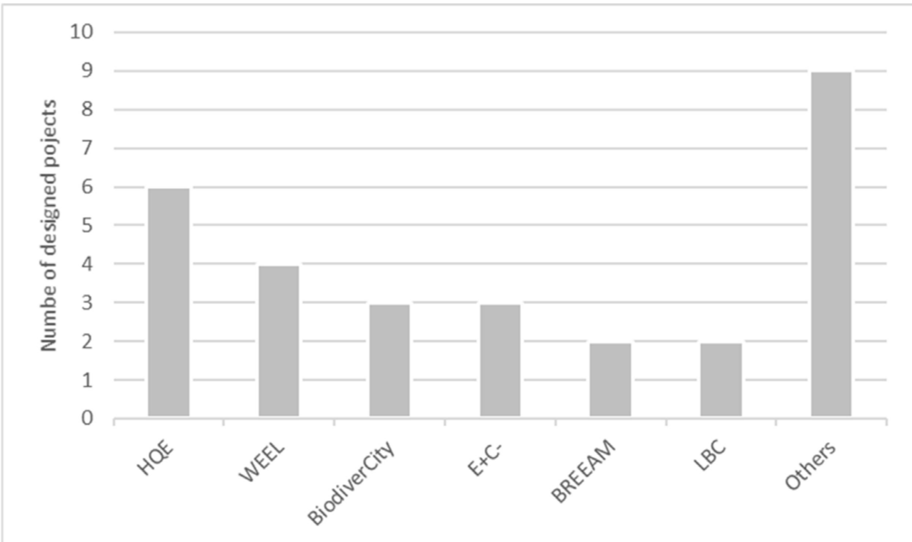

Figure 12. Green building labels.

3.7. Design Challenges

The main recurrent keywords in the "Lessons learned" section from the projects factsheets relates to the design process and its challenges as: "*conception*" (design), "*rechercher*" (research), "*étude*" (study), "*temps*" (time) and "*integration/intégrer*" (integration) (Figure 13).

Figure 13. "Lessons learned" section word cloud, using MaxQDA Analytics Pro 2020.

Figure 14 presents the interactive word tree for the word "*conception*" (design), the main identified keyword. The interactive word tree allowed us to identify passages and recurrent ideas presented by the designing teams.

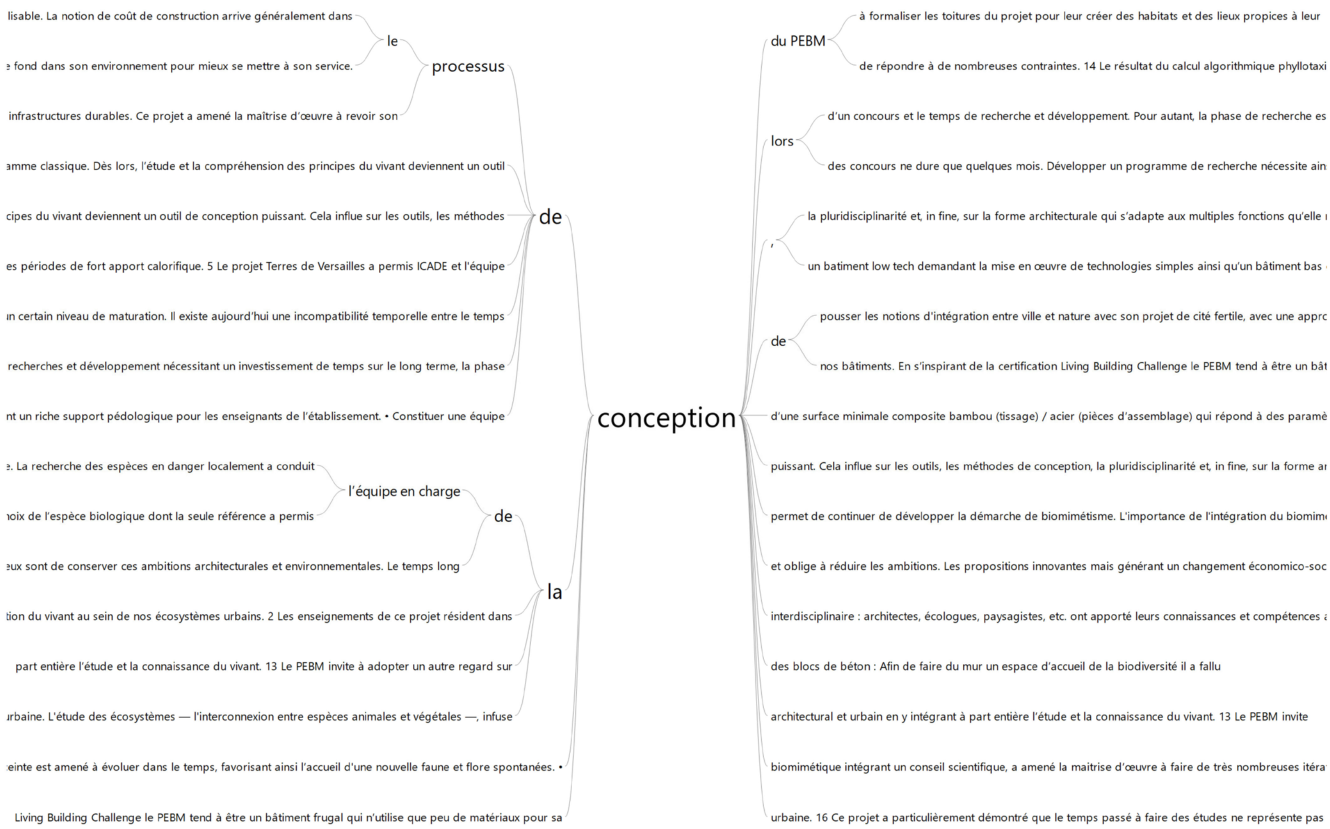

Figure 14. Interactive word tree for "*conception*" using MaxQDA Analytics Pro 2020.

The passages related to the challenges of the design process converge into two main topics: project temporality and team knowledge.

The result highlights that the temporalities of design and research process are distinct, as the available time for the design of urban projects, in the French concurrently context, is short. However, the research and development process usually necessary to apply biomimicry into the process is long. Nevertheless, designers acknowledge the importance of bridging the gap between the two practices. The following passages illustrate this:

1. *"research and development process at the heart of biomimetic solutions: the bio-inspired facades of the project were the subject of a research project, with several prototypes and tests before being integrated into the project."*
2. *"The long design time allows the biomimicry approach to continue to be developed."*
3. *"Today there is a temporal incompatibility between the design time in a competition and the research and development time."*
4. *"This project has particularly demonstrated that the time spent on studies does not represent a cost, but a real investment (...)."*
5. *"The limitations of this project are the number of associated research projects that would need to be launched over the long term."*

The second challenge is related to the team experience and knowledge of biomimicry, biology and ecology. Designers acknowledge the importance of working in a multi-disciplinary context, integrating experts, and building biomimicry capacity on the design team and other project stakeholders. The following passages support this:

1. *"The importance of integrating biomimicry right from the competition phase with an acculturation of the architects and the project owner upstream of the project is a key element."*
2. *"Set up an interdisciplinary design team: architects, ecologists, landscape designers, etc. contributed with their knowledge and skills to build a project (...)."*
3. *"This project provided an opportunity to explain the biomimetic approach and its potential to the contracting authority. The latter understood the real opportunities that the biomimetic tool offers (...) but we also identified some inherent obstacles related to their poor knowledge on the subject."*
4. *"This project led the project management to review its architectural and urban design process by integrating the study and knowledge of living things into it."*
5. *"The process of biomimetic design integrating a scientific council, led the project management to do many iterations and to develop their knowledge on many subjects. In return, the knowledge not directly used has enriched the process allowing the project management to improve its practice."*

4. Discussions

4.1. An Increasing Trend over Time

In the analyzed sample, we observed an increasing trend over time of projects applying biomimicry for sustainable development in France. This trend deserves further exploration with a larger and exhaustive sample. This trend converges with the increase in biomimicry research applied to architecture and urban design in the last years already demonstrated by previous research [4,5]. Two important milestones in the French timeline that contributed to more visibility and interest in biomimicry are the Alguesens project (2016) and the Ecotone project (2017). Alguesens is one of the winners of the "*Reinventer Paris*" competition, aiming to innovate and experiment with new approaches to bring selected Parisian sites to life. Ecotone is one of the winners of the "*Inventons la Métropole du Grand Paris*" competition, one of Europe largest contemporary competition, promoting innovative projects to rethink critical sites in the Parisian metropole region.

Nevertheless, our sample also presents a growing number of projects that do not reach the implementation phase. Several factors could be related to these projects non-acceptance, not related to the biomimetic approach, as the highly competitive context of urban projects competitions, the quality of the overall project, the project costs, and political preferences. However, the role of the biomimetic approach in the project acceptance by the final client deserves further exploration. Hayes et al. (2019) highlighted in their case studies that the absence of well documented and successful application examples remains a significant barrier in the field. Designers from the analyzed projects also indicated that the project owner's lack of understanding of biomimicry could be a barrier to the project success.

4.2. A Focus on Macroscopic Models

Most of the analyzed biological models remained at macroscopic scales such as ecosystems and eukaryotes. This finding converges with previous results highlighting a taxonomic bias in selecting biological models [14]. This trend can be explained due to the lack of academic knowledge of biological models by the design team and the lack of time to analyze, compare, and then select relevant living models to face the project challenges. Integrating stakeholders with a strong background in biology or ecology in the design teams can be a way to explore further biological models [19,20], mainly in a short delay design context. Another lever is developing tools and methods to help designers navigate biological knowledge easily, as being explored by fellow researchers as reviewed by Wanieck et al. [21].

Ecosystem-level biomimicry is a growing research topic [4,16], and its first position in our sample highlights a particular interest in the practice for this subject. We assume that ecosystem-level inspiration helps address transversal and systemic urban challenges such as biodiversity loss, the materials, and energy flows between urban and ecological systems [16,22,23].

4.3. Organising the Design Process

There is a significant challenge in integrating research and development with urban biomimetic practice [24]. Designing teams highlighted the different temporalities and the positive aspects of integrating research and specialists in the projects. Integrated design process (IDP) could be a helpful design framework to organize biomimetic architectural and urban projects design. It relies on multi-disciplinary teams early engaged in the project, with a straightforward decision-making process and an external facilitator, aiming to foster sustainable and regenerative development on urban projects keeping in mind the project quality and costs [25].

Another leverage point would be to work alongside project owners to raise awareness of the topic and integrate biomimetic specifications on their project briefing and technical specifications.

4.4. Thermal Comfort and Biodiversity Hosting: Two Major Entry Points

Thermal regulation is a contemporary urban challenge well-explored in biomimetic architecture and illustrated by numerous well-documented proofs of concept [2,5]. Successful biomimetic cases reduce the risks of rejection for project stakeholders [16]. This could explain the number of observations of this objective within the sample (n = 15). Among the analyzed projects, diverse solutions and strategies have been observed to reach this objective through biomimicry. The Skolkovo Innovation Center proposes a site organization that minimizes thermal loss, imitating penguins comportment to save and share heat. Other projects deal with thermal regulation through the façades, as the CIRC and Alguesens, and others with passive ventilation systems as the Nianing Church and Parramatta projects.

Regarding biodiversity, several projects declared to contribute to creating habitat for biodiversity (n = 13). However, only one project, the Ecole des Sciences et de la Biodiversité, clearly stated the biomimetic approach to reach this objective. To bring biodiversity back to the urban space and promote human and other species co-habitation, the building walls find inspiration in cliffs walls, using concrete blocks that create holes and niches for different animal and plant species (Figure 15).

Figure 15. Biodiversity at the walls of Ecole des Sciences et de la Biodiversité (© Myr Muratet/ChartierDalix).

Even if biodiversity and ecosystems models have a high interest in our sample and practice, very few bio-inspired projects achieve to address their complexity adequately. For example, projects finding inspiration on ecosystems tend to look mainly to materials and energy flows, translating it to into urban metabolism and circular economy solutions. However, the ecosystems biotic and abiotic structure and ecosystems functions are much less explored [22,26], leading to simplistic and metaphorical ecosystem-level biomimicry application.

4.5. Biomimetics Applied to Retrofit

The renovation of urban infrastructures remains the main lever over the coming years to reduce human impacts on biodiversity and ecosystems [27]. In 2019, retrofitting activities represented 54.4% of the building market in France [28]. For 2020, this activity is expected to increase +0.9% [29].

Biomimicry offers an opportunity to handle retrofitting with a sustainable development perspective [14,23]. Nevertheless, only a few of the analyzed projects had partially retrofitted existing infrastructures. This topic deserves further exploration. The reasons could be related to a lack of research and practice of biomimicry for architectural and urban retrofitting but also, retrofitting projects and stakeholders could be less open to innovative approaches.

5. Conclusions

Biomimicry seems to be a design approach with growing interest in the French market, but several unresolved questions and challenges remain.

The analyzed data highlighted the gaps between biomimetic and biological research teams and urban designers practitioners. To facilitate the knowledge transfer from biological and ecological disciplines to architecture and urban design practice is a major challenge. Our data demonstrated the importance of rethink design team composition and projects design phase organization to bridge this gap.

The case studies also highlighted the variety of sustainability goals addressed through biomimicry in France. Nevertheless, it would be worth formally exploring the different urban stakeholders' motivations applying biomimicry and the difference in design process and outputs between applying it with a narrow or a broad focus.

Furthermore, it would also be essential to study and evaluate the performance of these projects concerning their objectives. Projects tend to use labels to show their performances, but urban biomimicry still lacks specific sustainable performance metrics. The use of life cycle assessments and ecosystems services assessments could allow a proxy to these performance assessments.

Finally, to document and analyze the practice of biomimicry on architectural and urban projects allowed us to have some perspective from the French practice. To showcase national projects can tackle the incomprehension of biomimicry by urban stakeholders and project owners and raise awareness of the topic. Nevertheless, such benchmarks are rare and deserve to be enlarged. A more exhaustive study would probably highlight new challenges, and it remains relevant work to be done.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/biomimetics6020027/s1, Table S1: Projects data, Document S1: *Projets urbains bio-inspirés: un état des lieux des projets français*, Document S2: Variables and classification options definitions, Document S3: Leçons learned text excerpts.

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Review

Application of Biomimetics to Architectural and Urban Design: A Review across Scales

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Abstract: Application of biomimetics has expanded progressively to other fields in recent years, including urban and architectural design, scaling up from materials to a larger scale. Besides its contribution to design and functionality through a long evolutionary process, the philosophy of biomimetics contributes to a sustainable society at the conceptual level. The aim of this review is to shed light on trends in the application of biomimetics to architectural and urban design, in order to identify potential issues and successes resulting from implementation. In the application of biomimetics to architectural design, parts of individual "organisms", including their form and surface structure, are frequently mimicked, whereas in urban design, on a larger scale, biomimetics is applied to mimic whole ecosystems. The overall trends of the reviewed research indicate future research necessity in the field of on biomimetic application in architectural and urban design, including Biophilia and Material. As for the scale of the applications, the urban-scale research is limited and it is a promising research which can facilitate the social implementation of biomimetics. As for facilitating methods of applications, it is instrumental to utilize different types of knowledge, such as traditional knowledge, and providing scientific clarification of functions and systems based on reviews. Thus, interdisciplinary research is required additionally to reach such goals.

Keywords: biomimicry; built environment; interdisciplinary collaboration; sustainability; biophilia

1. Introduction

Biomimetics is defined as "the interdisciplinary cooperation of biology and technology or other fields of innovation to solve practical problems through the functional analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution" [1]. Biomimetics is an approach that develops solutions based on living systems, such as organisms or ecosystems. Although nature is mimicked, it is not re-productions but the requires further abstraction that solutions will derive from these models in nature and will align with life principles and potentially decrease the burden on the environment, as they may be less dependent on fossil fuels and more self-organizing and multifunctional, for example [2]

The range of applications of biomimetics is wide and promises to foster innovation [3]. Since 2000, biomimetics has been progressively applied beyond conventional chemistry and expanded into material science and engineering, mostly at the centimeter scale [4]. Furthermore, biomimetics is increasingly applied to design in architecture and urban areas, at the meter or kilometer scales [5] (Figure 1).

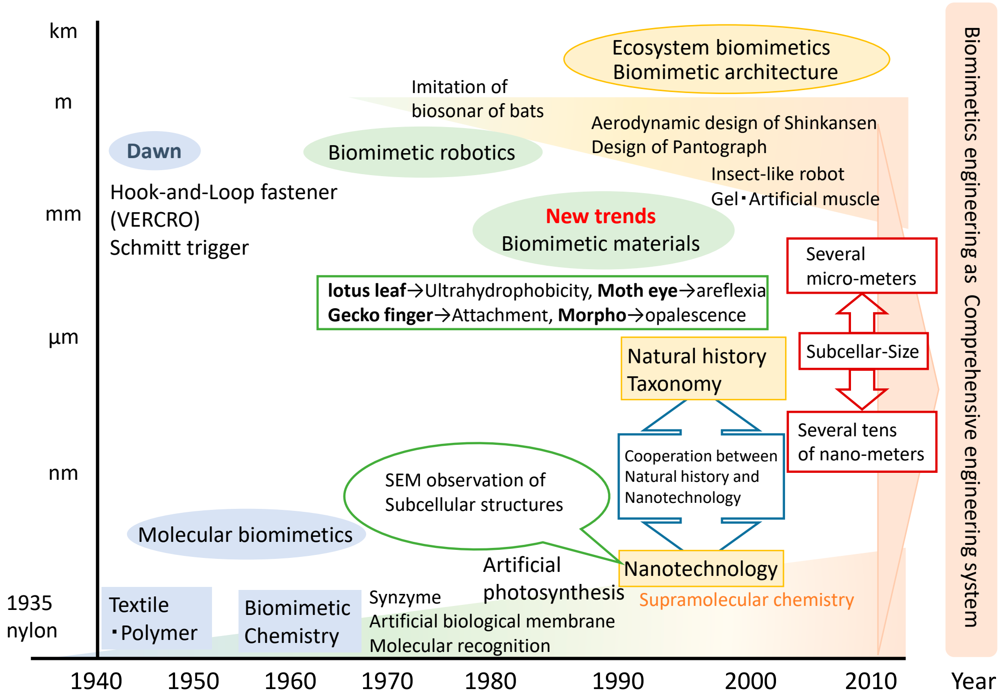

Figure 1. Historical trend of biomimetics. Source: Shimomura (2015).

Biomimetics is an approach toward sustainable whole systems design [6,7] that has the potential to develop ecological solutions to a given problem. However, it does not necessarily contribute to ecological solutions; Gebeshuber et al. [8] argue that designing sustainable products is independent from the specific design method.

However, a notion getting reinforced by scientists and designers is that biomimetic innovation must be promoted to make the goal of a sustainable society real [9]. Contributions of the biomimetic approach not only to environmental sustainability but to economic sustainability have been demonstrated [10]. Speck et al. [11] argue that sustainability, as a concept, cannot be transferred from biology to innovation easily, but that living systems have characteristics that, if systematically studied and transferred, can help us to move toward sustainability. Pedersen Zari [12] lists three main motivations to apply biomimicry approaches in the design process. The first is related to the development of new technologies and materials, without concern for ecological performance, and is called "biomimicry-for-innovation"; the second, aligned with previous consideration, seeks better ecological performance and is named "biomimicry-for-sustainability". The last, and least explored, is related to the development of human psychological well-being, and mostly applies to biophilic design theories.

Although biomimetic approaches could have positive and negative effects on the environment and society, exploring a method to enhance the positive effects of the technology is urgently required [13]. Wanieck et al. [14] identifies and analyzes 43 tools related to biomimetics application and discusses the interconnection of these tools to facilitate a problem-driven biomimetic approach, but sustainability is not at the center of the discussion.

In urban and architectural design, biomimetic concepts can be applied to tackle global environmental issues [12,15] Architecture in modern cities requires a huge amount of energy for construction, maintenance, and operation, directly and indirectly causing global environmental issues, such as loss of biodiversity or climate change through greenhouse gas emissions [16]. Urban areas are responsible for 70% of global carbon emissions and are also the cradle of major current social problems [17]. It has been proposed that the biomimetic approach can address these challenges [15,18] at multiple scales, from single mechanical units (materials) to buildings, up to entire urban areas.

Living organisms and the natural world are regarded as the key source of ideas for functional design of sustainable built environments [19,20].

Alongside the view of the biomimetic concept as a promising approach to move toward sustainable architecture, there is, however, a lack of methodologies to facilitate its application in building and urban design [21,22]. In this paper, trends in the application of biomimetics in the fields of architecture and urban design are reviewed, to identify the issues that may surround and successes that may emerge from implementation. Overall trends of the reviewed papers are analyzed in Section 2, and the papers related to architectural design and urban design are reviewed in Sections 3 and 4, respectively.

2. Trends of Application of Biomimetics in the Fields of Architectural and Urban Design

To conduct the review research, the related papers were collected using Google Scholar with the keywords; city/urban, architecture, biomimetics/biomimicry, in 2019. In total, 107 papers including proceedings and book chapters were identified, and 72 papers of them were discussing mainly about application of biomimetics in the fields of architectural and urban design (see Appendix A). The remaining papers did not not focus on our fields of interest but on general trends of biomimetic design. At first we identified the research topics of the papers, and at second we identified the target scales (architecture/urban) addressed by the selected papers.

Regarding the research topics papers were categorized into four topics: Material, Structure, System, and Biophilia. Examples of the subjects addressed in each topic are: Materials: bio-inspired building materials; Structure: bio-inspired building structure as façades and building structural design; Systems: biological system and ecosystem level biomimicry; bio-inspired traffic systems design; bio-inspired urban infrastructure systems management; Biophilia: use of natural patterns and systems on buildings and urban design aiming to improve users well-being and to foster sense of nature.

Some papers were conducting research on several topics as shown in the table presented in the Appendix A. The number of papers published in individual years and their research topics is presented in Figure 2. The bar chart shows that the topic "Structure" was relatively frequently discussed, and "Biophilia" seems to be emerging recently in our sample. The trends of papers with the topics of Material and System are similar, still the number of papers with the topic of System is relatively large compared with that of the papers related to Material.

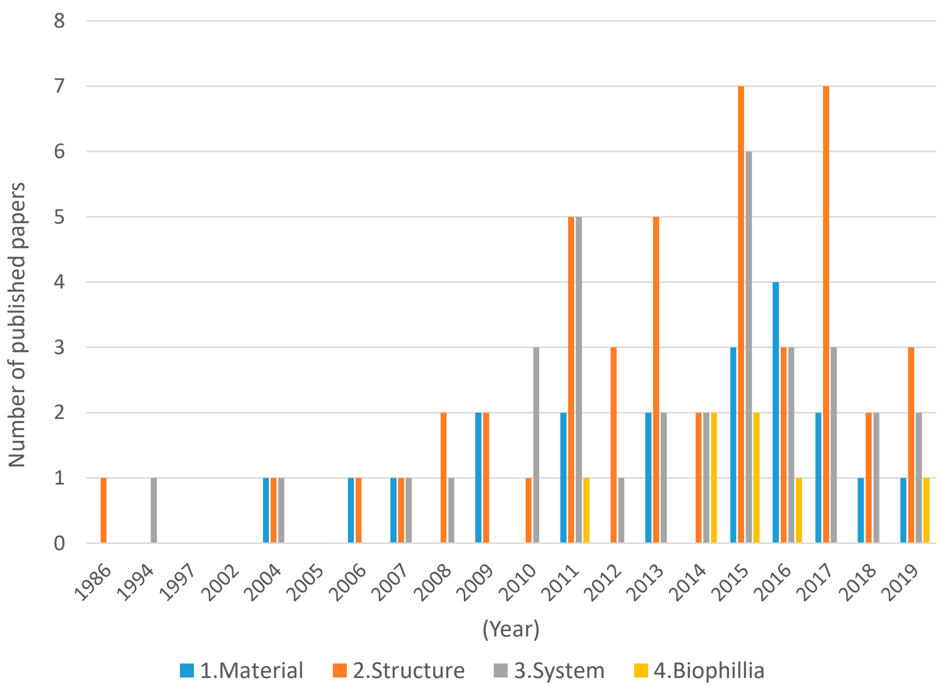

Figure 2. Number of papers published in individual years and research topics of the papers.

As for the concrete keywords in the research topics, subjects such as façades and buildings envelope were frequently mentioned and studied papers adressing the Structure topic. For example, structures of plants were mimicked in several research to design building envelope [23,24]. It's also important to observe that the energy efficiency of biomimetic design tended to be mentioned as a merit of application of biomimetics design in our sample.

Regarding the target scales (architecture/urban) of the reviewed papers, the trend of the publication is shown in Figure 3. The number of papers focusing on the architectural scale is much larger than papers adressing the urban scale. Papers adressing both scales are increasing, still the papers which are discussing and analyzing the application of biomimetics only at the urban scale are limited.

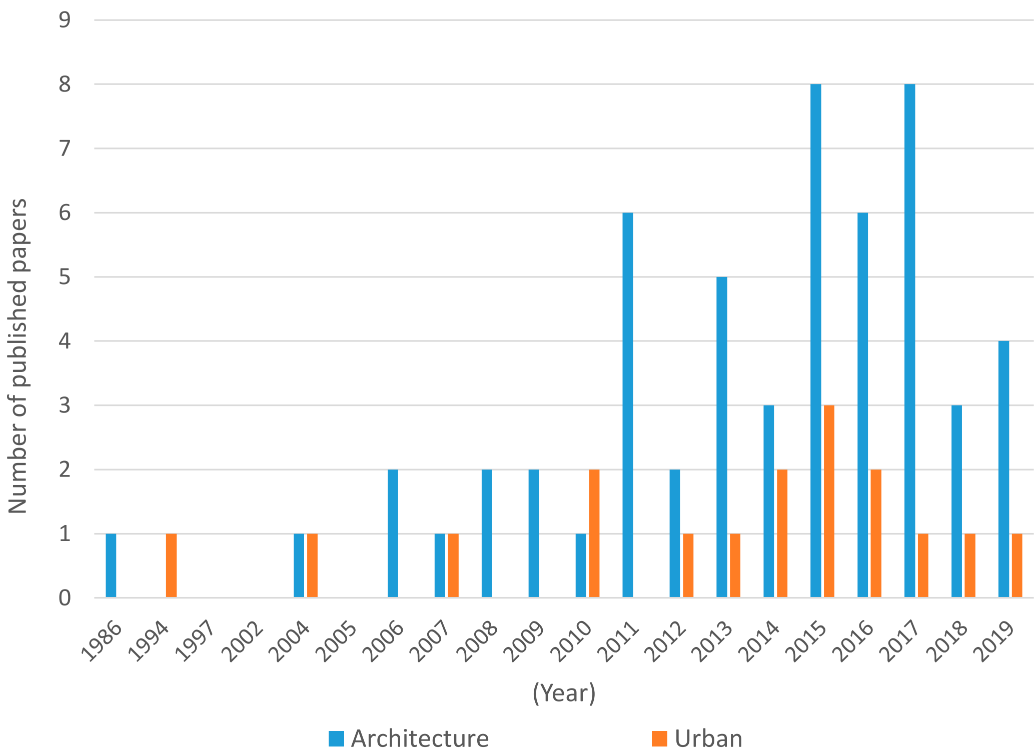

Figure 3. Number of papers published in individual years and target scales (Architecture/Urban).

According to the trends observed in Figures 2 and 3, biomimetic research topics related to Biophilia and Material are topics which need to be further explored in architectural and urban design. As for the scales, the biomimetic research at the urban-scale, adressing urban design, urban forms and sustainable urban performance, is promising to facilitate the social implementation of biomimetics, but is still lacks of attention.

In the following sections, detailed review results of research on architectural and urban design are provided and discussed.

3. Architectural Design

Nature has inspired built space since antiquity, when natural proportions were borrowed for aesthetic purposes [25]. Mimicking biological morphology is one of many conventional applications of biomimetics in the field of architecture [26], and the subjects of this mimicry are not exclusively single organisms or organisms per se, but also the products of their biological behavior, such as nests [27–29].

In modern architecture, the geodesic cupolas introduced by the architect Buckminster Fuller are one example of biomimetics application [30], as is the art nouveau style, in which biological structures were frequently mimicked.

Currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. As a measure to reduce the environmental impacts of buildings, the biomimetic approach provides design elements that, for example, collaborate with the economics of materials and the optimization of lighting and heating [31,32]. Creating the potential for cost reduction in civil construction can be facilitated by using this approach [33]. Biomimetics is expected to be a comprehensive approach based on environmental technologies, including applying renewable energy and repurposing it to optimize the global environment [34,35].

Contemporary applications at this scale aim mostly to reduce environmental impacts or improve human well-being, topics that will now be explored.

3.1. Reduction of Environmental Impact

Energy-use optimization has been a central subject in biomimetic architecture. Buildings can rely on living systems' strategies to reduce energy-resources consumption related to illumination, heating, and ventilation [36], for instance. Passive cooling and ventilation systems are a major application field of biomimetics [37]. Ventilation performance of building ducts can be enhanced by mimicking the shape of joints between plant trunk and branch [38]. An example of a building-scale application is the Eastgate Center in Harare (Zimbabwe), which takes inspiration from termite mounds' passive temperature-regulation systems, and another example is the phototropic function used to optimize natural lightning on buildings, applied in the Heliotrope in Freiburg, Germany [36]. Solar cells for on-site energy production, deriving from mimicking photosynthesis, were also proposed. Artificial photosynthesis systems can improve global and local carbon-neutral cycles [39].

Further applications rely on building structures and materials. The structures of coral reefs and plants have been mimicked in architecture or materials aiming to reduce material use and make buildings stronger, lighter, and easier to construct [40]. Other studies investigated load adaptation of natural materials, like bones, to develop new lightweight materials that can be applied to architecture [41].

New building techniques have also been a field of application of the biomimetic approach. Gruber and Imhof [42] explore natural growth patterns and their application in architecture, such as in additive buildings that can be operationalized through 3D printing and can contribute to the reduction of resources demand on architecture.

Relatively large technologies related to the façade have been developed. As architectural envelopes, façades present several opportunities. They can be designed to suppress heat islands in the center of the city, as do, for example, surface structures designed by mimicking flower petals [43], or the use of green façades to improve local biodiversity [44] and to reduce heat islands and promote the reduction of noise [23]. Sheikh and Asghar [45] implemented a biomimetic façade inspired by the shape of the sorrel leaf. They found a significant decrease in building energy load (32%), without blocking visibility to the outside of the building. Moreover, façades mimicking animal fur [46], animal blood perfusion, to improve thermal performance of the façades [47], movable façades mimicking the structure of animal wings [48], and façades inspired by the human skin system [49] have been developed.

The features of plants and their leaves have been applied to the development of building envelopes [50–55], where envelopes with shading mimicked the supple structure of plants [56]. Another example is Flectofin technology, developed by the Institute of Building Structures and Structural Design (ITKE), at the University of Stuttgart, which seeks inspiration from the pollination mechanism of the *Strelitzia reginae* flower to develop an adaptative shading system, and the HygroSkin pavilion envelope model, which seeks inspiration in spruce cones to create an adaptative envelope that works in response to environmental conditions [54]. Furthermore, there is an example of design of building envelopes mimicking plant-cell walls [24]. Biomimetic building skins show the potential for energy savings; a conceptual building skin developed based on the African reed frog and the Hercules beetle led to potential total energy savings of 39% in small office buildings in Chicago [57].

In addition to the structures and functions of organisms, products of organisms are also mimicked. For example, air-conditioning and energy supply to individual small residential districts have been constructed and optimized by mimicking the natural structure of the nests of ants [58–60]. These studies focused exclusively on air-conditioning and, to continue the metaphor used at the beginning, can be said to be at the individual "organism" level.

3.2. Enhancement of Well-Being

Well-being can be improved psychologically by the incorporation of biomimetic patterns into the structure and decoration of buildings, and research on visual patterns in biomimetics has been conducted for this purpose [25,61].

Biophilic design, as a subcategory of biomimetic design, can be understood as a biomimetic application aiming at human well-being [12]. This concept focuses on the psychological connection of humans with the natural environment, to promote a sense of belonging [62]. Biophilic design has several strategies to enforce this psychological connection; some examples are the use of natural lightning, organic morphologies, and views to natural spaces. Biophilic applications have garnered several quantifiable pieces of evidence in humans, in areas like stress control and better concentration [63].

Conventionally, biophilic structures and decoration patterns are found in religious buildings, including churches and mosques, as well as in indigenous architecture in different regions of the world [26]. In such contexts, biomimetics serves as part of the focus of architectural and urban design in terms of the creation of a place for humans, fostering their well-being. Learning from, and evaluation of, historical buildings can facilitate understanding of functions of biomimetics in enhancement of well-being.

4. Urban Design

Cases of the application of biomimetics on the architectural scale were reviewed in the previous section, as individual buildings or materials, in the attempt to underpin their functions. At this scale, individual functions are frequently mimicked. In contrast, at the urban-design scale, discussed in this section, ecosystems are referred to and mimicked.

Cities are huge resource-consuming areas [64], and their growth, activity, and resource needs are responsible for major biodiversity loss and damage to natural ecosystems [65,66], compromising the ability of these ecosystems to contribute to the maintenance of life on Earth by providing a set of ecosystem services from which the human being benefits.

A characteristic of ecosystems is the tendency to optimize themselves for the good of the whole (total optimization), rather than for individual parts, while maintaining the diversity of elements. These characteristics are reflected in the concepts of urban design, so that mimicking ecosystem functions and processes serves as a strategy to develop more sustainable urban spaces [67]. Methods of quantitatively evaluating various ecosystem services of urban ecosystems have been proposed, as a tool to promote biomimicry at the urban-design scale [68,69].

Relevant models and their application on the production of supporting, provisioning, and regulating services in an ecosystem in urban areas are discussed below.

4.1. Application of the Concept of an Ecosystem and Its Components

If we use ecosystem services as guidelines for urban design, the artificial environment can contribute to global sustainability and even regenerate natural ecosystems [70]. For cities that are rapidly urbanizing, symptomatic technological solutions are not effective in the long term. Rather, the concept of sustainable urban ecosystems, seen from a long-term, integrated perspective, is necessary [71]. The Ecosystem Services Analysis method helps urban designers draw goals and actions for the redevelopment of urban spaces, understanding local ecosystems and emulating it on the urban scale [72]. As a case study, Pedersen Zari [72] applied this methodology to evaluate the provision of water and energy in Wellington (New Zealand). The approach allowed the author to measure environmental performance in the city based on ecosystem performance and not on politically decided metrics. Biomimetics is regarded as an ontology in future urban design, incorporating perspectives, including governance and the participation of residents [32]. From the viewpoint of biomimetic simulation and analysis, organically linking the various elements of the city can contribute to the optimization of the whole urban system, going beyond the optimization of individual elements, such as housing, transportation, and business.

In addition to recent research that adapts ecosystem concepts to urban design and ecosystems (functions), there are also studies that directly apply specific ecosystems or organism systems [70]. For example, amoebal networks can give engineers insights to design robust transportation networks which include solutions to problems related to trade-off relationships between cost, transport efficiency, and tolerance [73–75]. Concerning infrastructure networks, studies suggest that increased efficiency can be reached through biomimetics [76]. Self-organization as a concept for optimizing the network structure can also be applied to the design of traffic infrastructure; for example, an optimal operation algorithm for traffic lights, based on the principle of self-organization, has been proposed [77].

In regard to urban infrastructure management, biomimetic materials have various self-organizing functions, such as self-cleaning, self-repairing, water repellency, and so on. Such functions are commonly discussed in the field of civil engineering, which focuses on large-scale (e.g., urban- or national-scale) infrastructure [78]. These functions contribute to the reduction of energy required for cleaning and restoration, while simultaneously enhancing amenities in urban areas. For example, Biocement is a self-repairing cement based on living processes [60].

As an advanced example of urban design, the structure of ant nests was applied to reduce the impact of flooding in an area of India with frequent floods, in an approach that can potentially be tailored for individual local contexts [79].

Biomimetic products that are compatible with urban environments have also been developed. For example, a small UAV designed by mimicking pterosaurs is expected to be usable in densely built environments [80,81]. Such products are developed based on the assumption of conditions like those in current urban environments.

4.2. Improvement of Socioecological Functions of Cities

In addition to functions like the reduction of environmental impact and food production, positive mental effects can be provided by mimicking ecosystems, as they can by mimicking organisms. Cultural ecosystem services provide psychological restoration and improve well-being, and they should be supplied by urban ecosystems. Biomimetics holds potential applications for planning and managing cities, districts, and architectural projects, to contribute to the enhancement of ecosystem services, including cultural ones [82].

As stated in Section 2, positive mental effects are expected in architectural designs deriving from biomimetics; such effects are expected in biophilic urban design, eco-city design, and green urbanism as well [62,83–85]. Such urban design concepts are being proposed, for instance, in countries undergoing rapid urbanization which need to avoid urban sprawl. Urban design by biomimetics has become a part of the trend of ecosystem-based environmental design, which is leading designers and engineers to rethink human–nature interaction and improve the socioecological functions of cities [86].

At the European level, the GREEN SURGE Project was conducted by researchers in a European region covering 11 countries, who proposed a policy to utilize socioecological linkages and biodiversity for urban environmental management, identifying and applying nature-based solutions. Based on the concept of biophilia, which, as noted, aims to reconstruct close relationships between nature and human society, the conservation of biodiversity in cities is implemented from a cultural point of view. Nature-based designs and biomimetics are practices that share and disseminate the concept of biophilia [87].

Biomimetics is expected to be a promising approach, as it supports a paradigm shift toward a sustainable society because of its effectiveness in improving well-being and its environmental efficiency at both architectural and urban scales [12] Based on this review at the urban scale in particular, it is possible to see biomimetic design as a driver to change our urban environment.

5. Future Challenges in the Application of Biomimetics in Urban and Architectural Design

The application of biomimetic approaches to urban and architectural design is driven by the development of methods leading to discoveries in biology and to innovation in engineering [88]. Cross-linking biological and engineering knowledge is globally urgent in these fields [24,89–92], as it allows innovations that are not merely or solely representations of living morphology [93]. Simultaneously, the establishment of biomimetic design methods is required [94]. In the promotion of a biomimetic approach, development of educational programs can serve as a fundamental aspect of enhancing awareness of the importance of cross-linking biology and engineering [95].

A database aimed at cross-linking these two fields has been proposed and is highly necessary [96–98]. Furthermore, methodologies that can be used in the design process to bridge the two fields have been proposed [99]. Examples of such methodologies are Bio-TRIZ [100,101], Design Spiral [2], Typological Analysis [102], and Nature Studies Analysis [103]. Bio-TRIZ is a database of technical contradictions in patented technology. It has a possible application in biomimetics for proposing problem-solving systems [101].

Innovation in information technology also contributes to the implementation of biomimetic solutions, including in urban and architectural design. A digital model for analyzing individual aspects of urban design and architecture, including the structure of buildings, external environments, and transportation systems, has been proposed from a biomimetic perspective; in addition, the necessity for an integrated model based on biomimetic concepts for analyzing urban and architectural systems has been identified [9] Digital tools are also being developed to help architects and urban designers bridge biological and architectural knowledge based on Bayesian Networks [21].

In recent years, it has become possible to design highly complex building structures because of innovations in information science which can analyze and reproduce the form and movement of an organism [104,105]. As a further step, a model of system dynamics developed for the analysis of ecosystems has also been applied to the analysis of architectural systems [106]. Ways of analyzing artifacts, including buildings and cities, have been proposed, using methodologies from biology and ecology.

Further, development of assessment tools for biomimetic products and projects is needed to evaluate their contribution to sustainable development in urban areas. In regard to assessment tools, tools including a life-cycle analysis method has been proposed to help designers and engineers find solutions, using a biomimetic approach [107], and development of relevant indicators is needed to assesss the impacts of biomimetic approaches on biodiversity and ecosystems based on existing indicators [108].

6. Conclusions

Applications of biomimetics, mimicking nature, can be observed in both contexts of historical and contemporary architecture design. At the urban design level, we can observe a trend of mimicking nature at the ecosystem level. It has been said that such applications are expected to lead to not only reduction of environmental impact but also positive effects on social aspects, such as enhancement of well-being. Based on our empirical review here, it was suggested that biomimetics in the field of architecture and urban design can contribute to the holistic sustainability of cities, particularly in the form of the application of the concept of biophilia to planning and managing built structures and urban areas. As shown in Section 2, research topics including Biophilia and Material need more research on biomimetic applications in architectural and urban design. Regarding the scale of the application, urban-scale research is limited and is a promising area of research that can facilitate the social implementation of biomimetics.

In the recent application of biomimetics to urban design, innovative information technologies facilitate understanding of the complex mechanisms of ecosystems and also the mimicry of such systems in urban planning and management. In this light, an ontology to connect different knowledge(s) and terminologies in biology, ecology, and engineering is required. Information technologies can contribute further to the social implementation of biomimetics based on a proper ontological platform.

For further innovations, an additional analysis of organisms, biodiversity and ecosystems in terms of functions and processes based on scientific knowledge from biology and ecology, and also rooted in local and traditional knowledge, can contribute to the development of biomimetic technology [109]. This local and traditional knowledge includes the wisdom of sustainable lifestyles, known before the era of dependence on fossil fuels. A method of extraction of appropriate local and indigenous knowledge that can help develop ideas and tailor technologies based on that knowledge has also been proposed [110]. Social science research on local and traditional knowledge should also continue, and its lessons should be applied in biomimetic design. The results of this research can be combined with those of advanced interdisciplinary research on biomimetics, in order to develop and implement biomimetic technologies for the sustainable management of cities and architecture.

There are works that identified practical application trends in the industry or lay people [111,112]. Still, the research foucing on social implementation of biomimetics is limited. The biomimetic methods for architectural design and urban design further need to be integrated in order to facilitate globally sustainable trajectories, and these two types of knowledge, scientific and traditional, can contribute to the integration of biomimetic methods in the design of structures and spaces at different scales.

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Appendix A. Topics and Target Scales of the Reviewed Papers

Table A1. Topics and target scales of the reviewed papers which are focusing on specific biomimetic applications.

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Architecture	Edmondson, A. C. (1986).		○		
Architecture	Aldersey-Williams, H. (2004)	○	○		
Architecture	Dollens, D. (2006)		○		
Architecture	Vincent, J. F. V. (2006)	○			
Architecture	Building Research Establishment (BRE). (2007). Naturally innovative :	○	○		
Architecture	Badarnah, L. & Knaack, U., (2008)		○		
Architecture	Turner, J. S., & Soar, R. C. (2008, May)		○	○	
Architecture	Memmott, P., Hyde, R., & O'Rourke, T. (2009)	○	○		
Architecture	Vincent, J. F. V. (2009)	○	○		
Architecture	Royall, E. (2010)		○	○	
Architecture	Eilouti, B. H. (2011)		○	○	
Architecture	French, J.R.J. and Ahmed, B.M. (2011)		○	○	
Architecture	Gamage, A., & Hyde, R. (2011)	○	○	○	
Architecture	Gruber, P. (2011)	○	○	○	
Architecture	Kellert, S. R., Heerwagen, J., & Mador, M. (2011)		○		○
Architecture	Peters, T. (2011)			○	
Architecture	Knippers, J., & Speck, T. (2012)		○		
Architecture	Menges, A. (2012)		○		

Table A1. *Cont.*

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Architecture	Fernández, M. L., Rubio, R., & González, S. M. (2013)	○	○		
Architecture	Taghizade, K., & Taraz, M. (2013)		○		
Architecture	Van Renterghem, T., Hornikx, M., Forssen, J., & Botteldooren, D. (2013)		○		
Architecture	Webb, M., Aye, L., & Green, R. (2013)	○			
Architecture	Zare, M., & Falahat, M. (2013)		○	○	
Architecture	Chen, D. A., Ross, B. E., & Klotz, L. E. (2014)		○		
Architecture	Raoa, R. (2014)		○	○	
Architecture	Browning, W.D., Ryan, C.O., & Clancy, J.O. (2014).				○
Architecture	Garcia-Holguera, M., Clark, G., Sprecher, A., & Gaskin, S. (2015)			○	
Architecture	Gil, P., Rossi, C., & Coral, W. (2015, July)				○
Architecture	Han, Y., Taylor, J. E., & Pisello, A. L. (2015)		○		
Architecture	Ramzy, N. (2015)		○		
Architecture	Sara, K., & Noureddine, Z. (2015, May)			○	
Architecture	Shimomura, M. (2015)	○	○	○	
Architecture	Madre, F., Clergeau, P., Machon, N., & Vergnes, A. (2015).		○		
Architecture	Menges, A., & Reichert, S. (2015).	○	○		
Architecture	Achal, V., Mukherjee, A., & Zhang, Q. (2016)	○	○		
Architecture	Elmeligy, D. A. (2016)	○	○	○	
Architecture	Fujii, S., et al. (2016)	○			
Architecture	Tsujino, M. (2016)	○			
Architecture	Vuja, A., Lečić, M., & Čolić-Damjanović, V. M. (2016, November)		○		
Architecture	Garcia-Holguera, M., Clark, O. G., Sprecher, A., & Gaskin, S. (2016).			○	
Architecture	López, M., Rubio, R., Martín, S., & Croxford, B. (2017)		○	○	
Architecture	Al-Obaidi, K. M., Ismail, M. A., Hussein, H., & Rahman, A. M. A. (2017).		○		
Architecture	Bechthold, M., & Weaver, J. C. (2017).	○	○		
Architecture	Chayaamor-Heil, N., & Hannachi-Belkadi, N. (2017).			○	
Architecture	Fecheyr-Lippens, D., & Bhiwapurkar, P. (2017).		○		
Architecture	Gruber, P., & Imhof, B. (2017).		○		
Architecture	Speck, O., Speck, D., Horn, R., Gantner, J., & Sedlbauer, K. P. (2017)		○		
Architecture	Yuan, Y., Yu, X., Yang, X., Xiao, Y., Xiang, B., & Wang, Y. (2017).	○	○		
Architecture	Gao, R., Liu, K., Li, A., Fang, Z., Yang, Z., & Cong, B. (2018).			○	
Architecture	Webb, M., Aye, L., & Green, R. (2018).		○		
Architecture	Xing, Y., Jones, P., Bosch, M., Donnison, I., Spear, M., & Ormondroyd, G. (2018)	○	○		
Architecture	Cuce, E., Nachan, Z., Cuce, P. M., Sher, F., & Neighbour, G. B. (2019).		○		
Architecture	Khelil, S., & Zemmouri, N. (2019).			○	
Architecture	Sheikh, W. T., & Asghar, Q. (2019).		○		
Architecture	Terrier, P., Glaus, M., & Raufflet, E. (2019).	○			
Urban	Todd, N. J., & Todd, J. (1994)			○	

Table A1. *Cont.*

Architecture/Urban	Author (Year of Publication)	1. Material	2. Structure	3. System	4. Biophillia
Urban	McLennan, J. F. (2004)			○	
Urban	Pedersen Zari, M. and Storey J. B. (2007)			○	
Urban	Pedersen Zari, M. (2010)			○	
Urban	Tero, A. et al. (2010)			○	
Urban	Kenny, J., Desha, C., Kumar, A., & Hargroves, C. (2012)		○	○	
Urban	Gruber, P., & Benti, D. (2013)		○	○	
Urban	Goel, S., Bush, S. F., & Ravindranathan, K. (2014, November)			○	
Urban	Hidalgo, A.K. (2014)				○
Urban	Buck, N. T. (2015).		○	○	
Urban	Pacheco-Torgal, F. (2015)	○	○	○	○
Urban	Pedersen Zari, M. (2015)			○	
Urban	Fink, H. S. (2016)				○
Urban	Pedersen Zari, M. (2016)			○	
Urban	Pedersen Zari, M. (2017).			○	
Urban	Pedersen Zari, M. (2018).			○	
Urban	Ferwati, M. S., Al Suwaidi, M., Shafaghat, A., & Keyvanfar, A. (2019).		○	○	○

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