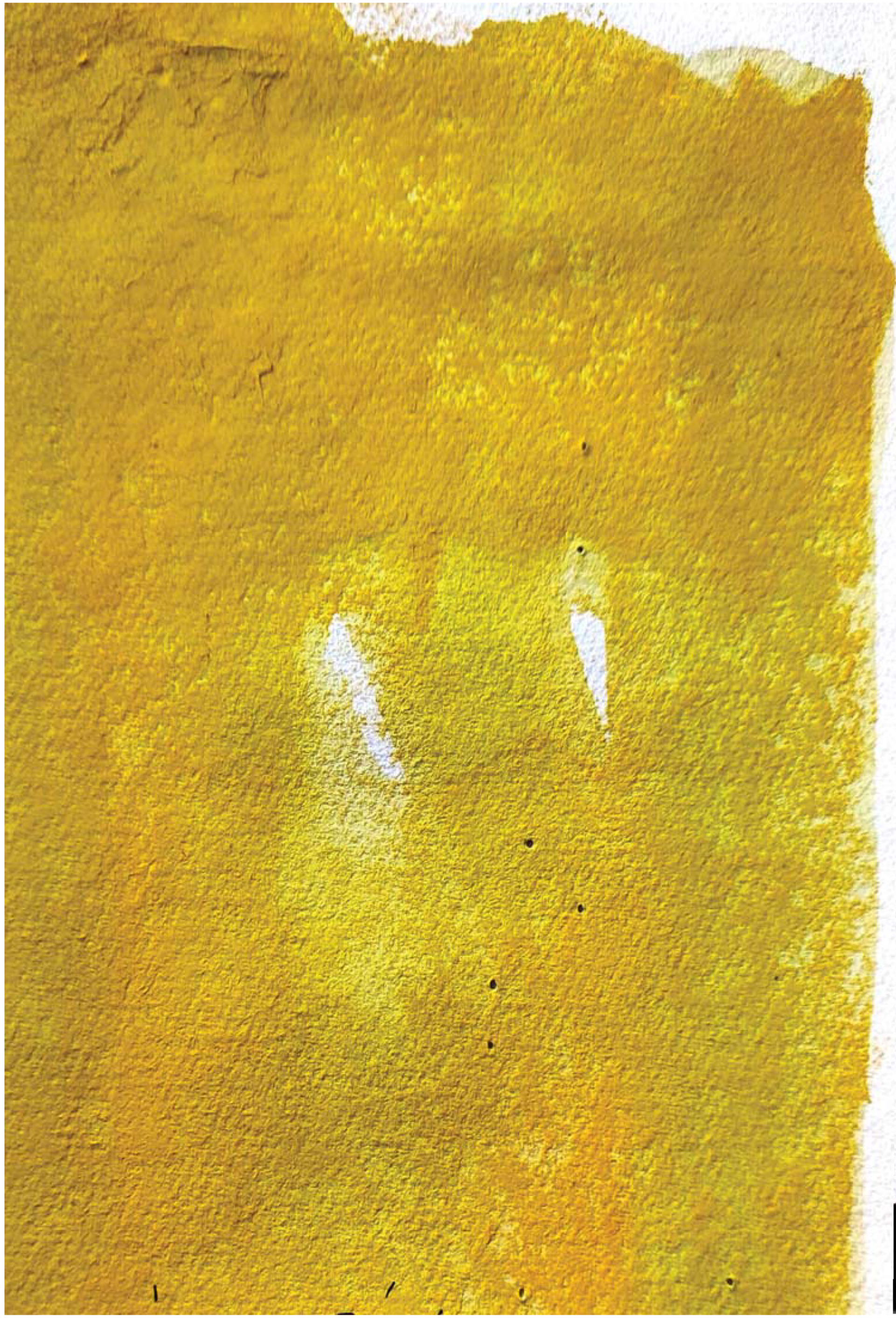

Angeliki Peponi

Ph.D. Thesis

2022

Smart Cities, Smart Growth.

Paving the Way to Urban Regeneration.

Smart Cities, Smart Growth. Paving the Way to Urban Regeneration.

Ph.D. Thesis

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Smart Cities, Smart Growth. Paving the Way to Urban Regeneration.

Ing. Angeliki Peponi

Thesis

This thesis is submitted in fulfillment of the requirements for the Ph.D. degree in Applied Landscape Ecology at the **Czech University of Life Sciences Prague, Faculty of Environmental Sciences**, and in Geography with a specialty in Regional and Urban Planning at the **Universidade de Lisboa, Institute of Geography and Spatial Planning,** under cotutelle agreement.

Smart Cities, Smart Growth. Paving the Way to Urban Regeneration.
Angeliki Peponi
Czech University of Life Sciences Prague,
Universidade de Lisboa (2022)

To those who were forced to put
their lives and dreams on hold
and managed to get them back,
and to those who are still trying to

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Abstract

As the global urban population continues to grow, expanded urbanization is inevitable. The massive, rapid, uncontrolled, and unplanned urbanization has negative socio-economic and environmental consequences that highly affect the life quality and public health. On the other hand, urbanization can benefit urban sustainability transitions when adequately planned and managed under a holistic, systematic approach. Urban systems represent nonlinear, dynamical, and interconnected urban processes and functions that require better design and management of their complexity to be able to tackle the current urban challenges such as intensive demographic growth, economic and social stagnation to resources salvation, and climate changes threats. Therefore, to benefit from urbanization and reduce the environmental impacts while maximizing the socio-economic benefits, it is essential to understand, measure, assess, and predict the complexity of urban dynamics, including an ecological perspective in the process. For doing so, we use the urban metabolism framework to study and assess to couple natural and human systems in an integrated interdisciplinary approach engaging social and ecological science. This thesis dissertation follows a two-fold methodology. Initially, we conducted a systematic literature review to study the evolution of the emerging concepts on sustainable urban development, shedding light on the state of the art of smart and regenerative urban design under the urban metabolism framework. Having identified the literature gaps, we propose a novel conceptual framework; smart and regenerative urban places (SRUP), able to tackle the urban complexity challenges. For the second part of the methodology of this dissertation thesis, we propose an original multidimensional systems-based methodology, coupling Life Cycle Thinking and Machine Learning under the perspective of urban ecosystem services. We apply the proposed methodology measuring the smart and regenerative urban metabolism of the urban core of the functional urban area of Lisbon, predict the metabolic changes for the year 2025 in terms of purchasing power per capita, and identify the key drivers for these metabolic changes. Using GIS, we mapped the predicted metabolic changes within the study area. The results showed that the urban processes related to employment and unemployment rates (17%), energy systems (10%), sewage and waste management/treatment/recycling, demography and migration, hard/soft cultural assets, and air pollution (7%), education and training, welfare, cultural participation, and habitat-ecosystems (5%), urban safety, water systems, economy, housing quality, urban void, urban fabric, and health services and infrastructure (2%), consists the prominent drivers for the urban metabolic changes. Conceptualizing SRUP, we contribute to urban and environmental planning and design, providing a framework to improve the quality of life in the built environment, highlighting the need to use ICT, Big Data, and ubiquitous technologies along with ecological principles. Smart and regenerative urban places are planned and designed to be safe and secure, attractive, liveable, healthier, and more creative. Appling SRUP using the proposed novel methodological protocol, we contribute to urban design, planning, and development, addressing gaps and research needs of previously applied methodologies for assessing urban metabolism, providing a tool for decision support systems and policymaking, ensuring sustainability enhancing system resilience.

Resumo

À medida que a população urbana continua a crescer à escala global, uma expansão da mancha urbana torna-se inevitável. A urbanização massiva, rápida, descontrolada e não planeada tem consequências socioeconómicas e ambientais negativas que afectam fortemente a qualidade de vida e a saúde pública das pessoas. Todavia a urbanização, quando adequadamente planeada e gerida sob uma abordagem holística e sistemática, pode beneficiar as transições de sustentabilidade urbana. Os sistemas urbanos representam processos e funções urbanas não lineares, dinâmicas e interligadas que requerem uma melhor concepção e gestão da sua complexidade para poder enfrentar os grandes desafios que as áreas urbanas têm de enfrentar, tais como o crescimento demográfico, a estagnação económica e social, a necessidade de salvar dos recursos naturais, e as alterações climáticas. Portanto, para beneficiar da urbanização e reduzir os impactos ambientais, maximizando simultaneamente os benefícios socioeconómicos, é essencial compreender, medir, avaliar e prever a complexidade da dinâmica urbana, incluindo uma perspectiva ecológica no processo. Portanto, para que se possa beneficiar do inevitável crescimento urbano e simultaneamente reduzir os impactos ambientais e maximizando simultaneamente os benefícios socioeconómicos, é essencial compreender, medir, avaliar e prever a complexidade da dinâmica urbana, adoptando uma perspectiva ecológica do processo. Para tal, adaptámos o conceito de metabolismo urbano de forma a mergir os sistemas naturais e humanos numa abordagem interdisciplinar integrada, envolvendo as ciência sociais e ecológicas. Esta dissertação adoptou uma metodologia de duas partes. Inicialmente, realizámos uma revisão sistemática da literatura para estudar a evolução dos conceitos emergentes referentes ao tópico desenvolvimento urbano sustentável, e para enquadrar o estado da arte sobre desenho urbano inteligente e regenerativo no âmbito do metabolismo urbano. A revisão da literatura permitiu ainda identificar as lacunas na literatura da especialidade, e consequentemente permitiu que proposéssemos um novo quadro conceptual; *Smart and Regenerative Urban Places* (SRUP), que julgamos ser uma solução para as cidades e áreas urbanas serem capazes de enfrentar os desafios que enfretam. Para a segunda parte da metodologia desta dissertação, estabelecessemos uma abordagem empírica e analitica baseada em sistemas multidimensionais, *associando Life Cycle Thinking and Machine learning* numa

perspectiva de serviços dos ecossistemas urbanos. A partir daesta metodologia foi possivel medir *Smart and Regenerative Urban Places* do núcleo urbano da área urbana funcional de Lisboa, prever as mudanças de metabolismo para o ano 2025 em termos de poder de compra per capita, e identificamos os principais motores para estas mudanças do metabolismo urbano. Com recurso aos SIG, mapeámos as mudanças de metabolismo previstas na área de estudo. Os resultados obtidos da implementação do modelo mostraram que os processos urbanos relacionados com as taxas de emprego e desemprego (17%), sistemas energéticos (10%), gestão/tratamento/reciclagem de esgotos e resíduos, demografia e migração, oferta cultural, e poluição atmosférica (7%), educação e formação, bem-estar, participação cultural, e ecossistemas de habitat (5%), segurança urbana, sistemas de água, economia, qualidade de habitação, vazio urbano, tecido urbano, e serviços e infra-estruturas de saúde (2%), são os principais motores das mudanças metabólicas urbanas. A adopção do conceito de SRUP, contribuí assim para um planeamento combinado de urbano e o ambiental, fornecendo um quadro conceptual para melhorar a qualidade de vida das pessoas que vivem e trabalha em espaços urbanos construídos, mediante a integração das TIC, Big Data, e tecnologias ubíquas juntamente com princípios ecológicos. *Smart and regenerative urban places* são planeados e concebidos para serem seguros, atraentes, habitáveis, saudáveis e mais criativos. Ao adoptar e implementar o conceito de *SRUP* como um novo protocolo metodológico, foi possivel identificar lacunas na investigação operativa feita até então para avaliar o metabolismo urbano de uma determinada área, e consequentemente contribuír para uma nova forma de concepção, planeamento e desenvolvimento urbano, assim como providencar uma ferramenta para apoio à tomada de decisão (e aos decisores) e formulação de políticas, assegurando a sustentabilidade e reforçando a resiliência dos sistemas.

Abstrakt

S rostoucím počtem obyvatel měst na světě je rozšiřování urbanizace nevyhnutelné. Masivní, rychlá, nekontrolovaná a neplánovaná urbanizace má negativní socioekonomické a environmentální důsledky, které silně ovlivňují kvalitu života a veřejné zdraví. Na druhou stranu může urbanizace prospět přechodům k udržitelnosti měst, pokud je vhodně plánována a řízena v rámci holistického a systematického přístupu. Městské systémy představují nelineární, dynamické a vzájemně propojené městské procesy a funkce, které vyžadují lepší plánování a řízení jejich komplexnosti, aby bylo možné řešit současné městské výzvy, jako je intenzivní demografický růst, ekonomická a sociální stagnace až vyčerpání zdrojů a hrozby klimatických změn. Proto, aby bylo možné těžit z urbanizace a snížit dopady na životní prostředí a zároveň maximalizovat socioekonomické přínosy, je nezbytné pochopit, měřit, hodnotit a předvídat složitost dynamiky měst a zahrnout do tohoto procesu ekologickou perspektivu. Za tímto účelem využíváme rámec městského metabolismu ke studiu a hodnocení, abychom propojili přírodní a lidské systémy v integrovaném interdisciplinárním přístupu, který zahrnuje sociální a ekologické vědy. Tato disertační práce se řídí dvojí metodikou. Nejprve jsme provedli systematický přehled literatury, abychom prostudovali vývoj nově vznikajících koncepcí udržitelného rozvoje měst, čímž jsme osvětlili současný stav inteligentního a regenerativního navrhování měst v rámci městského metabolismu. Poté, co jsme identifikovali mezery v literatuře, navrhujeme nový koncepční rámec; inteligentní a regenerativní městská místa (SRUP), která jsou schopna řešit výzvy spojené s komplexností měst. Pro druhou část metodiky této disertační práce navrhujeme originální vícerozměrnou metodiku založenou na systémech, spojující myšlení životního cyklu a strojové učení v perspektivě městských ekosystémových služeb. Navrhovanou metodiku aplikujeme při měření inteligentního a regenerativního městského metabolismu městského jádra funkční městské oblasti Lisabonu, předpovídáme metabolické změny pro rok 2025 z hlediska kupní síly na obyvatele a identifikujeme klíčové faktory těchto metabolických změn. Pomocí GIS jsme zmapovali předpokládané metabolické změny ve studované oblasti. Výsledky ukázaly, že urbanistické procesy související se zaměstnaností a mírou nezaměstnanosti (17 %), energetickými systémy (10 %), nakládáním s

odpadními vodami a odpady/zpracováním/recyklací, demografií a migrací, tvrdými/měkkými kulturními statky a znečištěním ovzduší (7 %), vzděláváním a odbornou přípravou, sociálním zabezpečením, kulturní účastí a biotopovými ekosystémy (5 %), bezpečností ve městech, vodními systémy, ekonomikou, kvalitou bydlení, městskou prázdnotou, městskou strukturou a zdravotnickými službami a infrastrukturou (2 %), tvoří významné faktory pro metabolické změny ve městech. Konceptualizací SRUP přispíváme k urbanistickému a environmentálnímu plánování a navrhování, poskytujeme rámec pro zlepšení kvality života v zastavěném prostředí a zdůrazňujeme potřebu využití ICT, Big Data a všudypřítomných technologií spolu s ekologickými principy. Chytrá a regenerativní městská místa jsou plánována a navrhována tak, aby byla bezpečná a chráněná, atraktivní, vhodná pro život, zdravější a kreativnější. Aplikací SRUP s využitím navrženého nového metodického protokolu přispíváme k navrhování, plánování a rozvoji měst, řešíme nedostatky a výzkumné potřeby dosud používaných metodik pro hodnocení městského metabolismu, poskytujeme nástroj pro systémy podpory rozhodování a tvorby politik, zajišťujeme udržitelnost zvyšující odolnost systému.

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Lexicon

Artificial Neural Networks "Artificial neural networks (ANN) or simply a neural network, is a set of independent neurons linked together in the same way as the synapses, neurons, and dendrites of our brain. Neurons are excited through these links, similar to electric signals, by the input values and by other neurons, propagating the excitation toward an output. In order for a neural network to learn and therefore execute some tasks, it must be trained. During the training, the network modifies the weights of the links among the neurons in a way that each input produces the expected output." **Peponi et al., 2019**[1]

Biocapacity Or bio-productivity refers to the capacity of a given bio-productive area to generate an ongoing supply of renewable resources and absorb its spillover wastes.

Biodiversity It refers to the variety of life on Earth, at all levels; genetic diversity, species (intraspecies, interspecies) diversity, and ecosystem diversity.

Circular economy "One that is restorative and regenerative by design and aims to keep products, components, and materials at their highest

[1] Peponi, A., Morgado, P., & Trindade, J (2019). Combining Artificial Neural Networks and GIS Fundamentals for Coastal Erosion Prediction Modeling. *Sustainability*, 11, 975. https://doi.org/10.3390/su11040975

	utility and value at all times, distinguishing between technical and biological cycles" It is driven by three main principles; eliminate waste and pollution, circulate products and materials, and regenerate nature. **Ellen Macarthur Foundation**
Gros domestic product	The total monetary or market value of goods and services produced in a country in a specific time period.
Ecosystem services	"Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth." **Millennium Ecosystem Assessment**
Functional Urban Areas	According to Urban Atlas Copernicus, FUAs are urban areas and their surroundings with more than 50,000 inhabitants for the year of reference 2018.
Innovation	It refers to the successful implementation of creative thinking. It can be an invention or the practice of developing and introducing new things.
Life Cycle Thinking	It is the way of thinking that includes the environmental, economic, and social consequences of a product/ process or system throughout its entire life cycle;

	extraction, conversion, transformation, distribution, use, and final destination.
Peri-urbanization	It refers to the dynamic transition of rural areas located in the perimeter of growing or established urban areas to urban status. The transition includes changes in land use and livelihoods.
Purchasing power per capita	In this thesis, purchasing power per capita refers to a composite indicator created by Statistics Portugal, that "aims to indicate purchasing power on a daily basis in per capita terms in the different municipalities or regions, using the figure of the country as a reference". **STATISTICS PORTUGAL, 2017**[2]
Reclaimed or salvaged	Reclaimed materials are the ones that have been previously used in the construction of buildings or projects and after their demolition, they are re-used in other projects.
Refurbished	Refurbished materials are products that had their specifications updated, their components replaced, or repaired and their cosmetic appearance improved.
Regenerative design	It seeks to not merely diminish the harm of new development, but rather to ensure that the built environment can work as a positive force that restores, repairs, renew, or revitalizes natural and human systems.

[2] STATISTICS PORTUGAL, (2017). Estudo sobre o Poder de Compra Concelho 2017. Retrieved from https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=358634546&PUBLICACOESmodo=2.

Repair	Repair or maintenance of defective products so can serve their original function.
Sensitivity analysis	Sensitivity analysis is a procedure where model input can be modified and parametrized in a way that we can evaluate its effects over the dependent variable (output) under certain conditions. Sensitivity analysis also evaluates the robustness of the model as a whole and assists in decision making.
Smart city	Smart cities aim to make better use of public resources, increasing the quality of services offered to the citizens, while reducing the operational costs of the public administrations **(Zanella et al., 2014[3])**. Smart cities promote sustainability
Urban sustainable development	"Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. " **UN World Commission on Environment and Development**
Urban agglomeration	"Urban agglomerations can be defined as contiguously built-up area, shaped by one core city or by several adjacent cities, sharing industry-, infrastructure- and housing-land use with high-density levels

[3] Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M (2014). Internet of Things for Smart Cities. *IEEE Internet of Things Journal*, 1, 22-32. http://dx.doi.org/10.1109/JIOT.2014.2306328

as well as embedded open spaces." **Loibl et al., 2018** [4]

Urban complexity

Urban complexity relies on the interlinked, non-linear network of feedback relations among the urban system elements. Urban systems are system far-from-equilibrium. They are subject to positive feedback that forces the overall urban system to an entirely new state when a disturbance occurs (spatial and temporal changes).

Urban core

In this thesis, we used the urban core area of Lisbon FUA as defined by Urban atlas, Copernicus, to delimit our study area. Urban core areas are highly densely populated, where most of the services, manufacture, and infrastructure co-exist.

Urban development

It refers to the development or improvement of an urban area and its infrastructures by building.

Urban growth

It is the rate that the population of an urban area increases as a result of urbanization. In the case of rapid, massive, uncontrolled, and unplanned urbanization, urban growth can take the form of sprawl.

Urbanism

It refers to the study of how the population of urban areas reacts with the built environment.

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[4] Loibl, W., Etminan, G., Gebetsroither-Geringer, E., Neumann, H., & Sanchez-Guzman, S. (2018). Characteristics of Urban Agglomerations in Different Continents: History, Patterns, Dynamics, Drivers and Trends. In (Ed.), Urban Agglomeration. IntechOpen. https://doi.org/10.5772/intechopen.73524

Urbanization	It refers to the swift of the population from rural to urban as well as the expansion of urban land, infrastructure, and lifestyle. In other words, it is a transformative phenomenon simultaneously demographic, societal, and land use land cover (LULC) change related
Urban metabolism	It refers to "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" **Kennedy et al., 2007**[5]
Urban place	An urban place is a "unique, multi-layered network of living systems within a geographic region that results from the complex interactions, through time, of the natural ecology and culture". **Mang & Reed, 2012**[6]**.** We used the urban place as the scale for our study to highlight the need to plan and design safe, secure cities with unique identities.
Urban resilience	"Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform

[5] Kennedy, C., Cuddihy, J., & Engel-yan, J (2007). The Changing Metabolism of Cities. *Research and Analysis*, 11(2), 43-59. http://dx.doi.org/10.1007/s00125-014-3420-8

[6] Mang, P., & Reed, B (2012). Designing from place: A regenerative framework and methodology. *Building Research & Information*, *40*, 23–38. http://dx.doi.org/10.1080/09613218.2012.621341.

	systems that limit current or future adaptive capacity." **Meerow, et al. 2016**[7]
Urban systems	Adopting a systematic approach, the internal structure of an urban area is organized by different systems offering different functions (shopping, entertainment, educational, cultural activities, government services, manufacturing, and so on). The basic elements of urban systems are people, land, buildings, physical and natural infrastructure, facilities, technical devices, and plants. Urban systems are interdependent through economic fluctuations, diffusion and exchange of information, and flow of goods, capital, and people.

[7] Meerow, S., Newell, J.P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, 147, 38-49. http://dx.doi.org/10.1016/j.landurbplan.2015.11.011

Chapter 1

1. Introduction

1.1 Urbanization in the era of Astycene

Growth is inevitable and desirable,
but the destruction of community character is not.
The question is not whether your part of the world is going to change.
The question is, how?"
Edward T. McMahon

In the current era of Astycene[8], urbanization differs from traditional patterns of urban growth in its scale, rate, location, form, and function (Seto et al., 2010). The scale of modern urbanization is massive. The physical size of cities and the urban population size are much larger than in the past, with higher economic, and political too, importance but also with greater environmental impacts. The rate of contemporary urbanization is much faster than in any other period in history, and the location where modern urbanization takes place also differs from the past. Globally speaking the urbanization of the 1950s-1970s occurred in Europe and South America, and for the coming decades, it will possibly take place in Asia and Africa, expanding in the forest, natural areas, and agricultural lands. Modern urbanization is also different in terms of form. Historically urban areas have been compact, and now we are witnessing increasingly suburbanization and peri-urbanization. Last, we can detect changes in urban life and urban function. Urban areas constitute social, economic, cultural, and political centers found in constant interaction with rural and peri-urban areas via the exchange of products and services. These social, economic, and cultural

[8] Astycene comes form the greek words ἄστυ (city) and καινός (new, something that just appeared/presented)

dynamics within the urban area and beyond affect the scale rate and spatial patterns of urbanization and make it different than the past (Seto et al., 2010).

The urban population at a European Union (EU) level is predicted to increase from +2.3% to +35.4% between 2019 and 2050. Three out of five urban regions in the 15 EU countries are likely to grow, while four out of five rural regions to shrink by 2050 (Eurostat, 2021). The increased urbanization results in urban growth, referring not just to the rise in the urban population but also to the expansion of urban land, infrastructure, and urban lifestyle in general in support of this population growth (Hosszú 2009 ex. Enyedi 1988). Hence, this transformative phenomenon is simultaneously demographic, societal, and land use land cover (LULC) change related. Nowadays, the complex process of growing urbanization is interconnected in terms of causal relationships with the fourth industrial revolution (industry 4.0), digitalization, globalization, agglomeration forces, governance, and institutional structures. Industry 4.0 and its complement Industry 5.0, through the development of digitalization, offer a more comprehensive, interlinked, and holistic approach to manufacturing using the Internet of things, cloud computing, cyber-physical systems, big data, machine-to-machine (M2M) communications, stressing collaboration networks and access across departments, partners, vendors, product, and people improving processes, products and business models and driving growth. Industry 4.0 requires new skillsets of factory workers. Globalization includes the increased flows of people, products, information, lifestyles, policies, and capital through local and global dynamics. In line with Spencer, (2014) in the current stage of globalization, to some extent, all cities share the characteristics of a global city, and even cities are unique; they share more similarities than differences. This pattern of increasingly globalized urbanization gives a rise to new geography integrating cities into the global city network. Another factor interrelated with increased urbanization and urban growth is the economic, political, and social agglomeration forces responsible for the spatial concentration of settlements. Last, the governance and the institutional structures of a city are responsible for delivering a board-spectrum of services and infrastructure (waste collection and disposal, transportation, public open spaces and recreation, citizens protection cultural facilities, affordable housing, among others) which their quantity and quality shape the physical and social aspect of urbanization (Slack & Côté, 2014).

This trend of modern urbanization is a critical phenomenon. On the one hand, it offers a variety of opportunities indicating economic, social, political growth. Yet, on the other hand, urbanization can be rapid, unplanned, uncoordinated, and uncontrolled taking the form of sprawl (Bhatta, 2012 ex. Roca et al., 2004; Ahmad & Goparaju, 2016). In fact, evidence from European cities shows that urbanization grows horizontally; the density of urban settlements is decreasing, and their discontinuity is increasing due to shrinking populations (Guastella et al., 2019).

Modern horizontal urbanization is affecting the social structure, political and cultural life, and urban economy. It results in the urban-rural divide. On one side, infrastructure, commercial activity, jobs, and public services are more available in urban areas than in rural. On the other side, rural areas are facing social, economic, and political marginalization and are viewed as a source of migrants, undeveloped and economic poor (United Nations, 2021). Poorly planned urbanization leads to economic, spatial, and social inequalities also within the cities. It results in inadequate provisions of public services, congestion, higher crime rates, social exclusion, the emergence of urban slums, poor sanitation, unemployment, transportation, and energy supply (United Nations, 2021; Wang et al. 2021). Rapid urbanization contributes to a dichotomy of urban/rural populations where rural migrant populations face economic, behavioral, psychological, and social identity integration challenges (Chen & Zhang, 2016). Rapid, massive, and uncontrolled urbanization has been found in literature associated with gender-related inequalities (Bruin & Liu, 2020). Even though urban women can have more life opportunities than rural women (higher average age of marriage, economic independence, better education, social and political participation), gender inequalities exist, especially in those who live under urban poverty. Specifically, gender inequalities in service, political and economic accessibility are found in most urban areas, caused by the existing patriarchal social structures and the lack of gender-sensitive urban planning and policies that address equal and adequate quality of life and well-being (Urban 20, 2020). Women face limited mobility due to safety issues, are disproportionally burdened with domestic responsibilities, are more likely than men to be employed in more insecure and informal jobs receiving lower salaries, unequal access to resources, and limited public participation (Tacoli, 2013; Bruin & Liu, 2020; Urban 20, 2020). Similarly, people with non-binary gender identities or having different sexual orientations are likely to not benefit equally from the opportunities offered by urbanization (Urban 20, 2020).

Modern urbanization occurs in line with the structural transformation process of the economy, but its impact on economic growth is debatable (Nayyar, 2019; Haryanto et al., 2021). The structural transformation process reflects the changing shares of the primary, secondary, and tertiary sectors in the country's income and total employment for an economy (Nayyar, 2019). It is the shift from low productivity and labor to high value and intensive economic activities and productivity associated with urbanization. The causal link between economic growth and urbanization has recently been disregarded, supporting that urbanization can occur in the absence of economic growth (urbanization of poverty) (Henderson 2003; Martine, 2012). However, empirical studies have proven that GDP per capita as a measure of the size and growth of an economy is strongly correlated with urbanization rates (Haryanto et al., 2021; Wang et al., 2021). The correlation between economic growth and modern urbanization has led the production, extraction, and consumption of resources to unsustainable rates (Lucertini & Musco, 2020; Ahmed et al., 2020). Massive and rapid urbanization leads to increased energy consumption and a decrease in energy use efficiency (Sheng et al., 2017). Also, it results in an increasing demand for housing, utility and mobility infrastructure, short-lived material flows (clothes, electronics, among others), and long-term stocks (building infrastructure and capital equipment) (Feiferytė-Skirienė & Stasiškienė, 2021). These changes in resources extraction and consumption are contributing positively to increasing pollutant emission and waste excretion causing global ecological problems.

In addition to the socio-economic and cultural effects, modern urbanization in form of sprawl is related to environmental deterioration and natural habitat degradation (Alberti, 2005; Torres et al., 2016). Natural habitats; forests, wetlands, deserts, and grasslands suffer from habitat loss and fragmentation. Habitat loss refers to the decrease of the area of the natural habitat, while habitat fragmentation is the division of the natural habitat into smaller and more isolated remnants. Both habitat fragmentation and loss normally occur simultaneously and affect the ecosystem's biodiversity and ecological processes (Liu et al., 2016). It affects the quality of water bodies by the influxes of anthropogenic substances and the increased amount of impervious surfaces that disrupt the hydrological systems (Komínková, 2012). Thus, as the infiltration to groundwater is reduced, stormwater runoff volume is increased. The urban drainage system collects stormwater runoff, discharging it directly to the recipients, increasing the possibility of flooding in wet weather and lowering outflows in dry weather, causing hydraulic stress to the aquatic biota of the recipients. This stormwater runoff has a high erosivity factor that can cause vegetation and soil loss, damaging habitats in streambanks and downstream water bodies or courses. As the stormwater flows over impervious urban surfaces, it carries with it a mixture of pollutants including oil, toxic chemicals, sediments, pesticides, nutrients, heavy metals, road salts, bacteria, and viruses, bypassing artificial and natural wastewater treatment systems impacting the water quality and harming the aquatic biota. Moreover, water pollution in urban areas can be caused by point sources such as discharges from municipal or industrial wastes, and wastewater treatment plants, and leakages of sewerage systems.

The sprawling urbanization is also related to soil degradation (Salvati et al., 2012). Soil is a habitat for numerous species, including microorganisms, plants, animals, and their abiotic environment. These living organisms and their interactions are essential for basic soil functions such as organic matter decomposition, nutrient cycling, soil structure formation, water purification, soil contaminant reduction, climate regulation, food, fiber, and fuel supply (Pulleman et al., 2012). The alterations in land use and land cover (LULC) caused by urban expansion affect soil's physical and chemical properties and, therefore, its ecosystem functions. The main soil problems related to these alterations are soil erosion, organic matter decline, soil compaction, contamination, soil sealing, salinization, and climate change (Pavao-Zuckerman, 2012; Karlen & Rice, 2015; Bajocco et al., 2018).

Sprawling urbanization is associated with local and regional air pollution generated mainly by fossil fuel combustion, power plants, industrial facilities, and chemical solvents, and noise pollution caused mainly by automobile travel and construction sites. Urban-related air pollutants include mainly greenhouse gases, toxic gases, heavy metals, particulate matter, volatile organic compounds (VOCs), nitrogen oxides, sulfur dioxide, and carbon monoxide. Some secondary air pollutants are released into the atmosphere from chemical reactions between these emitted pollutants and sunlight. Tropospheric ozone, for instance, is created when VOCs are oxidized in the presence of nitrogen oxides and sunlight (Baklanov et al., 2016). Urban Heat Island (UHI) formation is the most well-known meteorological effect of urbanization that influences regional climate and eventually regional air quality. UHI occurs when the air temperature of urban areas is increased due to the lack of vegetation and the increase of impervious surfaces combined with the urban emitted air pollutants (Stone Jr., 2008). Exposure to air pollution and environmental noise pollution has shown serious impacts on both physical and mental health causing heart disease, hearing loss, respiratory disease, asthma, anxiety, and depression. Air and noise pollution can also affect behaviors due to sleep disturbance, annoyance, aggression, and the cognitive impacting on productivity levels and causing learning disturbance (Science for Environment Policy, 2016). Besides the local and regional effects of urban forms in air quality and climate changes, urbanization is related to global climate change issues mainly due to direct emissions of greenhouse gaseous emissions (GHGs) (mainly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases,) and changes to earth's atmospheric chemistry and surface albedo (Seto & Shepherd, 2009; Zhao & Zhang, 2018).

1.2 Urbanization an opportunity for sustainable development

"Dull, inert cities, it is true, do contain the seeds
of their own destruction and little else.
But lively, diverse, intense cities contain the seeds
of their own regeneration,
with energy enough to carry over for problems
and needs outside themselves."
Jane Jacobs

As briefly mentioned in the previous subchapter, urbanization generates social-political-cultural-economic, technological, and ecological changes. These changes can provide opportunities for sustainability (Gu et al., 2019). To do so, it is essential to examine if the urbanization processes are in line with sustainable urbanization principles (Shen et al., 2017).

The modern concept of sustainability in urban development originated mainly from Brundtland's conceptualization (WCED, 1987) that critical global environmental problems were caused mainly by the combination of the extremely disproportionate consumption patterns and production in the global North with the poverty in the global South. Thereafter it is broadly accepted that sustainability is related to social equity, economic development, and environmental protection (Lombardi et al., 2011).

These three pillars or dimensions of sustainability (economy, society, environment) are found in the literature either as three interlocking rings with sustainable development placed in their intersection or as three nested rings with the economy as a societal construct delimited by society and the natural environment as the outer ring containing society and therefore economy highlighting the fact that society depends on natural resources for survival and growth (subchapter 3.2.2, Figure 2). The sustainability model adopted in this thesis is the dual nested rings similar to three nested rings removing the debatable distinction between society and economy all contained by the environment (Lombardi et al., 2011). The argument to remove the unnecessary separation between economy and society is based on the non-bidirectional nature of human systems' dependence on the natural environment; in other words, nature would survive without humanity but not the other way around (Lombardi et al., 2017 ex. Giddings et al., 2002). Therefore society, including its economic activities/ systems, can be categorized as such, and no further distinction is required (Lombardi et al., 2017).

Global development agreements and frameworks such as the 2030 Agenda for Sustainable Development, and the Paris Agreement present a series of objectives and targets to address the negative impacts of modern urbanization, fighting poverty, inequality, and injustice, and tackling the climate crisis. Studying these and other agreements, we understand that cities and therefore urbanization, if well-planned and well-managed provide the solutions/ opportunities to achieve the three-dimensional sustainability model. The New Urban Agenda (UN-HABITAT III, 2017) shares this vision for a better and more sustainable future benefiting from the opportunities offered by urbanization. The transformative commitments of the New Urban Agenda for sustainable urban development focus on social inclusion and ending poverty, on sustainable and inclusive urban prosperity and opportunities for all, and on environmentally sustainable and resilient urban development. To effectively implement transformative sustainable urban development, it is essential to build the urban governance structure, establishing a supportive framework, to promote integrated planning and management of urban spatial development, and identify the means of the implementation.

The social-economic-oriented sustainable urban development reduces inequalities, eradicates poverty, and develops inclusive urban economies. For doing so, it is essential to implement equitable and affordable access for all to social, technological, and cultural infrastructure and services, including affordable housing, education, health care, sustainable transport, and utility services, culture, and innovation. Effective participation, collaboration, and engagement of all stakeholders in decision-making, planning, and follow-up processes are crucial to identifying and addressing existing and emerging challenges (UN-HABITAT III, 2017). Inclusive and quality education is fundamental to move upwards in the socioeconomic ladder escaping poverty and at the same time reducing inequalities, achieving gender equality, nurturing tolerance, and more peaceful societies (UN DESA, 2017) promoting empowerment. One of the main concerns in sustainable development is ensuring public health (physical and mental) and promoting well-being in order to build prosperous societies (UN DESA, 2017). To enable health-oriented sustainable urban development, it is vital to underly the leading causes of public health deterioration where most of the time lie beyond the direct jurisdiction of the health domain, for instance, causes related to sanitation, energy, housing, employment, etc. Thereafter, it is needed to develop smart tools to link health systems and the systems of other sectors to ensure and sustain public health. The transformation to sustainable transportation is another key element to foster social-economic and environmental sustainability. Resource-efficient and better-coordinated transport systems using opportunities from digitalization and innovative technologies, and clean energy are far from just the mobility of people and goods across places and services. Sustainable transportation can support job creation, poverty, and inequalities reduction, and fight the climate crisis. According to the definition provided by the UN, 2016 sustainable transport "*is the provision of services and infrastructure for the mobility of people and goods advancing economic and social development to benefit today's and future generations in a manner that is safe, affordable, accessible, efficient, and resilient, while minimizing carbon and other emissions and environmental impacts*". Sustainable transportation enhances the connectivity between urban, peri-urban, and rural areas, including waterways, and transport and mobility planning, encourages shared mobility and non-motorized options such as walking and cycling. Sustainable transportation systems reduce the financial, environmental, and public health costs of inefficient mobility, congestion, air pollution, urban heat island effects, and noise (UN-HABITAT III, 2017). In a similar way, sustainable utility systems support social-economic sustainable urban development through job creation and offer equitable and affordable access to basic life support services such as safe drinking water, risk protection, sanitation, efficient and renewable energy supply, ICT, urban drainage, solid waste disposal, and wastewater, management, and treatment supported by advanced technologies. The transformative sustainable economies prioritize poverty and unemployment reduction, the environmental responsibility of economic systems/processes, and moral obligation and value-led profit-making (van Niekerk, 2020). Sustainable economic development supports the transition to higher productivity, competitiveness, and innovation by promoting diversification, technological upgrading, providing better quality and productive jobs positions in sustainable tourism, cultural sector, recognizing the working in the informal economy, and moving to formal and more inclusive economy.

UCLG, 2010 recognized culture as the fourth dimension of sustainable development, arguing that the current society's complexity cannot be reflected only by the three standard dimensions (social, economic, environmental) of sustainability. UCLG, 2010 supports that culture is the force that shapes people's understanding and actions in development initiatives. Cultural heritage nurtures a sense of place and belonging, empowering the community and fostering a mutual understanding that diversity and minorities are included in social engagement, cooperation, and decision-making. Therefore, culture and cultural diversity contribute to the promotion of tolerance and peace, harnessing societies to adapt to the changes and challenges caused by rapid urbanization. Cultural diversity is also a source of creativity that builds knowledge societies able to generate innovative solutions and maintain their competitive advantage. As the saying goes "*where oil was the primary fuel of the 20th-century economy, creativity is the fuel of the 21st century*", the creative economy is one of the most rapidly growing sectors in the global economy considering income, job creation, and export earnings (UNESCO, & UNDP, 2013). Thus, the sustainable leveraging of cultural heritage in urban areas through policies and investments to safeguard and promote cultural infrastructure and knowledge ensure sustainability bridging its social, economic, and environmental dimensions.

Environmentally sustainable and resilient urban development changes the unsustainable consumption and production patterns caused by modern urbanization, facilitating the sustainable management of natural resources. It prevents biodiversity loss, minimizes the pressure on the ecosystems, and reduces waste disposal and pollution, mitigating and adapting to the climate crisis. When properly planned, developed, governed, and managed, globalization and urbanization contribute to environmental sustainability and resilience within and beyond the boundaries of an urban area by creating environmental awareness for a sustainable lifestyle and providing the means for the urban environmental transition and biocapacity conservation. Through smart-driven strategies for spatial planning and environmental assessment tools, urbanization supports the protection of the natural ecosystems' biodiversity. For example, protecting, conserving, and restoring urban parks, green and blue areas, designing and implementing green roofs and vertical gardens, community gardens, waterfront areas contribute to biodiversity enrichment, well-functioning of ecosystem services, and prevent urban sprawl. Biodiversity and ecosystem functioning are vital for human well-being since they provide co-benefits addressing a range of environmental challenges mitigating the impacts of urban living. Another impactful practice to achieve environmental sustainability through urbanization is to incorporate salvaged or materials, reused materials, diverted materials from landfills, and eco-friendly materials into building projects. Low-carbon urbanization moves towards achieving environmental sustainability using clean energy and smart technologies, sustainable use of water, and solid waste management based on the seven R-principles of circular economy (Rethink-Reduce-Reuse-Repair-Refurbish-Recover-Recycle).

It is now apparent that urbanization, if properly planned and managed fosters sustainability and resilience. Urbanization brings higher productivity and taking advantage of urban agglomerations uses fewer resources. In the context of Industry 4 technologies, smart factories, smart cities, sustainable supply chains reduce workloads, enhance employee wellbeing, achieve energy and resource efficiency, innovation and competitiveness, and environmental awareness (Khan et al., 2021). Combined with urban ecology principles urbanization protects preserves and restores the ecosystem's services and functioning beneficial for public health and wellbeing. To benefit from urbanization and reduce the environmental impacts while maximizing the socio-economic benefits, it is essential to understand, measure, assess, and predict the complexity of urban dynamics. In the following subchapters 1.3 and 1.4, we describe how we can accomplish this, using an integrated and multidisciplinary way able to create resilient, healthy, inclusive, circular, and green urban areas.

1.3 Hypothesis

"We can only see a short distance ahead,
but we can see plenty there that needs to be done."
Alan Turing

As urban areas constitute complex and strongly artificialized landscapes with unhealthy ecosystems, it is essential to include an ecological perspective in urban planning to conserve urban biodiversity and establish three-dimensional urban sustainability. Therefore, to address the modern urbanization complexity challenges, we need to couple human and natural systems (CHANS concept), study, and assess them in an integrated interdisciplinary approach engaging social and ecological science.

Coupled human and natural systems are emerged systems from the interactions between them, having their own structure, function, and dynamic mechanisms. This coupling urban system is formed as; the natural system with the main function to support life (ecosystem services) and, the human system with the main function to ensure the survival and reproduction of the human population (sciences, technology, culture, regulations, consumption, production. The dynamic mechanism of the system comes from both natural (solar energy) and human (economic; funds, social; power, cultural; spirit) forces (Wang et al., 2018).

To study, measure and assess the complexity of the dynamic mechanism of the urban systems, we use the urban metabolism framework from an ecosystem services perspective adopting a life cycle thinking. Under the urban metabolism framework, we understand urban areas as "living" organisms where the symbiosis between social-cultural-ecological-technological systems is responsible for the flows and stocks of energy, materials, and information within the urban areas and beyond them. From an ecosystem services perspective, urban areas can be seen as complex ecosystems found in an eternal exchange of materials, energy, and information between its processes/systems and beyond its boundary in order to function and grow. Studying the way that the natural ecosystem services are beneficial to human well-being and applying this knowledge to urban planning and design we are able to reinforce system resilience ensuring urban sustainability. Moving the focus beyond mass balance and linear fluxes, we adopt life cycle thinking (LCT) to obtain a holistic vision of all direct and indirect generated impacts of urban systems improving their multidimensional nonlinear performance throughout its entire value chain.

We envision smart and regenerative by design, and we with this urban places are now able to address various urban stressors with minimal environmental impact enhancing the quality of Life (QoL) and subjective well-being. "Conceptualizing smart and regenerative urban places (SRUP), we face the complexity of the urban systems holistically by applying advanced technologies and real-time data-driven approaches in conjunction with urban ecology principles" (Peponi & Morgado, 2020). This vision of smart regenerative urban places is the key solution that restores the complex relationship between urban and natural systems, developing greener, healthier, compact, efficient, and competitive places to live.

Extensive analysis of the key concepts; *urban place*, *urban metabolism*, *smart cities*, *regenerative design*, and their coupling under sustainability principles forming an original conceptual framework SRUP can be found in Chapter 3.

1.4 Methodology

Adopting Life Cycle Thinking to study urban metabolism under ecosystem services perspective for the design of smart and regenerative urban places is the way to achieve sustainability and reinforce system resilience.

This dissertation thesis has been conducted as a collection of three articles with a common goal to prove the above hypothesis statement true as follows (Figure1). Chapter 2 is based on the article entitled "Smart and Regenerative Urban Growth: A Literature Network Analysis" published in the International Journal of Environmental Research and Public Health (IJERPH), with an assigned Scientific Journal Ranking index (SJR) Q2 and Impact Factor (IF) 3.390. In this chapter, we explore the evolution of the emerging concepts on urban sustainable growth (smart city, regenerative city, urban metabolism, urban sustainability) apply an original bibliometric network analysis to conduct a systematic literature review using VOSviewer software. The main objectives in this part of the thesis dissertation are to disclose the main research trends found in the literature under review, the key scholarly sources revealing the sub-research trends, and to detect the most influential authors and identify the literature gaps on urban sustainability. We then analyze concepts and theories coming from the key scholarly sources their origins and their relatedness as appear on the different bibliometric networks.

Chapter 3 is based on the article entitled "Transition to Smart and Regenerative Urban Places (SRUP): Contributions to a New Conceptual Framework" published in the Land journal, with an assigned Scientific Journal Ranking index (SJR) Q2 and Impact Factor (IF) 3.398. In this Chapter based on the key findings of the previous Chapter 2, we built a novel conceptual framework for smart and regenerative urban places as complex systems. The first step is to study urban places as complex systems, indicating the need to shift to the urban metabolism approach. After this, we demonstrate the opportunities of applying urban smartness to the urban metabolism complexity on facing modern urbanization's challenges. Then we show how the regenerative design of the urban metabolic processes and systems tackles urban challenges and helps to overpass limitations of other circular metabolism concepts. We depict how the two concepts of urban smartness and regenerative design are interconnected under the broader theoretical framework of sustainability and how by integrating them we go beyond sustainability transforming urban places into truly smart and regenerative, by being attractive and liveable, competitive and effective, and innovative restoring the health of natural resources and recognizing the value of ecosystem services and the cost of their loss.

Chapter 4 is based on the article entitled "Life Cycle Thinking and Machine Learning for urban metabolism assessment and prediction" published in Sustainable Cities and Society journal, with an assigned Scientific Journal Ranking index (SJR) Q1 and Impact Factor (IF) 7.587. Under the SRUP conceptual framework defined in precious Chapter 3, the metabolic urban processes, or system of processes are multidimensional, circular, ongoing, and co-evolutionary, eliminating waste by regenerating resources using advanced technologies (Peponi & Morgado, 2020). In this Chapter, we develop a novel methodology led by the following objectives: to measure and assess these urban metabolic processes/systems to identify the main drivers responsible for urban metabolic changes and predict metabolic changes for the near future. To do so, we review the literature on urban metabolism methodologies, and identify their limitations. To overpass these limitations and accomplish our objectives we couple LCT and machine learning (ML) from an ecosystem services perspective. Coupling LCT and ML we adopt a data-driven bottom-up methodology allowing us to obtain knowledge from systems dialectic. We start the implementation of our methodology by conducting the first step of LCT the life cycle inventory (LCI) in urban ecosystem services perspective. For doing so, we define the dimensions, subdimensions, and indicators for the urban metabolic processes in line with SRUP conceptual framework. Adopting the ecosystem services perspective, we classify the representative indicators of each subdimension using the four well-known groups; provisioning services, regulating services, supporting services, and cultural services coming from the classification system Millennium Ecosystem Assessment (MA), 2005. We build the dataset of 4 dimensions organized in 15 sub-dimension, including 29 indicators and 254 measures, for two time periods. Using ML we are able to capture the feedback effect coming from the different urban processes and system dynamic components encapsulating the SRUP urban metabolism attributes. We developed an algorithmic representation of the urban metabolism creating a Multilayer Perceptron (MLP) neural network, after trying different training algorithms, hyperparameters tuning and network's topology by testing rules of thumb suggested by the literature. Eventually, the network was appropriately trained and therefore able to make predictions and perform sensitivity analysis on the network inputs allowing us to investigate the interdependencies of the metabolic processes corresponding to different dimensions holistically through time and space. The proposed research framework is applied to the urban core of Lisbon's functional urban area as defined by Urban Atlas. Using GIS we mapped the predicted metabolic changes within the study area.

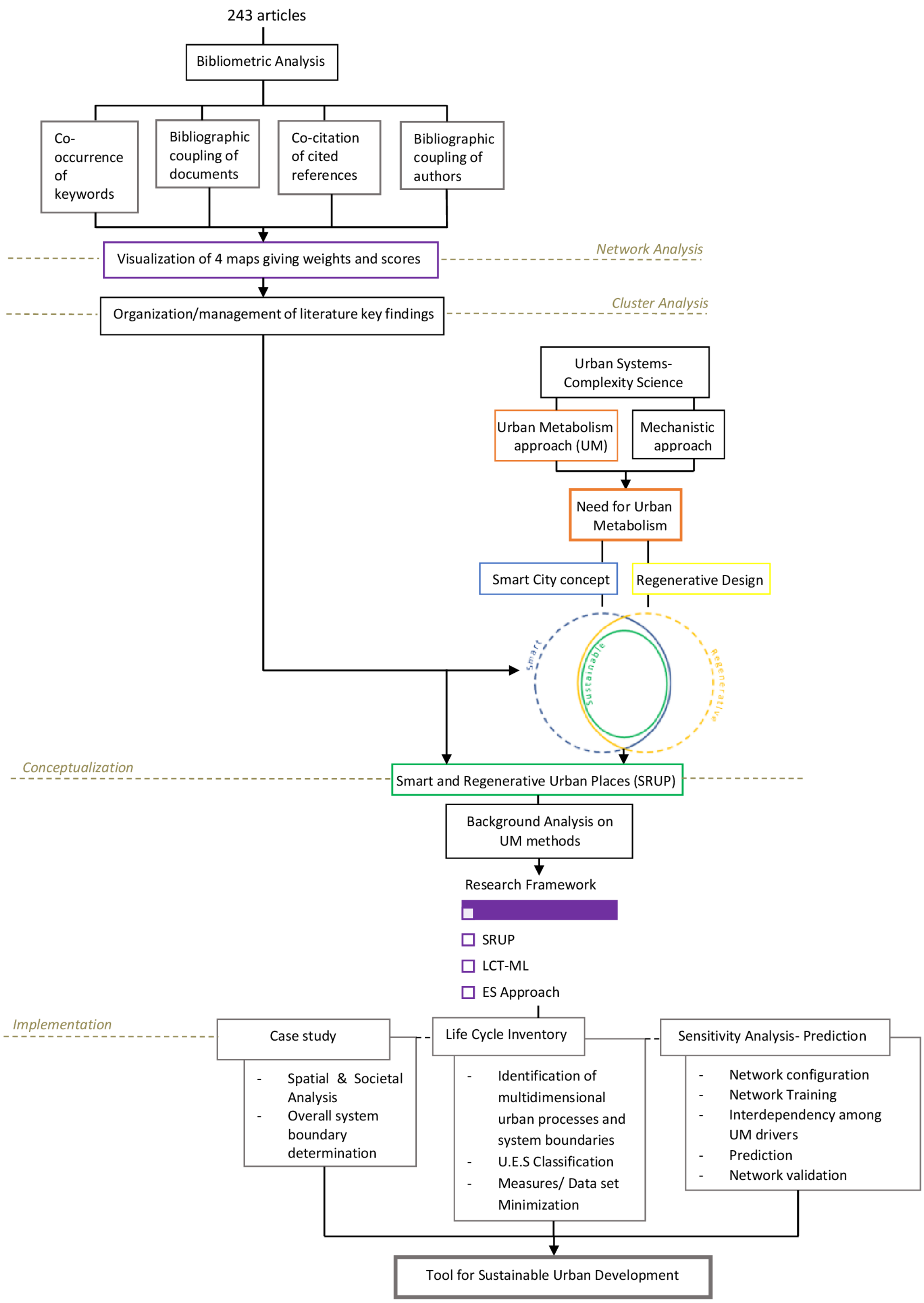

Figure 1. Dissertation thesis flow chart

1.4.1 List of articles

Article 1. Smart and Regenerative Urban Growth: A Literature Network Analysis

Citation: *Peponi, A., & Morgado, P. (2020). Smart and Regenerative Urban Growth: A Literature Network Analysis. International Journal of Environmental Research and Public Health, 17(7), 2463.*

Keywords: bibliometric network; distance maps; smart and regenerative urban growth; urban ecology; urban metabolism

Author Contributions: All authors have read and agree to the published version of the manuscript. Conceptualization, P.M. and A.P.; methodology, A.P.; software, A.P.; validation, A.P., and P.M.; formal analysis, A.P.; investigation, A.P.; resources, P.M and A.P.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, P.M and A.P.; visualization, A.P.; supervision, P.M.; project administration, A.P. and P.M..; funding acquisition, P.M. and A.P.

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Article 2. Transition to Smart and Regenerative Urban Places (SRUP): Contributions to a New Conceptual Framework

Citation: *Peponi, A., & Morgado, P. (2020). Transition to Smart and Regenerative Urban Places (SRUP): Contributions to a New Conceptual Framework. Land, 10(1), 2.*

Keywords: smart city; circular economy; urban metabolism; sustainability; resilience

Author Contributions: Conceptualization, A.P.; investigation, A.P.; writing—original draft preparation, A.P., and P.M.; writing—review and editing, A.P. and P.M. All authors have read and agreed to the published version of the manuscript.

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Article 3. Life Cycle Thinking and Machine Learning for urban metabolism assessment and prediction

Citation: *Peponi, A., Morgado, P., &Kumble, P. (2022). Life cycle thinking and machine learning for urban metabolism assessment and prediction. Sustainable Cities and Society, (80), 103754.*

Keywords: Life cycle inventory; Sensitivity analysis; ANN; Urban core; Case study; Land use planning; Urban metabolism

Author Contributions: Conceptualization, A.P., P.M., and P.K.; methodology, A.P., P.M.; software, A.P.; validation, A.P.; formal analysis, A.P.; investigation, A.P.; data curation, A.P., P.M; writing—original draft preparation, A.P.; writing—review and editing, A.P., P.M., and P.K.; visualization, A.P.; supervision, A.P., P.M., and P.K.; project administration, A.P. All authors have read and agreed to the published version of the manuscript.

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Chapter 2

Based on: Peponi, A., & Morgado, P. (2020).
Smart and Regenerative Urban Growth: A Literature Network Analysis.
International Journal of Environmental Research and Public Health, 17(7), 2463.

2. Smart and Regenerative Urban Growth: A Literature Network Analysis

"*Smart city*", "*sustainable city*", "*ubiquitous city*", "*smart sustainable city*", "*eco-city*", "*regenerative city*" are fuzzy concepts; they are established to mitigate the negative impact on urban growth while achieving economic, social, and environmental sustainability. This chapter presents the result of the literature network analysis exploring the state of the art in the concepts of smart and regenerative urban growth under urban metabolism framework. Heat-maps of impact citations, cutting-edge research on the topic, tip-top ideas, concepts, and theories are highlighted and revealed through VOSviewer bibliometrics based on a selection of 1686 documents acquired from Web of Science, for a timespan between 2010 and 2019. This chapter discloses that urban growth is a complex phenomenon that covers social, economic, and environmental aspects, and the overlaps between them, leading to a diverse range of concepts on urban development. In regards to our concepts of interest, smart, and regenerative urban growth, we see that there is an absence of conceptual contiguity since both concepts have been approached on an individual basis. This fact unveils the need to adopt a more holistic and interdisciplinary approach to urban planning and design, integrating these concepts to improve the quality of life and public health in urban areas.

2.1 Introduction

Humankind alters the earth´s natural processes and shapes the landscapes causing alterations in global scale phenomena such as land use/land cover change, economy, energy, transport, population, and urbanization, among others [1]. Globally, cities expand, and their population is growing; one in five people on earth lives in a city with a population of more than one million, and sixty percent of the global population is projected to live in urban settlements by the year 2030 [2]. At the European level, we notice two extremes; around hundred sixty-five million citizens live in dynamically growing cities mainly due to migration, and around twenty-five million citizens live in "dynamically shrinking" cities [3]. Approximately forty percent of European cities with a population of more than two hundred thousand are witnessing urban shrinkage from economic and demographic perspectives [4]. Urban shrinkage is caused mainly due to changes in economic demographic and political systems as well as environmental hazards, and it leads to "under-utilization, vacancy, demolition, emerging brownfield sites, and de-densification of spaces" [3]. The analysis of the dynamics and the spatial configuration of the trends of urban growth consists of an essential topic in current urban studies [5].

Urban growth has a double meaning; on one hand, it signifies the constant rise of urban population (urbanization) and, on the other hand, the expansion of urban lifestyle and infrastructure within the settlement system [6,7]. Urban growth offers a variety of opportunities (economic, social, political growth), but it has a negative impact as well. Urban sprawl is the type of urban growth having a negative meaning [5,8]. Despite the dialogue about the definition of urban sprawl, it represents overall a wasteful type of urbanization. It is related to an uncontrolled expansion of urban areas, scattered settlement areas (how dense or scattered are the buildings and patches of built-up areas within the landscape), and low-density development (high area of land per person) [9–11]. Urban sprawl has significant negative impacts regarding land use/land cover change and energy efficiency, urban economy, social structure, physical environment, public health, as well as the form and spatial arrangement of urban development [12–14].

Although there is a growing body of empirical studies that analyses urban growth and reveals its impacts, less attention has been devoted to studies that review the evolution of various concepts on sustainable urban development. This part of the thesis seeks to explore the evolution of the emerging concepts on sustainable urban development (smart city, sustainability, regenerative city, and urban metabolism) through a novel network analysis of the existing literature, using VOSviewer software.

Initially, we attempt to disclose the main research trends found in the literature under review. Then, we detect the key scholarly sources considering firstly, the number of their citations, and secondly, their overall conceptual relevance to the topic under review. Looking at the way that these key scholarly sources are connected, we reveal the sub-research trends. The next steps are to analyze the key concepts and theories coming from these key scholarly sources and find their origins and connections. The last step of the literature network analysis is to detect the most influential authors and see how they are related to each other.

VOS mapping and clustering techniques are both promising and useful. They have been applied to conduct bibliometric analysis in various fields of studies for instance co-occurrence term analysis in psychology [15], bibliographic analysis of the concept safety culture [16] of the Journal of Infection and Public Health [17], of thermal comfort and building control research [18] and a bibliometric analysis on connection between urban governance, planning, design and development [19] among others. Thus, we adopted the software and adapted the network analysis algorithms to decode the degree of connectivity between smart and regenerative urban growth concepts.

The remainder of this chapter is organized as follows. The Subchapter 2.2 describes the methodology applied to conduct the literature network analysis. Initially, Subchapter 2.2.1 provides information regarding the data acquisition. Subchapter 2.2.2 presents the theoretical background and the technical settings for the construction of the desired bibliographic networks. In Subchapter 2.3, the key findings of the literature network analysis are accompanied by maps and tables. Subchapter 2.4 discusses the methodology results, and limitations of the literature network analysis review, and Subchapter 2.5, the overall contribution of this study to the field of urban and environmental planning.

2.2 Review Method

A methodology comprises a set of applied procedures and techniques, unveiling information regarding a specific topic or research subject, to provide overall scientific credibility of the study. Similarly, the literature review should have a specific and tailored methodology, instead of being opaque or even randomly and unstructured made as in most of the papers. Considering this, the complexity of the topic under study, and its societal significance, there is a need for a multidisciplinary systematic literature network analysis able to provide scientific evidence upon the conceptual evolution of sustainable urban growth.

Here, we have conducted a literature network analysis using Web of Science (WOS) as the main bibliographic data source, VOSviewer software for the bibliometric network analysis and visualization. Docear software was used to organize and manage the key findings of the literature, and Mendeley software was used to generate the references and citations to scientifically support the idea of smart and regenerative redesign of urban areas (Figure 1).

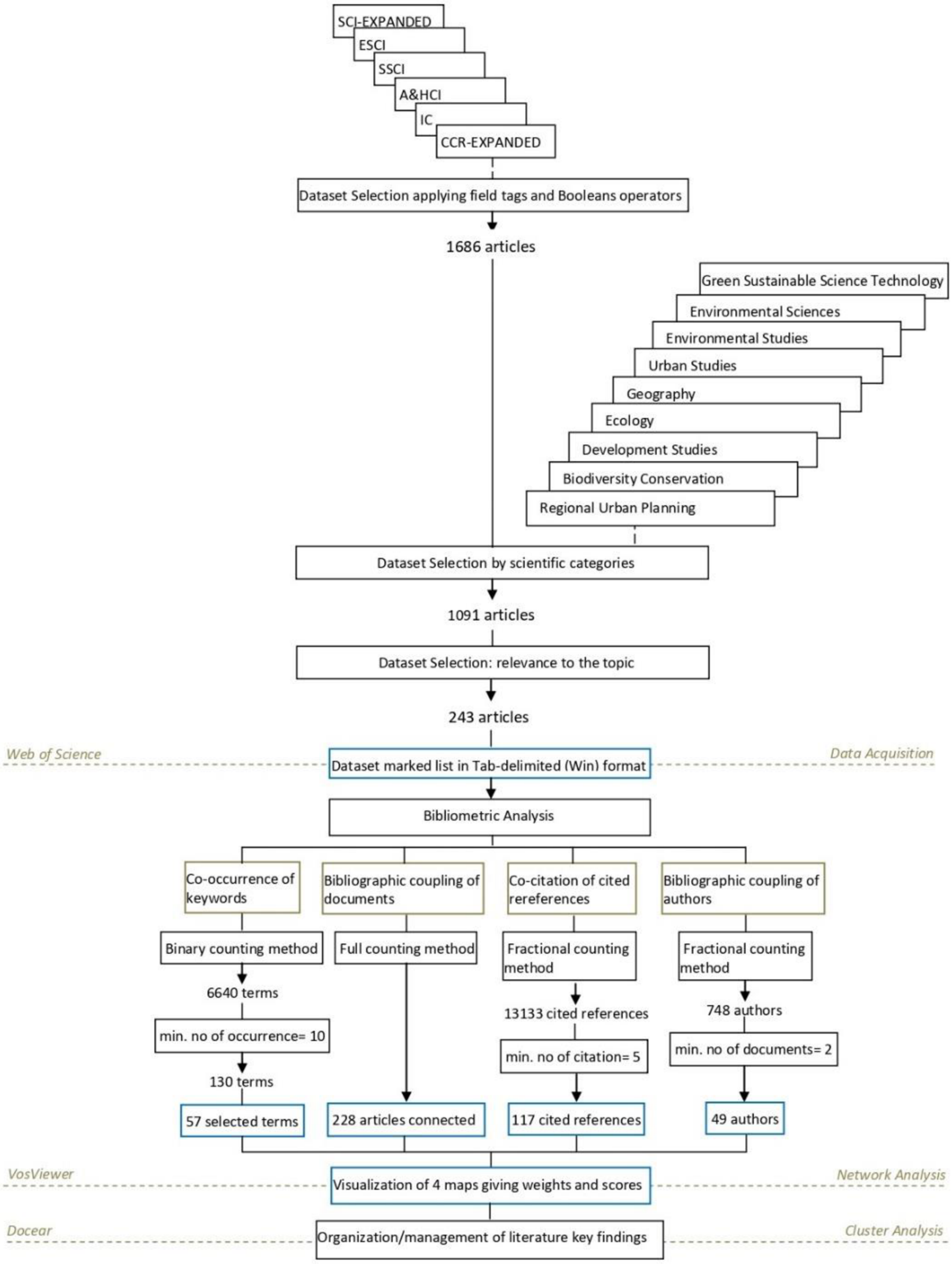


Figure 1. Flowchart of the developed methodology.

2.2.1 Data Acquisition

To acquire the relevant literature, the Web of Science Core Collection database was selected, applying an advanced search filter by using field tags and Booleans operators as in the following expressions; (TI=(smart* AND urban) OR TI=(sustainable AND urban) OR TI=(regenerat* AND urban) OR TI=(metabolism) AND TS=(urban AND sprawl)), (TI=(urban AND metabolism)), where TI refers to the title of the document and TS to the topic. We used timespan between 2010 and 2019, English language, Article type of document for the search and Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI) Emerging Sources Citation Index (ESCI), Current Chemical Reactions (CCR-EXPANDED), Index Chemicus (IC) indexes.

These two searches resulted initially in 1686 related articles in total. We reduced the amount of literature to 1091 selecting specific WOS categories (Environmental Sciences OR Environmental Studies OR Urban Studies OR Green Sustainable Science Technology OR Regional Urban Planning OR Geography OR Ecology OR Development Studies OR Biodiversity Conservation). From this search set, we created a marked list selecting finally 243 articles considering their relevance to the topic and the times cited by reading their title, abstract and keywords. These 243 records were saved in Tab-delimited (Win) format considering their full records and cited references.

2.2.2 Bibliometric Analysis

To construct and analyze our bibliometric network of the 243 articles, we used VOSviewer software. VOS mapping technique is applied to create distance maps. In distance maps, the distance between two items of the network shows the strength of their relatedness; shorter distance means higher relatedness. This method comes as an alternative to the multidimensional scaling technique traditionally used for the visualization of these types of maps [20–22]. The VOS mapping technique consists of three parts; a) the normalization, b) the mapping, and c) the clustering of the network nodes. In the first part, the association strength normalization is performed by default, normalizing the strength/weight of the links between the items of the nodes. The second part is the two-dimensional mapping of the nodes of the bibliometric network placing the nodes with strong relation closer to each other and the nodes with weak relation in longer distance to each other. In the third part, the clustering technique is applied, which assigns each node of the network to clusters considering their relatedness. More information regarding the expressions applied from the VOS mapping technique can be found in [23–25].

Depending on the type of analysis we want to conduct, the items of our interest can be connected by co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links calculated in one of two ways. The full counting versus the fractional counting method is used to calculate bibliographic coupling, co-citation, or co-authorship links and the binary versus the full counting method is used to calculate co-occurrence links in networks/ maps created based on text data.

Initially, we created a co-occurrence map based on text data to see which keywords/terms are related to each other in our bibliographic data set, revealing the research trends in our data set. The terms were extracted from both the title and abstract fields of the documents. For the construction of this map/network, we used the binary counting method instead of full counting (Table 1, Figure 2). In this way, the co-occurrence links between the keywords are based on the number of documents that they occur together at least once. Looking at Table 1, we see the number of occurrences of three keywords in five documents. Figure 3 demonstrates the number of occurrences (No Oc.) and the strength of the links (l.s.) between the keywords using binary and full counting method. Applying the full counting method signifies that all occurrences of a term in all documents are counted. On the contrary, using the binary counting method, the number of occurrences of a term is not taken into consideration; only the presence or the absence of a term in a document counts. Defining a minimum number of occurrences of a term equaling ten, from 6640 terms, 130 meet the threshold, and 57 were selected as the most relevant terms based on our interpretation and their relevance score. Terms with higher relevance scores tend to represent specific concepts under study, while terms with lower relevance score appear to represent more general topics. The network was normalized with the association strength method and clustered with resolution parameter equals one and the minimum cluster size equals five. The co-occurrence links were weighted considering the occurrence of the terms. The average of citations was used as the score attribute.

Table 1. Number of occurrences of keywords (K1-3) in documents (D1-5).

	Documents				
Keywords/Terms	**D1**	**D2**	**D3**	**D4**	**D5**
K1	1	2	3	4	5
K2	1	2	3	1	2
K3		1	1	2	

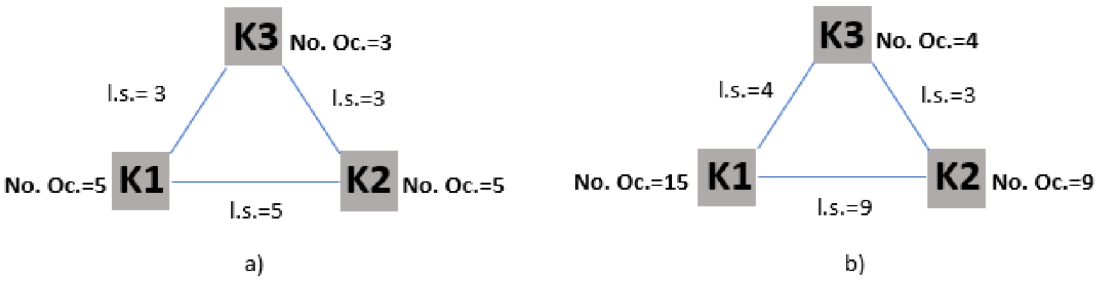


Figure 2. Co-occurrence network of keywords, (**a**) binary counting method, (**b**) full counting method.

Then, we constructed a bibliographic coupling network of documents intending to see which are more related to each other and more cited. In this map, the relatedness of the documents is based on the degree that they cite the same document. Considering that all the documents of our bibliometric network are related to the main topic, we used the full counting method to highlight the influence of high cited documents to the network. From the total 243 documents, the 228 were connected. We mapped and visualized the network into six clusters using association strength as a normalization method with resolution parameter equaling one and minimum cluster size equaling five. The bibliographic coupling links were weighted using the total link strength, and the number of citations was used as the score attribute.

Afterwards, we constructed the bibliographic coupling network of authors using the fractional counting method to examine which authors share a common field of studies. Giving the minimum number two for documents per author, of the 748 authors, only 49 meet this threshold. In this network, the relatedness of the authors is based on the degree that they cite the same document. In this way, the bibliographic coupling links between the authors are based on the number of documents that they commonly cite, not including the total number of authors of each of the same documents that they cite. For example, if an author A2 cites the same document D1 with the authors A1 and A3, the links between the author A2 and A1 and A2 and A3 will have strength of 1 / 2= 0.5, and at the same time if the authors A1 and A3 have cited another document D2, the strength of the link between A1 and A3 will be 1.5 (1/2 =0.5 for the D1, plus 1 for the D2) (Figure 3). We mapped the network into four clusters using association strength as a normalization method. The minimum cluster size was equal to five. We gave the total link strength the same score as the weight and the average of citations as the attribute of the items.

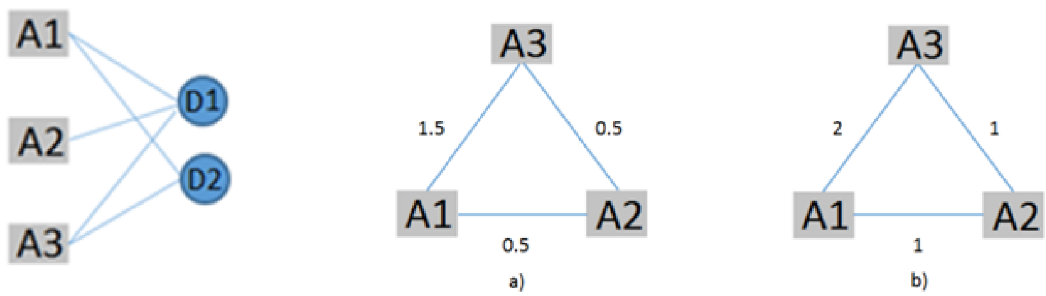


Figure 3. Bibliographic coupling network of authors, a) fractional counting method, b) full counting method.

Thereafter, we intended to see the relatedness of the cited references based on the degree that they have been cited together by another document. For this type of analysis, we constructed a co-citation map of cited references using the fractional counting method to avoid the influence of documents with a long list of references, as mentioned previously. Giving a minimum number of citations of a cited reference equals to five from 13133 cited references 117 meet this threshold.

2.3 Results

The first map produced presents a bibliographic network of 57 nodes/keywords connected with co-occurrence links and grouped into three clusters (Figure 4a, Table 2). This first part of this analysis shows the keywords that appear together and their frequency in the data set. Their proximity to another reveals the relatedness of each pair of terms. The color of each node indicates the cluster in which it belongs. These keywords clusters can be interpreted as the research trends of the topic under review.

Looking at the links between the keywords we identify that the top five pairs of keywords with the greatest co-occurrence are city and process with link strength equaling to 44, city and system with link strength of 43, city and strategy with link strength of 30, city and smart city with link strength of 28, city and management with strength of 26. Our general understanding from these links is that the most connected/related part of the literature treats cities as systems, and under system analysis the literature studies the associated processes seeking for strategies to ensure a smart and more efficient urban management.

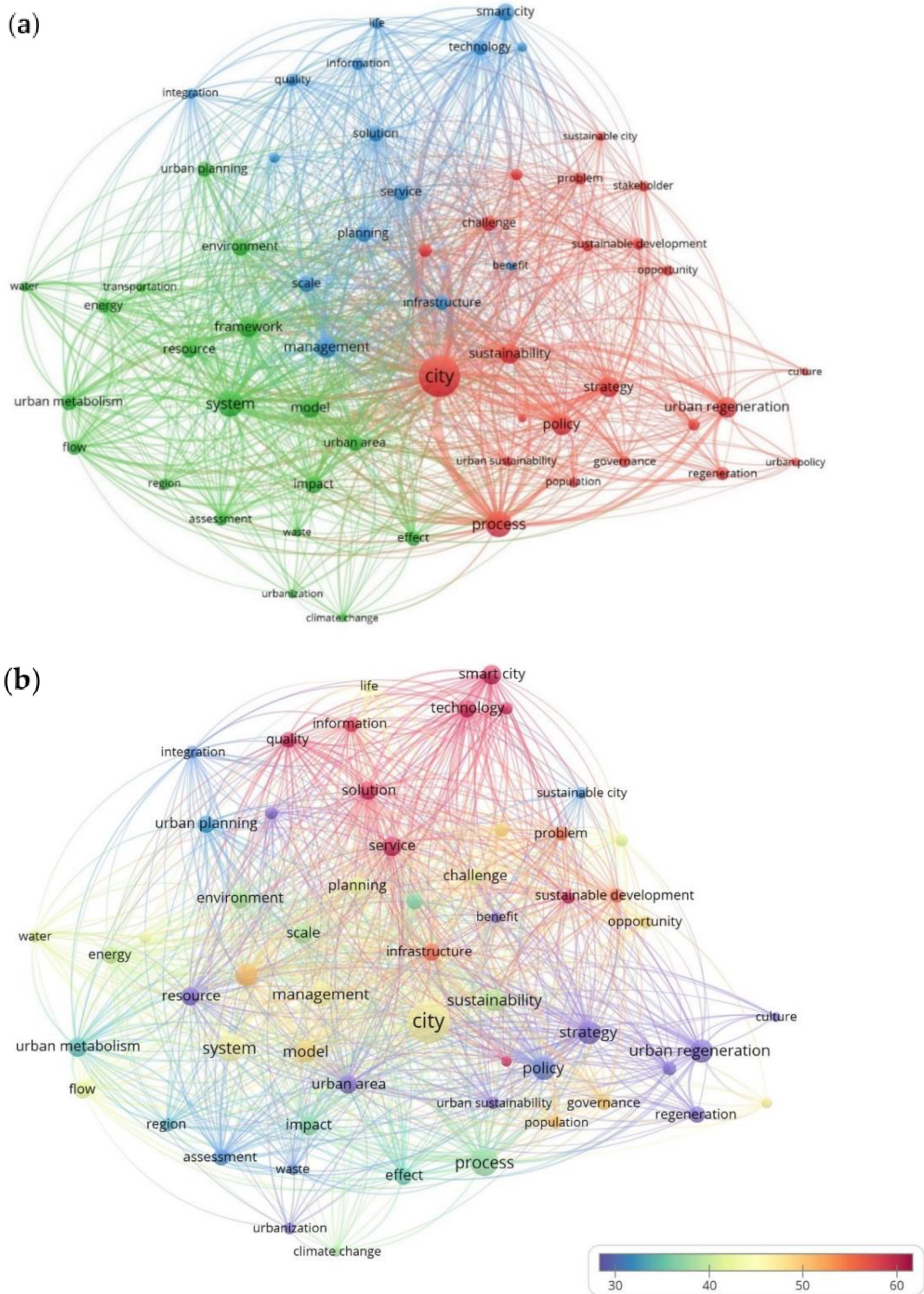


Figure 4. (**a**). Map of co-occurrence analysis based on keywords. (**b**). Map of co-occurrence analysis based on keywords indicating the average of citation.

Table 2. Number of co-occurrences (Oc.) of the selected keywords per cluster.

CLUSTER 1 (23 Items)		CLUSTER 2 (19 Items)		CLUSTER 3 (15 Items)	
Keywords	**No. Oc.**	**Keywords**	**No. Oc.**	**Keywords**	**No. Oc.**
Challenge	32	Assessment	27	Benefit	16
City	143	Climate change	14	Citizen	17
Culture	12	Effect	32	Information	25
Governance	22	Energy	30	Infrastructur e	30
Knowledge	19	Environment	38	Integration	18
Opportunity	20	Flow	30	Intervention	18
Policy	50	Framework	48	Life	19
Population	18	Impact	39	Management	53
Problem	24	Model	47	Planning	35
Process	72	Region	21	Quality	25
Regeneration	27	Resource	35	Scale	36
Stakeholder	19	System	71	Service	36
Strategy	50	Transportati on	16	Smart city	38
Sustainability	49	Urban area	34	Solution	33
Sustainable city	15	Urban metabolism	36	Technology	32
Sustainable development	23	Urban planning	31		
Sustainable urban development	22	Urbanization	15		
Transformation	21	Waste	15		
Urban development	27	Water	17		
Urban environment	14				
Urban policy	14				
Urban regeneration	52				
Urban sustainability	17				

In Table 2, we can see all the keywords per cluster and how many times they appear in the data set (number of occurrences). In the first cluster (red color), which contains 23 keywords, the top five keywords with the greatest number of occurrences are city which appears 143 times; *urban regeneration* 52 times; *policy* 51; *strategy* 50 times; and s*ustainability* 49 times. The second cluster (green color), which contains 19 keywords, denotes a more engineering approach as the five terms with the higher occurrence, are *system* 71 times; *framework* 48 times; *model* 47 times; *impact* 39 times; and *environment* 38 times. The third cluster (blue color) of 15 keywords presents mixed terms from different scientific fields since the top five terms are *management* 53 times; *smart city* 38 times; *scale and service* 36 times each; and *planning* 35 times.

Figure 4b and Table 3 present the results of the second part of this analysis. We can see the co-occurrence network of keywords weighted by the number of occurrences of each keyword and colored considering the average number of citations of the documents that these keywords have. Looking at Table 3, we see the exact number of average citations that corresponds indirectly to each keyword per cluster. In the first cluster, the five first keywords with the greatest number of average citations are *knowledge* (100.11), *sustainable development* (54.70), *problem* (54.46), *population* (50.44), and governance (50.05). In the second cluster, the keywords framework (50.58), *model* (48.45), *system* (45.38), *transportation* (44.88), and *water* (41.71) are the five keywords that occurred in documents with the greatest average citations. In the third cluster, these keywords are *smart city* (91.68), *citizen* (89.65), *technology* (88.41), *service* (74.25) and *quality* (64.76).

Table 3. Average citations (Avg. Cit.) of the selected keywords per clusters in co-occurrence analysis.

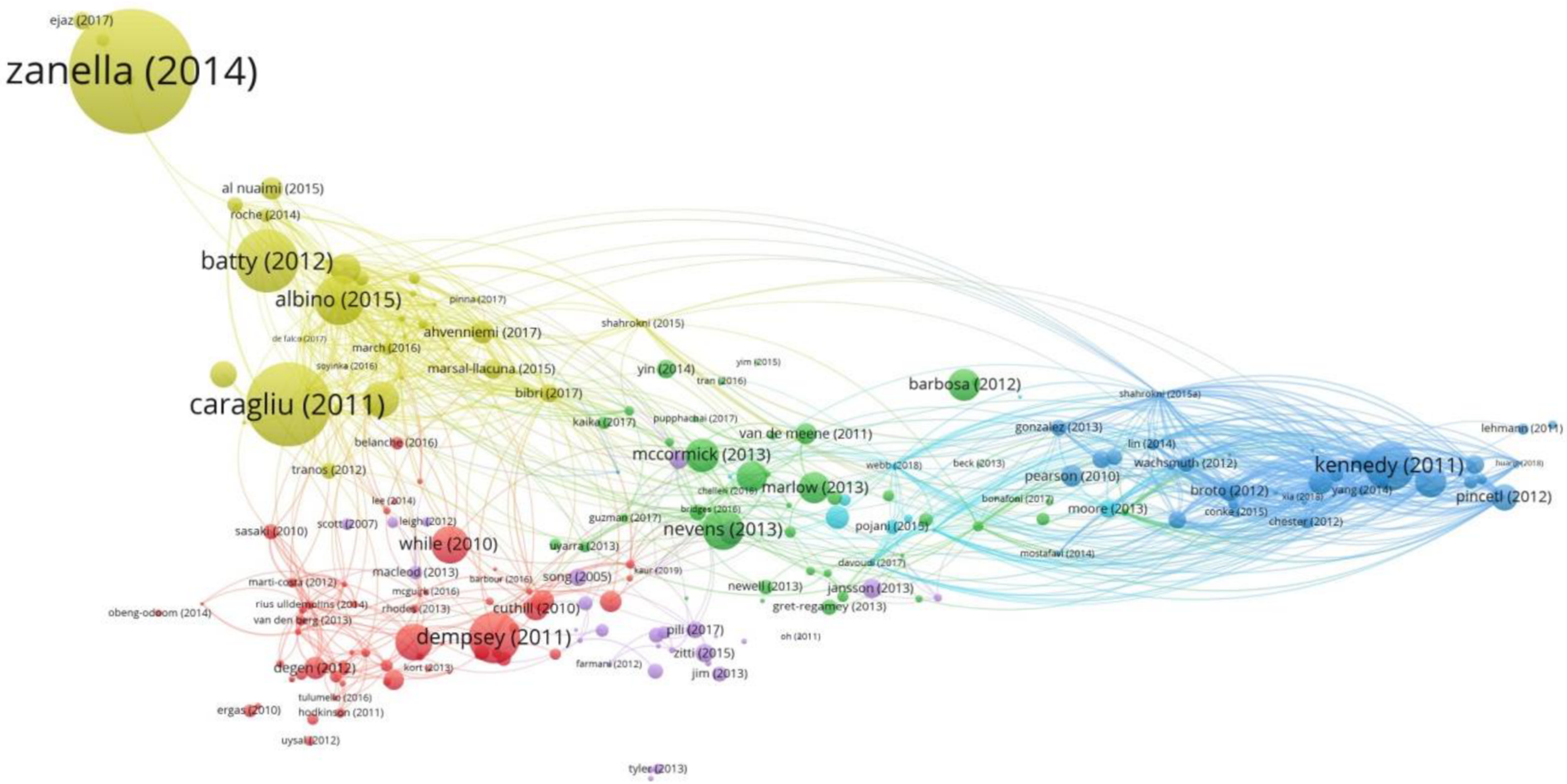
CLUSTER 1 (23 Items)		CLUSTER 2 (19 Items)		CLUSTER 3 (15 Items)	
Keywords	**Avg. Cit.**	**Keywords**	**Avg. Cit.**	**Keywords**	**Avg. Cit.**
Challenge	44.22	Assessment	32.37	Benefit	26.88
City	46.08	Climate change	39.07	Citizen	89.65
Culture	26.17	Effect	35.66	Information	57.72
Governance	50.05	Energy	40.57	Infrastructure	54.53
Knowledge	100.11	Environment	39.16	Integration	31.89
Opportunity	48.35	Flow	43.23	Intervention	15.78
Policy	31.31	Framework	50.58	Life	45.42
Population	50.44	Impact	37.10	Management	46.09
Problem	54.46	Model	48.45	Planning	43.77
Process	38.00	Region	34.24	Quality	64.76
Regeneration	21.15	Resource	23.36	Scale	39.42
Stakeholder	42.84	System	45.38	Service	74.25
Strategy	26.54	Transportation	44.88	Smart city	91.68
Sustainability	40.37	Urban area	25.09	Solution	59.06
Sustainable city	32.40	Urban metabolism	34.92	Technology	88.41
Sustainable development	54.70	Urban planning	33.03		
Sustainable urban development	48.77	Urbanization	30.13		
Transformation	25.81	Waste	31.93		
Urban development	37.44	Water	41.71		
Urban environment	72.71				
Urban policy	46.79				
Urban regeneration	15.17				
Urban sustainability	19.76				

Based on this analysis and looking at the number of occurrence and average citations, we understand that the literature is divided into three main research trends (clusters) of urban growth. The first research trend tries to understand the urban processes and to apply this knowledge in order to tackle related urban challenges and problems. This part of the literature is seeking policies and strategies that support sustainable urban development, offering opportunities for urban regeneration involving different stakeholders. The second research trend studies urban systems, on a regional scale using an urban metabolism framework to tackle the negative environmental impacts of these urban systems. In this way, we model the consumption of resources, the flows of energy and material within urban systems (i.e., water, transportation), and the resulting outcomes to other systems in the form of pollution, waste or export product. The third research trend refers, to the integration of the concept "smart city" in urban planning and management at different scales of analysis. Smart city concept benefits the citizens by increasing the overall quality of life offering solutions, using technological infrastructures to have access to services and information.

Figure 5a,b present the bibliographic coupling network of the documents, our second analysis. As shown in Figure 5a, the network of 228 nodes represents the connected documents of our data set under this analysis, and it is grouped into six clusters. The size of the labels of the documents represented by circles varies depending on the number of citations referring to the documents (weight) (Table A1, and Table A3, Appendix A). The top five cited documents in the first cluster of 60 items (red color) are Dempsey et al. (2011) 275 times cited, While et al. (2010) 172 times cited, González et al. (2013) 166 times cited, Cuthill (2010) 91 times cited, and Degen & Garcia (2012) 79 times cited. In the second cluster of 47 items (green color), the top five documents with more citations are Nevens et al. (2013) with 191 citations, McCormick et al. (2013) with 144 citations, Barbosa et al. (2012) with 135 citations, Marlow et al. (2013) with 126 citations, and Zhao (2010) with 121 citations. For the cluster three (blue color) of 40 items Kennedy et al. (2011) 258 times cited, Chen & Chen (2019) 127 times cited, Pincetl et al. (2012) 98 times cited, Barles 2010) 86 times cited and

Pearson et al. (2010) 74 times cited are the top highly cited documents. The most cited documents of the fourth cluster of 40 items (yellow color) are Zanella et al. (2014) with 1065 citations, Caragliu et al. (2011) with 576 citations, Batty et al. (2012) with 372 citations, Albino et al. (2015) with 260 citations and Lombardi et al. (2012) with 158 citations. For the fifth cluster (purple color) of 31 items the top five cited documents are Haapio (2012) 88 times cited, Yigitcanlar & Lee (2014) and Jansson (2013) with 60 times cited each, Zitti et al. (2015) with 58 times cited and Pili et al. (2017) with 51 times cited. For the sixth cluster of 10 items (light blue color), Haghshenas & Vaziri (2012) with 80 citations, Moore et al. (2013) with 56 citations, Pojani & Stead (2015) with 40 citations, Liu (2012) with 30 citations, and Newton & Glackin (2014) with 19 citations are the top five cited documents. The results of this analysis show the scholarly sources with a higher impact in the general field of urban and environmental planning. These sources constitute publications with a greater number of citations.

(a)



ejaz (2017)
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pearson (2010)
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yang (2014)
pincetl (2012)
lee (2014)
bonafoni (2017)
moore (2013)
conke (2015)
chester (2012)
sasaki (2010)
scott (2007)
leigh (2012)
guzman (2017)
nevens (2013)
pojani (2015)
while (2010)
uyarra (2013)
mostafavi (2014)
davoudi (2017)
macleod (2013)
marti-costa (2012)
song (2005)
kaur (2019)
newell (2013)
jansson (2013)
mcguirk (2016)
rius ulldemolins (2014)
rhodes (2013)
cuthill (2010)
gret-regamey (2013)
obeng-odoom (2014)
van den berg (2013)
dempsey (2011)
pili (2017)
oh (2011)
zitti (2015)
degen (2012)
kort (2013)
farmani (2012)
jim (2013)
tulumello (2016)
ergas (2010)
hodkinson (2011)
uysal (2012)
tyler (2013)

(**b**)

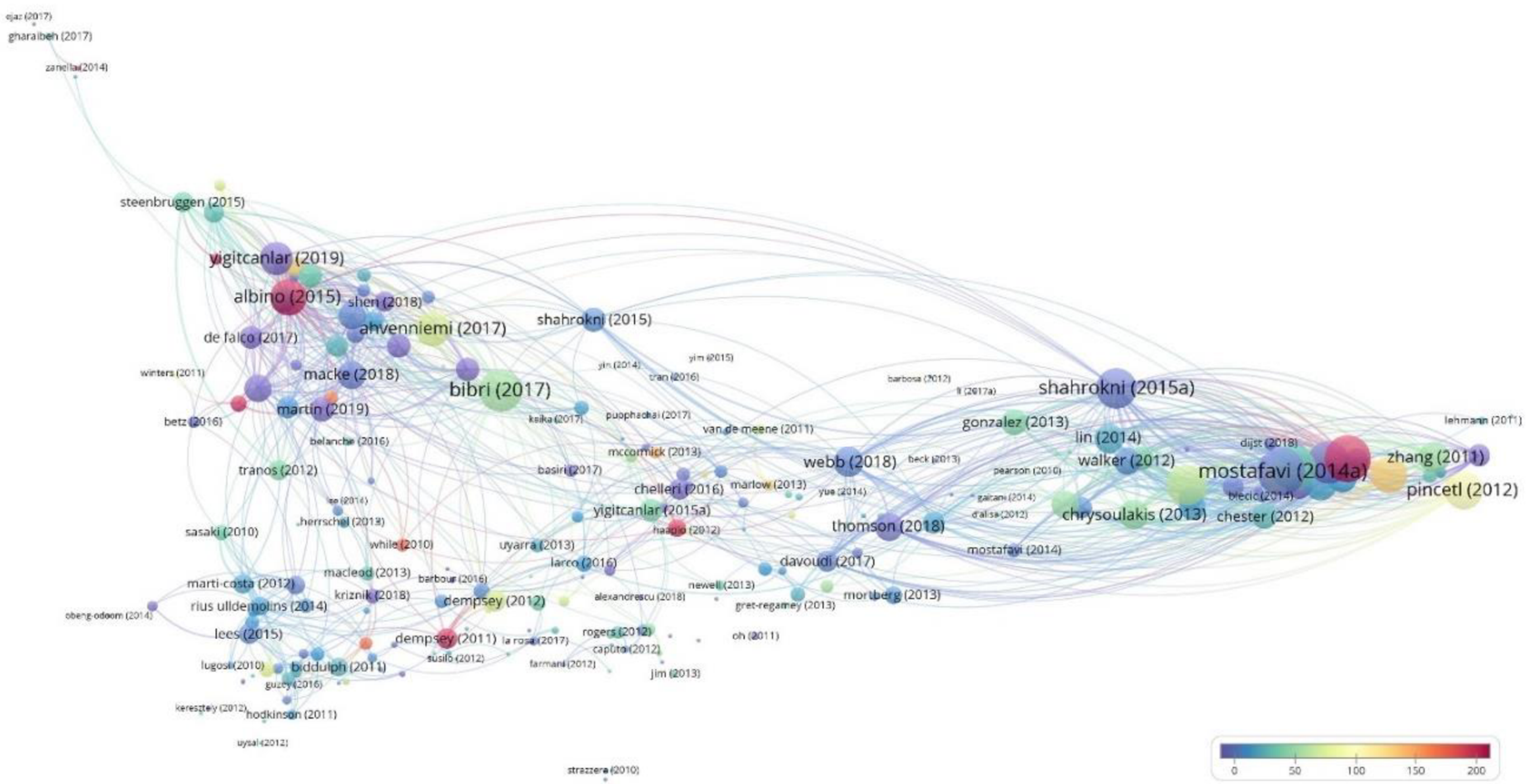


Figure 5. (**a**). Map of bibliographic coupling analysis based on documents with the weights of the links on the number of citations. (**b**). Map of bibliographic coupling analysis based on documents with the weights of the links on the total links strength and indicating the number of citations.

In the second part of this analysis shown in Figure 5b, we see the network of the key scholarly sources based on their relevance to the topic under analysis. The size variation of the labels of the nodes is determined by their total link strength, which here is the number of common documents that they cite with the documents on the other edge of the links. On the other hand, the differentiation in color is based on the number of citations of each document. Looking at Table 4, we see the top five more important scholarly sources per cluster considering their total link strength, as well as the sub research trends per cluster in titles.

Table 4. Top five publications per infometric cluster with stronger links based on bibliographic coupling analysis. References can be found in Table A3, Appendix A.

	No. Citations	No. Links	Total Link Strength	Important Publications	Main Topics of the Clusters
CLUSTER 1 (60 Items)	76	38	87	Dempsey et al. (2012)	Socially, environmentally equitable, and sustainable communities for sustainable urban development.
	12	35	83	Lees and Melhuish (2015)	
	275	40	82	Dempsey et al. (2011)	
	23	32	72	Martí-Costa and Miquel (2011)	
	22	35	70	Rius Ulldemolins (2014)	
CLUSTER 2 (47 Items)	3	56	93	Yigitcanlar and Teriman (2015)	Inclusion of ecological principles in urban planning through urban metabolism for a
	26	44	87	Romero-Lankao et al. (2014)	
	14	41	81	Lu et al. (2016)	

	2	62	80	Chelleri et al. (2016)	sustainable urbanized world.
	191	36	62	Nevens et al. (2013)	
CLUSTER 3 (40 Items)	7	53	282	Mostafavi et al. (2014a)	Urban metabolism evolution towards urban sustainability.
	258	46	266	Kennedy at el. (2011)	
	42	52	252	Goldstein et al. (2013)	
	1	50	232	Zhang et al. (2018)	
	70	55	222	Broto et al. (2012)	
CLUSTER 4 (40 Items)	58	78	242	Bibri and Krogstie (2017)	Disclosure of the smart concept meaning.
	260	52	188	Albino et al. (2015)	
	77	55	177	Ahvenniemi et al. (2017)	
	0	46	162	Yigitcanlar et al. (2019)	
	8	56	127	Macke et al. (2018)	
CLUSTER 5 (31 Items)	17	48	62	Mortberg et al. (2013)	New economy paradigm: A socio-ecological systematic economy supported by technology.
	40	44	52	Lombardi et al. (2011)	
	37	32	49	MacLeod (2013)	
	60	31	39	Jansson (2013)	
	60	19	36	Yigicanlar and Lee (2014)	
CLUSTER 6 (9 Items)	11	73	138	Webb et al. (2018)	Urban metabolism and regenerative urban design for future cities.
	4	64	127	Thomson and Newman (2018)	

56	51	124	Moore et al. (2013)
10	54	82	Davoudi and Sturzaker (2017)
6	40	45	Van Timmeren et al. (2012)

The first cluster introduces the social dimension to sustainable urban development; in this way, urban sustainability refers not only to the environmental concerns but also includes social and economic aspects to the concept. Social equity, environmental equity, and the sustainability of the community itself are the main dimensions of social sustainability. Social equity relates to the access to services and facilities, environmental equity relates to the access to green and open spaces, and the sustainability of community includes perceptions of safety, social interaction, and community stability. Overall, social sustainability is seeking social cohesion, capital inclusion, and high quality of the living environment. A question raised here is if high-density neighborhoods support less social sustainability than the low-density ones. Findings reveal that denser areas provide access to services and facilities at the neighborhood level, but the use of them depends on their quality. Regarding the aspect of environmental equity, urban denser areas appear to offer less public green open spaces than the low-density urban areas. Furthermore, residents chose or not to use the local green areas according to the feeling of safety and the level of maintenance of the site. It appears that in higher-density neighborhoods, the local parks and green spaces are less attractive and unsafe than in the lower-density areas. From a community stability and social interaction point of view, high-density areas appear less stable with residents expressing the feeling of lower satisfaction with their neighborhood and tendency to move somewhere else. Moreover, high-density areas seem to have weaker social interaction and social networks than the lower-density areas. A solid way to combat social exclusion is though urban regeneration supported by arts and culture. Artists using ethnographic methods can challenge the links between regeneration and gentrification. This new form of economy based on culture, creativity, and knowledge makes cities unique avoiding standardization and by giving them authenticity, it turns them into globally competitive cities.

There is a lack of greater knowledge about patterns of urbanization and the types of urban areas over time and space. It is, however, known that the contemporary urbanization in both low/middle-income and high-income countries differs from the historical urbanization and coevolution of urban areas. The dynamics of the built environment and socio-institutional and natural systems show constraints and alternative opportunities not viewed in the earlier urbanization patterns. Nowadays, urban areas originate negative environmental consequences associated with carbon flows, energy demands, waste, air pollution, and noise pollution, loss of biodiversity. At the same time, since urban areas constitute the basic units for policies, they have environmentally beneficial consequences in three scales; global, local, and individual environmental behavior. Thus, rapid urbanization can accelerate a transition to sustainability due to agglomeration, increased innovation, and increased wealth, requiring suitable governance structures. The lack of a standardized definition for an urban area is challenging the scholars, shifting the focus from politico-administrative boundaries to physical or geomorphological boundaries, and leading to the need to rethink the sustainable urban development concept and practice towards an integrated planning and development process. The process can be achieved by integrating the systematic rational urban planning approach with ecosystem sustainability to increase the livability of urban areas and maintain the existence of urban ecosystems. One attempt to include ecological principles to urban planning is the regenerative urban metabolism systematic approach to conduct a quantitative analysis of human activities and land use. Also, the integration of people-centered and top-down approaches is required to enhance urban metabolism participation management when addressing urban sustainability transitions. People-centered approaches could be related to both urban metabolism management facets, via the participation within decentralized or inverse infrastructures management or contributing to leveraging behavioral changes in resources consumption. The urban metabolic facets are the *built facet*, which includes the physical infrastructures and the *intangible facet* meaning the services, resources, and flows of consumption.

The third cluster describes the evolution of the urban metabolism concept seeking a sustainable urbanized planet. In 2007 C. Kennedy, following Wolman´s work, updates urban metabolism as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste." The concept has been used from two different schools; the first one focuses on the energy equivalents (influenced by Odum's emergy method), and the second one tries to describe urban metabolism using a broader approach uttering the flows of water, materials, and nutrients as mass fluxes. Successive generations of urban metabolism are identified based on analytical methods. The earliest generation uses mainly Material Flow Analysis (MFA) measuring the material fluxes into the urban systems, the stocks and flows within the systems, and the resulting outcomes to other systems in the form of pollution, waste, or export products. The second urban metabolism generation uses the Energy method and the Ecological Footprint (EF), moving the focus beyond mass. The most recent urban metabolism generation couples urban metabolism with Life Cycle Assessment (LCA) with Integrated Urban Metabolism Analysis Tools (IUMATs). Integrated urban metabolism tries to simulate the inter-dependencies between the variables and subsystems of an urban region to compute the urban environmental performance. Since the first mention of urban metabolism in urban ecology history, the concept reveals six themes in context of interdisciplinary synergies: 1) the city as an ecosystem; 2) the material, and energy flows in the city; 3) the economic drivers of rural-urban relationships; 4) the material basis of the economy; 5) the reproduction of urban inequality and the re-signifying of the city via new socio-ecological relationships, and finally 6) the hybrid nature-socio-eco-politic urban metabolism of the last generation considers the dynamics of choice, time, and scale for the plan and design of sustainable urban areas.

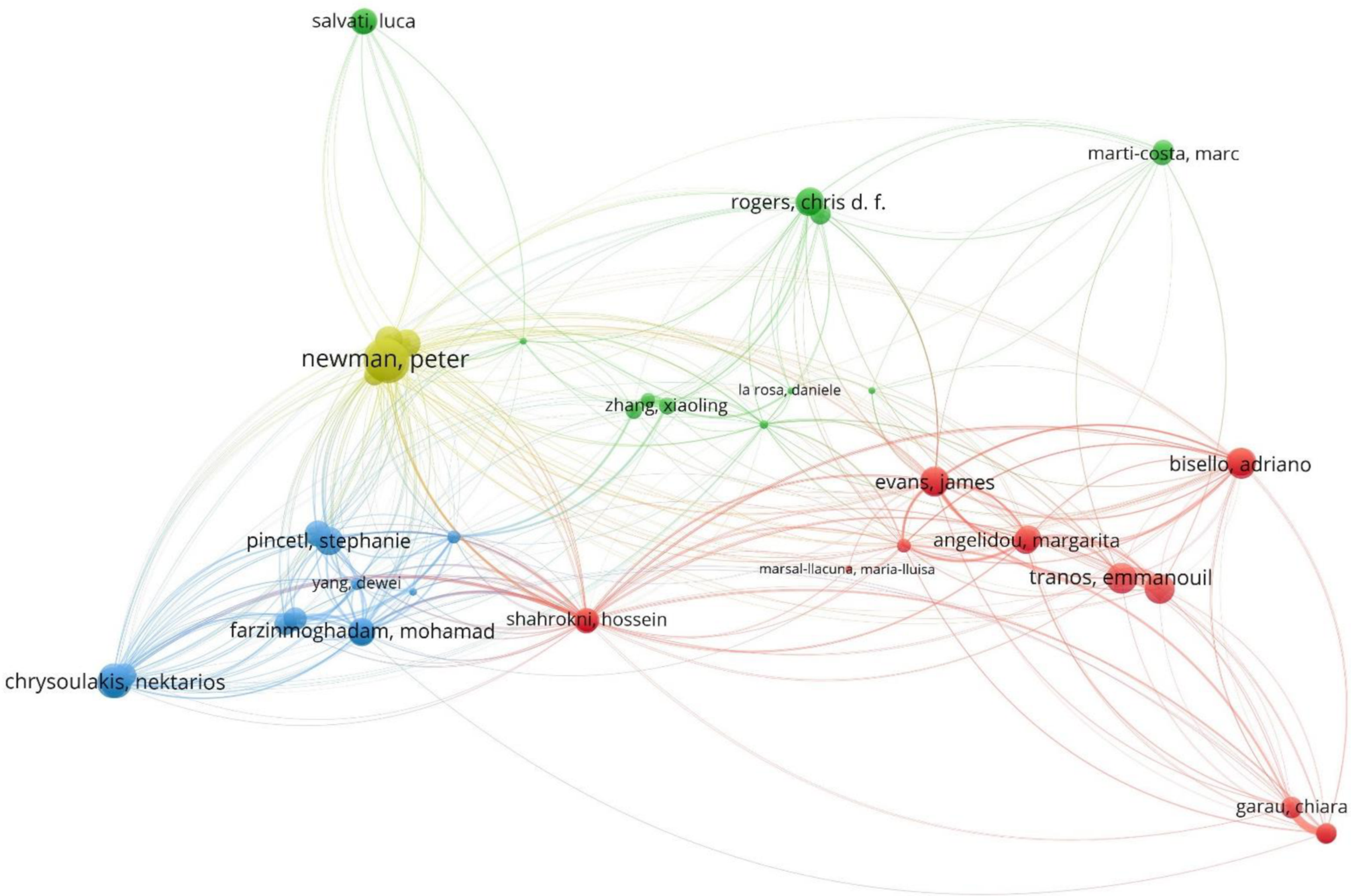
Cluster four examines the concept of smart and sustainable cities by looking at their similarities and differences, and the overall contribution of smart city concept to the goals of sustainable urban development to answer the main question if cities can be smart without being sustainable. The concept of "smart city" is a fuzzy concept that has been used since the 1990s with many definitions, all of them far from just the application of technologies to cities. There are two successive main parts of smart city literature. The first one focuses principally on the technical and environmental aspects of a city applying modern technologies in daily urban life for a better quality of life, decreasing the environmental impacts. The second part adds to that the variable of human capital in developing smart cities, "as a holistic understanding that smart cities bring together technology, government, and society." In other words, there is the (ICT)/technology-oriented approach and the people-oriented approach. The goal of sustainable urban development is to "achieve a balance between the development of the urban areas and protection of the environment with an eye to equity in income, employment, shelter, basic services, social infrastructure and transportation in the urban areas," to create healthy, livable, and prosperous human environments minimizing the demand of resources and the environmental impacts. Smart cities with a holistic understanding of the investment in human, social, and environmental capitals generate urban sustainability. Thus, cities cannot be truly smart if they are not sustainable, so the term "smart sustainable city" instead of smart city is suggested.

Cluster five highlights the need to include ecological processes to the analysis and assessment of urban systems under a sustainable urban development concept. Urban policy and planning must emphasize ecosystem functions and services to sustain biodiversity in urban landscapes. Tools and models such as urban metabolic models, land-use modeling, transportation models, and urban growth models can integrate both urban systems and ecosystems. Merging the concepts of "ecology in cities" and "ecology of cities" in combination with the ecosystem services framework, we as urbanites acknowledge the city as an ecosystem that depends on its surrounding landscape. In this way, human development is reconnecting to the biosphere and ecosystem services. The final step to establish sustainable future urbanization is to operationalize this knowledge of the socio-ecological interconnections, by translating the work of biodiversity into ecosystem services and the quantification of resilience. One good example of this reconnection is this of TEBEE that gives economic value to ecosystem services. Sustainability is an elastic concept that can be weak when it relies on technological fixes with little change of individual behaviors and lifestyle towards sustainability, and strong when changes are applied on the three dimensions of sustainability; economy, society and environment using advanced technologies. This new urbanism movement, focusing on the regeneration of the urban environment, converges with smart growth concept under the principle of sustainable development and branding cities as low-carbon, carbon-neutral, smart sustainable, smart eco-city, and ubiquitous eco-city (u-eco-city). Moreover, this new urbanism movement is now re-directing research to answering the following key-question: who is economically benefitting the most, if there is true e-democracy, true quality of life, if a city is treated as a whole, including citizens' voice in city planning and management.

Cluster six explores the regenerative design of urban areas using the urban metabolism framework. Urban metabolism framework quantifies the consumption of energy and materials and helps to compare the ecological footprint of this consumption. Furthermore, using the LCA method, it captures the hidden fluxes of energy and materials associated with the manufacturing of various products. Cities as complex social-ecological-technological systems require a holistic multi-scale approach of co-design and co-production of knowledge to support urban policy and development. This knowledge framework helps to understand how urban systems behave and evolve, how different urban fabrics and urban profiles determine the urban resource flows having different urban metabolisms. The next step is to apply this knowledge and to implement the methodology, by redesigning a city, in a regenerative way, to reduce its ecological footprint. A regenerative city environmentally enhances and restores the relationship between the cities and the natural systems they depend on. Urban regeneration based on decentralized energy systems allows mixing different renewable systems for energy generation and supply. Moreover, it offers new lifestyle choices and economic opportunities, which lead to long-term community involvement in this transformation process. Thus, the regenerative urban metabolism framework offers solutions to megatrends such as climate change through energy use reduction, resource scarcity through efficient material use, biodiversity loss, and urban encroachment on rural areas through compact city footprints.

From the third analysis, we created a map of 49 bibliographic coupled authors grouped in four clusters (Figure 6a). In this map, we can see which authors have stronger bibliographic coupling links between each other. By looking at the size variation of the links (thinker the line of the link stronger connection between authors) and at the size variation of the nodes we can see which authors have the total stronger bibliographic coupling links in the literature network. In this way, we detect which authors share similar ideas and or influence each other. The top five stronger connected authors per cluster are mentioned in Table 5. Looking at Table A1, the articles found in dataset understudy and combining this with the knowledge obtained from previous analyses, we conclude that authors in the first cluster share ideas based on the sub-research trends present in cluster 1 and 4 of our second analysis (Table 4), authors in the second cluster study sub-research trends found in cluster 1 and 5 (Table 4), the work of authors in the third cluster is based on cluster 3 of the second analysis (Table 4) and authors in the fourth cluster study the main topics found on cluster 2 and 6 in the second analysis (Table 4).

(a)


salvati, luca
marti-costa, marc
rogers, chris d. f.
newman, peter
la rosa, daniele
zhang, xiaoling
bisello, adriano
evans, james
pincetl, stephanie
angelidou, margarita
marsal-llacuna, maria-lluisa
tranos, emmanouil
yang, dewei
shahrokni, hossein
farzinmoghadam, mohamad
chrysoulakis, nektarios
garau, chiara

(b)

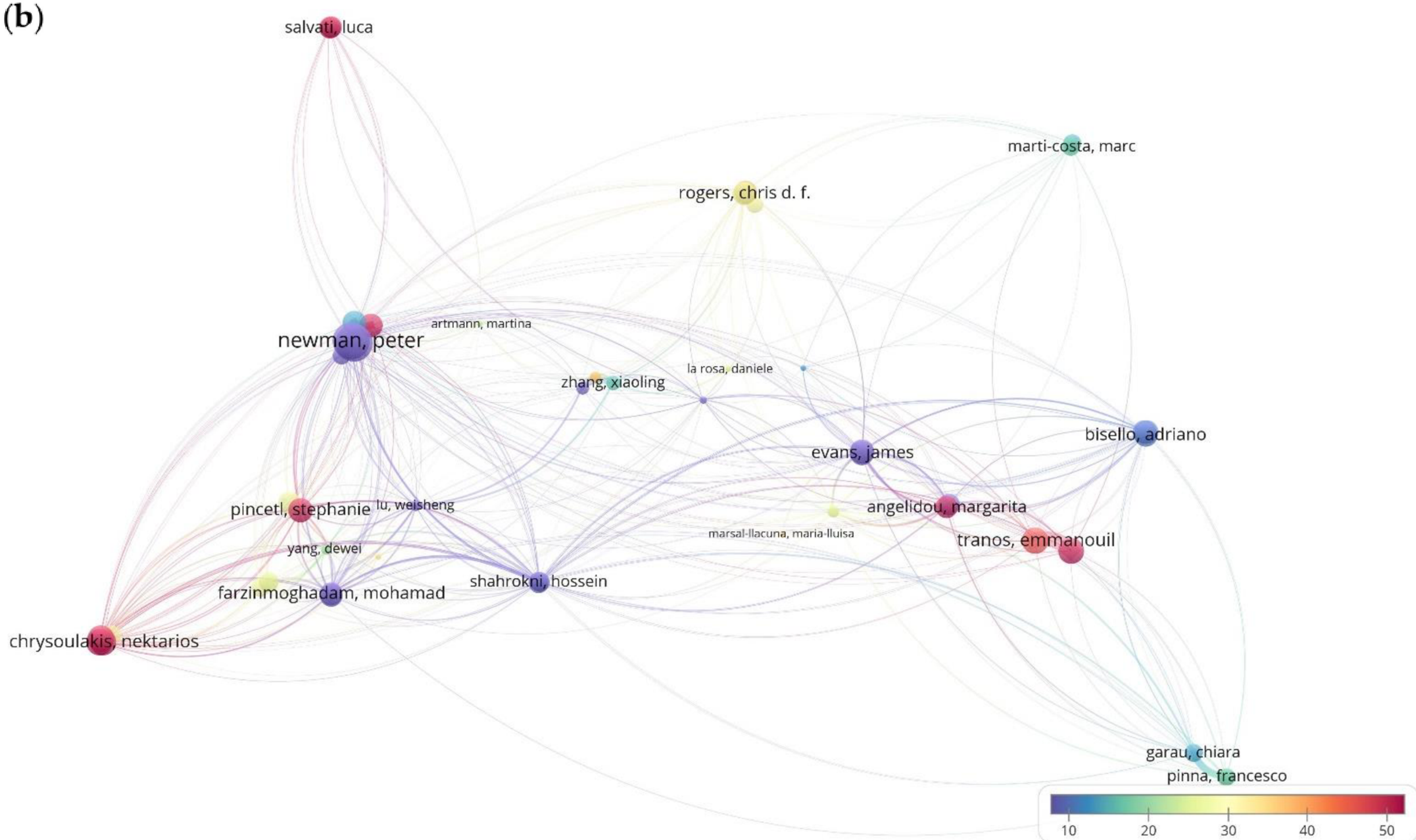


Figure 6. (**a**). Map of bibliographic coupling analysis based on authors (weights on the total link strength) (**b**). Map of bibliographic coupling analysis based on authors with the weight on the number of documents and indicating the number of average citations.

Table 5. Most connected authors per infometric cluster.

	Link Strength	Most connected Authors
CLUSTER 1 (17 Items)	151.35	Tranos Emmanouil, Nijkamp Peter
	118.58	Evans James, Karvonen Andrew
	99.80	De Falco Stefano, Angelidou Margarita
	66.86	Mosannenzadeh Farnaz, Bisello Adriano, Vettorato Daniele
	40.91	Lazarevic David, Brandt Nils, Shahrokni Hossein
CLUSTER 2 (14 Items)	118.20	Carlucci Margherita, Salvatti Luca
	90.77	Lombardi Rachel, Rogers Chris D. F.
	88.53	Pares Marc, Marti-Costa Marc
	40.23	Porter Libby, Rogers Chris D. F.
	39.90	Porter Libby, Lombardi Rachel
CLUSTER 3 (13 Items)	107.80	Chester Mikhail, Pincetl Stephanie
	99.64	Farzinmoghadam Mohamad, Mostafavi Nariman
	77.82	Zhang Yan, Liu Gengyuan
	61.44	Lopes Myriam, Chrysoulakis Nektarios, Gonzalez Ainhoa
	32.60	Spano Donatella, Lopes Myriam, Gonzalez Ainhoa, Chrysoulakis Nektarios
CLUSTER 4 (40 Items)	142.43	Thomson Giles, Newman Peter
	44.36	Newton Peter, Thomson Giles
	44.36	Newton Peter, Newman Peter
	43.61	Moglia Mangus, Thomson Giles
	43.61	Moglia Mangus, Newman Peter

In Figure 6b, the color variation of the nodes of the network shows the average citation of each author under bibliographic coupling analysis. The average citation and the total link strength for each author are found in Table A2, Appendix A. We see the top five authors with the greatest number of average citations for cluster 1 are *Nikjamp Peter* (309.0), *Angelidou Margarita* (62.50), *Tranos Emmanuil* (45.00), *Maria Luis* (34.50), and *Yigitcanlar Tan* (27.00). In the second cluster the authors *Carlucci Margherita* (54.50), *Salvati Luca* (54.50), *Lombardi D. Rachel* (37.00), and *Wang Rusong* (36.50) are the five top authors with the greatest number of average citations, in the third cluster, these authors are *Pincetl Stephanie* (51.67), *Chrusoulakis Nektarios* (50.00), *Lopes Myriam* (50.00), *Rosado Leonardo* (33.00), and *Spano Donatella*

(31.50), and in the four cluster the authors *Moglia Mangus* (68.50), *Newton Peter* (15.00), *Davoudi Simin* (7.00), *Newman Peter* (15.00), and *Thomson Giles* (6.33).

In our last analysis, we constructed the co-citation map of the 117 connected cited references of our data set, grouped in four clusters (Figure 7). On this map, we can identify the connections-links of the cited references that have been cited jointly by another document, which allow us to infer about the relativeness importance of the document, i.e., the more cited, the higher the importance of the document. In this analysis the strength of the links (weights) represents the number of citations made to the cited reference of each node. In Table 6, we can see the top five cited references per cluster, their links with other cited references of our data set, and their number of citations. Knowing the most influential cited references of the documents under review per infometric cluster, we can detect which authors have been influenced by whom and how specific concepts have been formed and evolved over the years. We can also go back to study the original ideas and draw a concept evolution timeline.

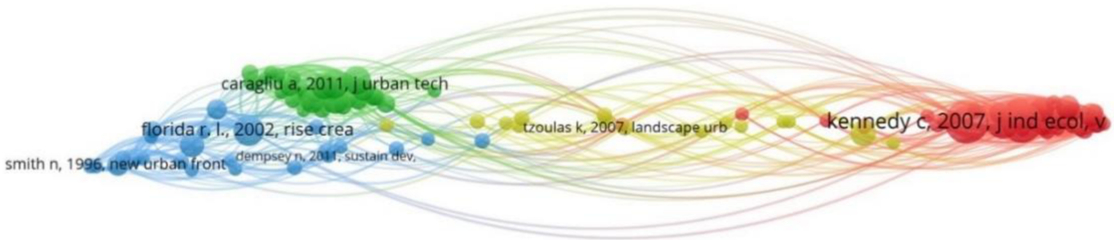


Figure 7. Map of co-citation analysis based on cited references.

Table 6. Important cited references under co-citation links per infometric cluster.

	No. Cit.	No. Links	Important Cited References
CLUSTER 1 (43 Items)	29	63	Kennedy, C.A., Cuddihy, J., Engel Yan, J., 2007. The changing metabolism of cities. Journal of Industrial Ecology 2007 (11), 43-59
	26	53	Wolman, A., 1965. The metabolism of cities. Scientific American 213 (3), 179-190
	20	55	Newman, P.W.G., Birrell, R., Holmes, D., Mathers, C., Newton, P., Oakley, G., O'Connor, A., Walker, B., Spessa, A., Tait, D., 1996. Human settlements. In: Australian State of the Environment Report. Department of Environment, Sport and Territories, Canberra, Australia.
	18	51	Kennedy, C., P. Pincetl, and P. Bunje. 2011. The study of urban metabolism and its applications to urban planning and design. Environmental Pollution 159(8–9): 1965–1973.
	12	46	Niza, S., L. Rosado, and P. Ferrao. 2009. Urban metabolism: Methodological advances in urban material flow accounting based on the Lisbon case. Journal of Industrial Ecology 13(3): 384–405.
CLUSTER 2 (34 Items)	15	58	Hollands, R.G., 2008. "Will the Real Smart City Please Stand Up?" City: Analysis of Urban Trends, Culture, Theory, Policy, Action 12: 3, 303–320.
	15	57	Caragliu, A., Del Bo, C., & Nijkamp, P. (2009). Smart cities in Europe, series research memoranda 0048. VU University Amsterdam, Faculty of Economics, Business Administration and Econometrics.
	14	51	Giffinger, R., Fertner, Ch, Kramar, H., Kalasek, R., Pichler-Milanovic, N., et al. (2007). Smart cities-ranking of European medium-sized cities. Centre of Regional Science (SRF), Vienna University of Technology.

	13	49	Vanolo, A. (2014). Smart mentality: The smart city as a disciplinary strategy. Urban Studies, 51, 883–898.
	11	46	Neirotti, P., De Marco, A., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in smart city initiatives: Some stylized facts. Cities, 38, 25–36.
CLUSTER 3 (24 Items)	17	33	Florida, R. (2002) The rise of the creative class. Basic Books, New York.
	12	26	Harvey D (1989) From managerialism to entrepreneurialism: The transformation in urban governance in late capitalism. Geografiska Annaler: Series B, Human Geography 71(1): 3–17.
	10	13	Smith, Neil (1996). The new urban frontier. Gentrification and the revanchist city. London: Routledge.
	9	35	Florida, R (2005). Cities and the Creative Class. Routledge, New York.
	7	17	Peck, J (2005) Struggling with the creative class. International Journal of Regional Research 29(4), 740–770.
CLUSTER 4 (16 Items)	13	35	Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., et al. (2008). Global change and the ecology of cities. Science, 756–760.
	7	16	Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., & James, P. (2007). Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landscape and Urban Planning, 81(3), 167–178.
	6	37	Campbell, S. (1996). Green cities, growing cities, just cities? Urban planning and the contradiction of sustainable development. Journal of the American Planning Association, 62, 296–312.

2.4 Discussion

2.4.1. Discussion and limitations of methodology

The novelty of the proposed methodology of literature network analysis in comparison with the traditional way of conducting a literature review is the fact that it is using bibliographic metrics. Therefore, we can distinguish that this analysis has a threefold objective. Firstly, it is pedagogical. Secondly, it eliminates the uncertainty of a randomly casual literature review and reduces complexity by mitigating all the noise of the big volume of data accessible through the internet. Thirdly, it is methodological, thus it provides a literature review with coherence and a scientific protocol to acquire oriented-knowledge. The undertaken literature network analysis is detailed and descriptive, discussing the planning stages and explaining the operational steps of the literature review. Finally, the obtained results are illustrated through tables and distance maps, providing insights for scholars who are beginning their research on the topic avoiding an initial random search.

It is essential to clarify that these bibliographic networks show the relatedness of the items under study based on how strong the links that they share are. In bibliographic coupling networks, links exist between items that cite the same document, in co-citation between items that they have been cited by the same document, in co-occurrence networks regarding the number of documents in which they occur together. Thus, from a technical point of view, this method demonstrates effectiveness. Nevertheless, limitations are stemming from the interpretation of these networks in the cluster analysis stage. For instance, in case of co-occurrence networks, keywords can occur together in more that one paper having different meanings and thus generating misleading bibliographic networks. In bibliographic coupling networks, two items can cite the same document but expressing disagreement about the topic under study. In order to diminish these issues in the network analysis, we carefully selected the initial literature dataset based on multiple group discussions by experts. Other limitations arise from the methods applied to conduct network analysis. As mentioned in a previous subchapter, there are two counting methods, the full and fractional counting methods. A researcher has to be aware of the limitations arising from the different methods applied in various networks. For instance, using fractional counting method, highly cited articles that have a smaller influence on the construction of bibliographic coupling networks and articles with many references like review articles, have a less important role in the construction of co-citation networks. Articles with many authors have the same weight with articles with less authors in the construction of co-authorship networks [25,26]. We used fractional counting method when we wanted to give equal importance to the items under network analysis. Despite the identified limitations, it is our understanding that literature network analysis provides a faster rate of discovery, more accurate and more in-depth insights than other literature review methods we have known and experimented with until now.

2.4.2 Discussion of Results

A general observation from all the different types of bibliometric analysis we conducted here is that the number of citations cannot be taken as the main driver to show the importance of an item without taking into consideration the total link strength of the item; meaning the degree of connection with the rest of the items in the dataset under analysis. For instance, comparing the two maps (Figure 5 a,b), we see that documents with an extremely high number of citations are not the best connected to the rest of the documents of the data set, and therefore they are not the most related to the topic of analysis. Looking at the links of the items of all our bibliometric analysis, we observe that the links between the concepts of smart and regenerative metabolic urban growth do not appear to be strong, or appear to be absent. As an example, shown in Figure 8, we have made a selection of the keywords of our interest *smart city*, *urban metabolism*, and *urban regeneration*, and can clearly see that they are not connected.

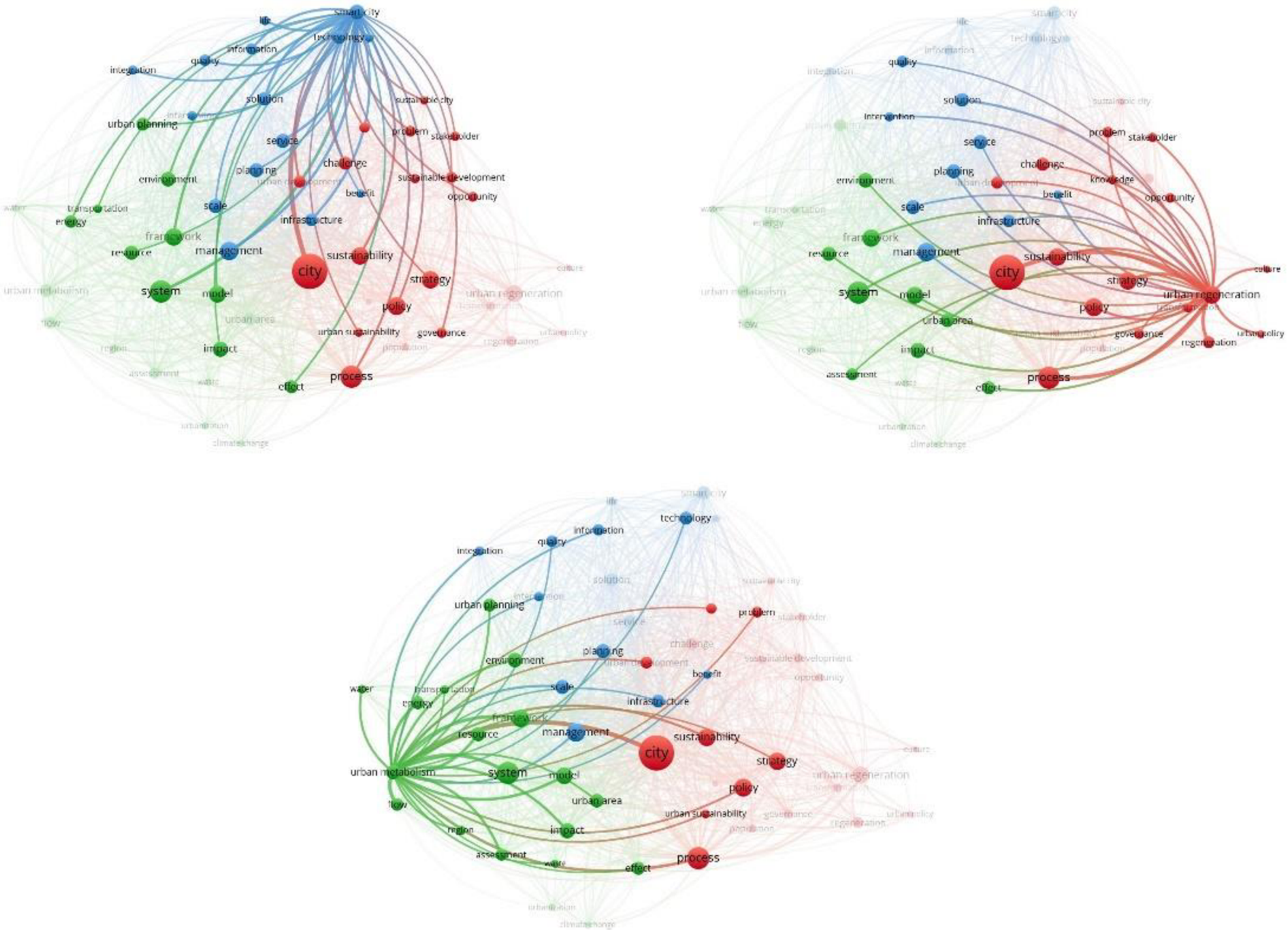


Figure 8. Links between main keywords under co-occurrence analysis.

We obtain the same image when looking closely at the links in our second analysis of the bibliographic coupling of documents (Figure 5a). In Figure 9, we have selected one representative document of each concept smart city; Ahvenniemi et al. (2017), urban metabolism; Dempsey et al. (2012), urban regeneration; Kennedy et al. (2011) to make this statement better understood.

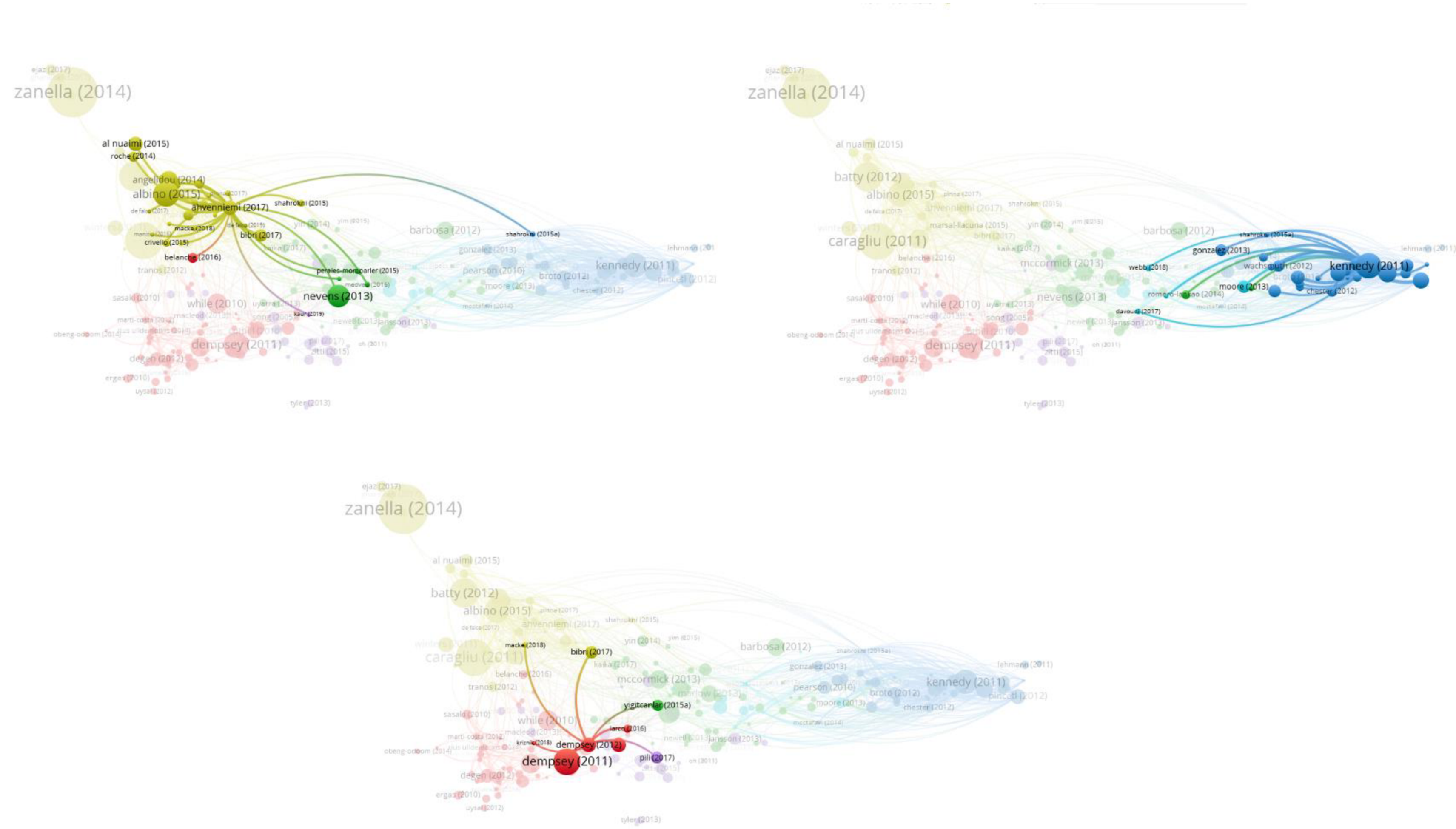


Figure 9. Links between main concepts under bibliographic coupling analysis based on documents.

2.5 Conclusions

In this study, we conducted a literature network analysis to review the concept of urban growth under metabolic framework focusing on smart and regenerative urban design within the last ten years. Using VOSviewer we constructed network maps that helped us detect relatedness of concepts, documents, main referenced works, and top influencers authors along with tip-top cutting-edge research upon the topic. Initially, we indicated three main research trends related to urban growth (see results of analysis 1) and going one step further, we were able to identify six key sub-research trends (see results of analysis 2) and their relatedness. We detected the most influencer authors within our dataset per sub-concept (see results of analysis 3) (Figure 10), and finally, we tracked the origins of these key sub-research trends related to the urban growth concept under analysis (see results analysis 4). The overall findings showed that urban growth research is simultaneously multidisciplinary and interdisciplinary integrating social, ecological, politic, economic sciences, culture, and arts, environmental, and computer sciences. We identified a lack of connectedness between smart and regenerative concepts for urban growth. Therefore, this provides scientific evidence that in order to adopt a holistic approach allowing future cities to tackle challenges related to unbalanced urbanization-economy-environment dynamics, and to provide a better life quality and wellbeing, we need to turn the research focus on building this link between the fields of smart and regenerative urban studies. We have already started to conceptualize the framework of smart and regenerative urban growth in post anthropocentric urbanism.

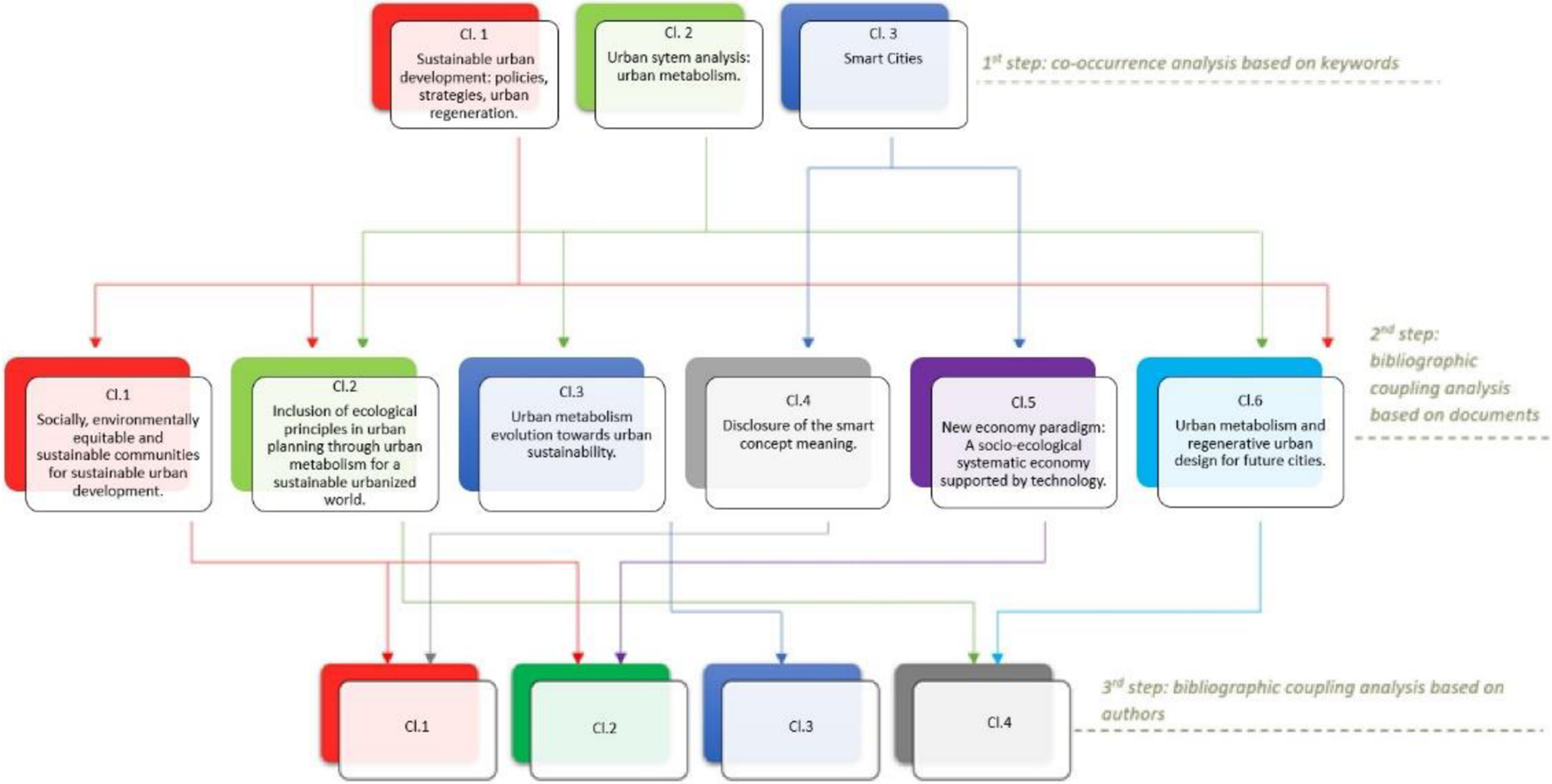


Figure 10. Map of cascade relations among the bibliometric clusters.

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Chapter 3

Based on: Peponi, A., & Morgado, P. (2020).
Transition to Smart and Regenerative Urban Places (SRUP):
Contributions to a New Conceptual Framework. Land, 10(1), 2.

3. Transition to Smart and Regenerative Urban Places (SRUP): Contributions to a New Conceptual Framework

Modern urbanism is called to face current challenges ranging from intensive demographic growth, economic and social stagnation to resources salvation and climate changes. Under the broader scope of sustainability, we argue that the transition to a holistic perspective of smart and regenerative planning and design is the way to face and yet to prevent these urban challenges. In doing so, we adopt systematic thinking to study the complexity of urban metabolisms at an urban place scale, emphasizing the ongoing coevolution of social-cultural-technological and ecological processes. Focusing on urban places, we give a city or region the sense of a place of stability, security, cultural and social interactions, and a sense of uniqueness. We plan and design innovative urban places that improve the environment and the quality of urban life, able to adapt and mitigate climate changes and natural hazards, leverage community spirit, and power a green-based economy. Designing the conceptual framework of smart and regenerative urban places we contribute to the field of modern urban studies helping practitioners, policymakers, and decision-makers to vision and adopt more environmental-friendly policies and actions using a user-centered approach.

3.1 Introduction

A city is an open system with interactions within the region and beyond, driven by endogenous and exogenous factors acting either short term or long term. Apart from factors like population growth and demographic changes the modern urbanization is essentially shaped by the impact of the international capital, the change to a new urban governance and institutional structures as well as by agglomeration forces [1]. These drivers stimulate changes in the scale, rate, location, form, and function of urbanization [1], generating spatial and temporal heterogeneity of social, biophysical and physical patterns and processes associated with physical, financial/economic, natural, human and social urban assets or resources [2].

Cities are expanding as urbanization is growing, and as McMahon affirmed, "*growth is inevitable, and desirable, but destruction of community character is not*" [3]. People, the social tissue, represent the social system that makes a city. Thus, cities are made by and for people, and the main goal should be to be fun and vibrant and make people happy [4,5]. Following MacMahon's idea of community, we second Batty, (2018) [6] in his statement that we need to think of cities "*as places where people come together to interact with one another*" and with the surrounding environment. In line with Tuan, (1977) we adopt the notion of a place as "*an image of complex often ambivalent feelings (…), security and stability (…), a center of value built to satisfy particular needs (…), an organized world of meaning*" [7]. Mang and Reed, (2012) define urban places as "*unique, multi-layered network of living systems within a geographic region that results from the complex interactions, through time, of the natural ecology and culture*" [8]. In our work, we use the urban place as the scale for our study to highlighting the need to plan and design safe, secure cities with unique identities. Combined with the systematic approach we study urban systems' structure, functions and interactions, highlighting their complexity and proposing a novel way to tackle the impacts of modern urbanization.

A more defined mention of the Urban Systems concept can be found in Central Place Theory (CPT), developed by Christaller in 1933 and Lösch in 1940 [9]. In short, CPT attempts to explain space arrangement, size, and distribution of settlements/towns in the belief that there is some sort of order principle governing the distribution [10]. In the 1950s, the concept of urban systems started to be formed by applying the general system theory and cybernetics to soft social sciences. Main contributors to this growing interdisciplinary field of studies, supporting the idea that phenomena of interest in various disciples can be articulated as systems, were Ludwig von Bertalanffy in biology and Norbert Weiner in engineering [11]. Different parts and elements structure a system, and through their interactions, the system functions are generated to maintain the system working. Within the general system, negative feedback occurs when the system functions reinforce the equilibrium structure to keep the systems resilient and sustainable over time [12,13]. While general systems tend to be structurally static, ordered hierarchically (systems parts, elements), and existing in equilibrium to be optimum functional, most systems, indeed biological and human systems, are subject to positive feedback [12]. When a disturbance continues to force the system to move away from its earlier state, positive feedback pushes the system dynamics leading it to an entirely new state in contrast with the negative feedback, which brings the system to its pre-disturbance state [13].

By the mid-1970s, system theory applied in cities and city planning has appeared lifeless and the complexity science concept started to be developed gradually [12]. According to Wilson, (2000), Warren Weaver, (1948, 1958) first distinguished simple (or general) systems as these that require a small number of variables to describe them and complex systems that require a large number of variables. Weaver further subdivided complex systems into those of disorganized complexity and those of organized complexity [14]. Before the 1960s, the available tools for quantitative analysis were limiting scientists to involve linear approximation in their analysis. Later, in the mid-1990s, we witnessed the emergence of an interdisciplinary science-based approach and analogies coming from philosophies of sciences, along with the ubiquity of computational capability in all scientific branches, which led to what became known as nonlinear dynamics methods. In favor of the nonlinear dynamics approach lies the notion that optimizing and defining a system through design, management, and control is suitable for solving human problems [12,13].

Based on the literature, salient concepts in urban complexity have appeared, namely: emergence systems; self-organization; non-linearity; evolutionary dynamics; adaptive behavior; and hierarchical ordering properties [15]. Among the various existing methods to explore and analyze urban complexity are the application of agent-based models, cellular automata, graph theory, fractal theory, spatial network analysis, urban scaling, and Bayesian belief networks [16,17]. These methods describe the urban complexity adopting urban form perspectives to study urban pattern changes, focusing on an urban subsystem component. The fact that a city cannot exist in isolation but only as part of a system of cities, and the elements of the city's urban systems exist only through their interactions, make the urban systems complex [18,19]. Thus, to fully understand and prepare the next generation of cities, we need to re-think cities on an inter-disciplinarily base and to launch a debate framed by this new challenging-context of global urbanization, urban sprawl, networked cities [20].

In this chapter we are proposing a new conceptual framework for an integrated and expanded systematic analysis of urban places under an urban metabolism perspective, a changing paradigm of urban planning and design to face urban complexity challenges. Moving from the mechanistic approach that has been used for more than half a century in urban planning, we adopt the urban metabolism approach to capture holistically the positive feedback of nonlinear system dynamics. Peponi and Morgado, (2020) conducting a systematic extensive literature review, have recently proven that smart and regenerative urban growth concepts have been approached separately [21]. This chapter intends to demonstrate that by integrating them, we improve people's quality of life and public health in urban places through a more holistic and interdisciplinary urban planning and design.

This third chapter is organized as follows: After this introduction, Subchapter 3.2 presents the synthesis of our novel conceptual framework.

Starting with Subchapter 3.2.1, we present urban places as metabolic complex systems applying the urban metabolism approach to our framework. We then demonstrate in Subchapter 3.2.2 urban places as smart complex systems in line with the smart city concept, followed by Subchapter 3.2.3, which represents urban places as regenerative complex systems in line with regenerative design of circular metabolisms. In Subchapter 3.3, we integrate our key concepts into a new holistic conceptual framework adopting a systematic and metabolic thinking. Subchapter 3.4 unfolds the main challenges related to the framework's implementation and Subchapter 3.5 draws the conclusions upon it.

3.2 Conceptualizing a Smart-Regenerative Framework for Urban Complex Places

Nowadays, it is essential to adopt a different way to plan and design urban systems' complexity to tackle the current urban challenges, accepting that urban systems are dynamic and evolving out off-equilibrium. Through a systematic review of the literature based on bibliometric network analysis, Peponi and Morgado, (2020) have identified that there is an absence of conceptual continuity between smart and regenerative urban growth/ development. Here, we attempt to synthesize these separate strands of literature into a novel holistic and integrated conceptual framework adopting an urban metabolism systems-based approach. In this way, we contribute to planning and designing future urban places bridging the environment and people, tackling pressures on resources, and being resilient to social-economic and environmental challenges.

In line with Jabareen, (2009) we perceive a conceptual framework as a network of linked concepts where each concept has an integral role instead of just been a collection of concepts [22]. We use a two-fold methodology based on grounded theory to conduct our conceptual framework. In the first part of our conceptual analysis, we demonstrate each pillar concept's unique characteristics, functions, and contributions to face the current urban challenges. In the second part, we integrate these concepts into one new conceptual framework pinpointing their node-bridge and analyzing the interplay among their components. The methodology we followed for building the smart and regenerative urban places (SRUP) conceptual framework is depicted in Figure 1.

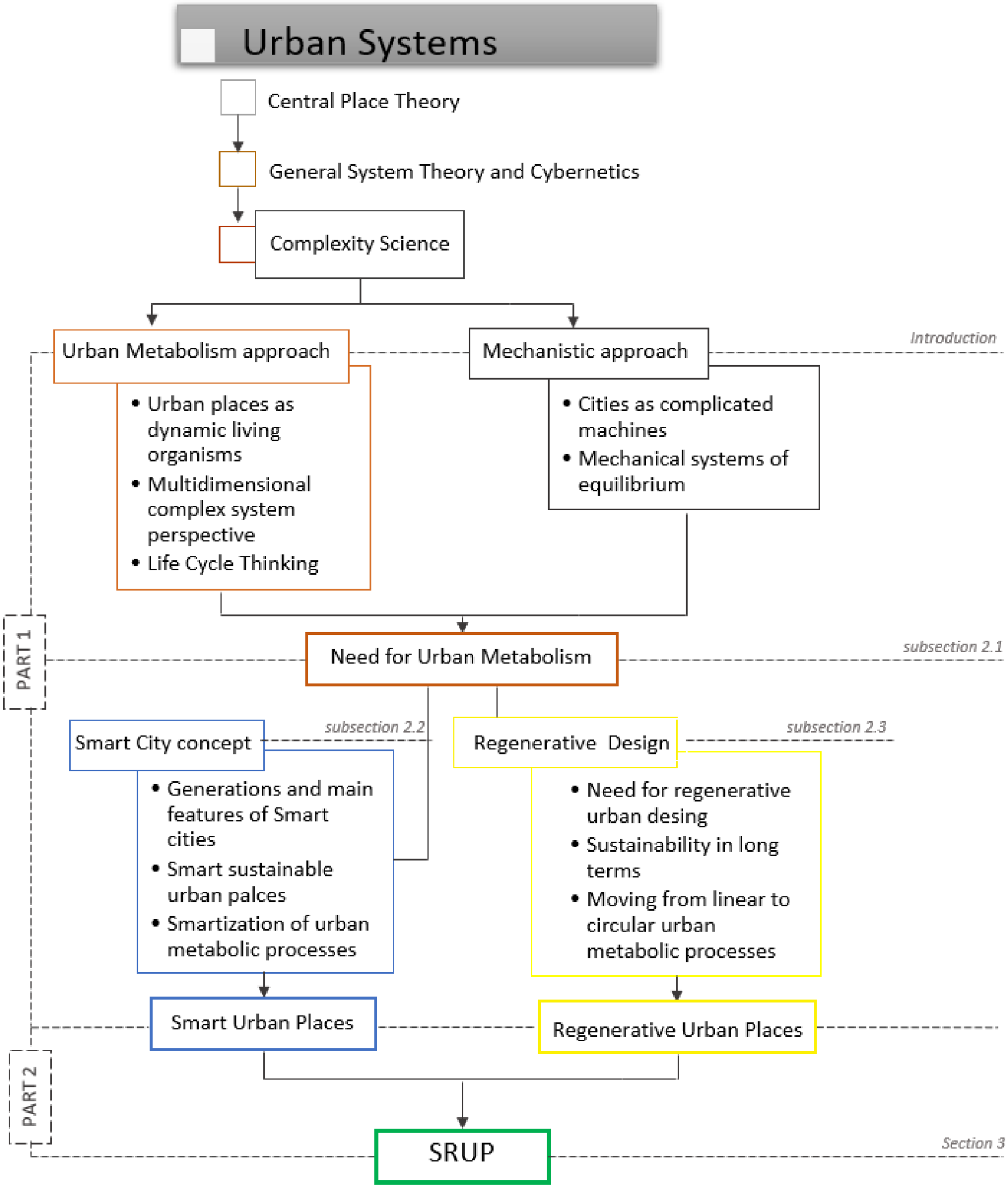

Figure 1. Conceptual framework analysis of Smart and Regenerative Urban Places (SRUP).

3.2.1 Urban Places as Metabolic Complex Systems

In this subchapter, we define urban places as metabolic complex systems, and we explain why adopting the urban metabolism approach in our conceptual analysis is essential to tackle current urban challenges. Starting to unfold the characteristic of urban metabolic systems, we conduct a comparative analysis of how the concept of urban metabolism has been used to support urban sustainability over time in relation to other disciplines.

The metaphor of metabolism is used to liken a city as a *living organism*. The first mention of the term metabolism in that way (*Stoffwechsel*) was made by Karl Marx in 1883, as "a process between man and nature, a process by which man, through his own actions, mediates, regulates and controls the metabolism between himself and nature". He observed an "irreparable rift" caused by capitalistic production and the city's antagonistic division and rural area. Thus, it is essential to "govern the human metabolism with nature in a rational way" [23]. The Chicago School of Sociology in the 1920s–1930s uses ecology metaphors best known through the works of Park, Burgess, and McKenzie. Metaphors such as "physical growth", cities having "metabolism, pulse, a heart, erogenous zones", ecological theoretical concepts such as succession, symbiosis, competition, and adaptation, have been used to explain the urban expansion from the city center to suburbs. This expansion forms concentric circles, analyzing the spatial distribution of different social groups as "invasion-succession cycles" [24,25].

In 1965s, Wolman, in his work "*The Metabolism of Cities*," first conceived the concept of urban metabolism to support cities' sustainable development. A city is a closed system that converts inputs to outputs, or in other words, metabolizes resources to waste [25,26]. After this, the term has been used from two different schools. The first focuses on the energy equivalents, and the second attempts to describe urban metabolism under a broader approach expressing the flows of water, materials, and nutrients as mass fluxes [27]. In 2007 Kennedy, following Wolman's work, updates urban metabolism as *"the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste"* [27].

The urban metabolism approach is found in the literature in relation to the three successive ecologies. Newell and Cousins, (2015) analyzed the emergence of the industrial ecology, the Marxist ecologies, and the urban ecology as the thought traditions of urban metabolism [28]. The industrial ecology accepts Kennedy's definition of urban metabolism. It provides methods such as material flow analysis (MFA), ecological footprint (EF), emergy based accounting (EMA) and more recently life cycle assessment (LCA), to assess the stocks and flows of materials and energy within and beyond the city. Marxist ecologies conceive urban metabolism as a mix of socionatures that produce and reproduce uneven outcomes. Urban ecology theorizes urban metabolism as a complex socio-ecological system providing the theory to investigate urban space's ecological and biophysical properties in nature-society construction (the urban political ecology metabolism).

Similarly, Wachsmuth, (2012) interprets the three ecologies as successive periods of urban metabolism [25]. The first one is the human ecology of the Chicago school, which treats the city as an ecosystem analogous to external natural ecosystems, and urban metabolism is conceptualized as a process of social change in the interior of the city. The second one is the industrial ecology, which following Wolman's concept, places society in the city but considers nature merely in a take-and-dispose of scheme-receiving raw inputs and disposing of social wastes. The third era is the urban political ecology. Political ecology is a mixture of the two previous approaches, and the city is conceptualized as an amalgam of socio-natural flows.

We understand an urban place as a "living" organism where interdisciplinary synergies between social-cultural-ecological-technological systems are responsible for the flows and stocks of energy, materials, and information within it and beyond it. Moving the focus beyond mass balance we couple life cycle thinking (LCT) to the multidimensional metabolism of an urban place to consider the direct and indirect impacts of the urban processes. Opposed to the mechanistic vision of cities as mechanical systems that exist in permanent equilibrium to be optimum functional, urban metabolism captures the dynamics, the dialect and flows of all cities' components. The mechanistic approach treats cities as complicated machines that need to be tested, calibrated, and approved through all processes and by analyzed piece by piece. This approach does not allow self-organization and the emergence of spontaneous formation of distinctive spatial and temporal or functional structures from the interaction of many small parts of the city [29]. Therefore, key features of any complex system, such as biological living systems, are not included in the analysis.

We argue that shifting from viewing a city as a system in permanent equilibrium to a complex metabolic system driven from the bottom-up, continually out-of-equilibrium, have strong implications on how we see cities, on our deep understanding on how they function and on their dynamics over time and space, and therefore enable our ability to plan and design better cities. Even though the systems of urban places they are not organic by nature, treating them as such we give a new perspective to the science of cities tracing all nonlinear urban dynamics and relating them to urban problems. Therefore, urban metabolism offers methodologies to support sustainable urban development. We focus on developing a smart and regenerative way to re-plan and re-design the urban metabolisms of the different urban fabrics and profiles of an urban place, making it more natural-human oriented.

3.2.2. Urban Places as Smart Complex Systems

The uncontrolled and rapid urban growth generates various types of challenges as traffic jams, environmental pollution, wasteful energy consumption, safety, security and healthcare issues, and inefficient waste management. Many authors have studied the concept of smart city since the 1990s as a possible remedy to tackle these urban challenges enabling a sustainable and liveable urban future. The smart city concept's lifecycle appears to have passed through three generations. The first generation includes smart cities totally technology driven by private sector technology companies that offer their solutions to improve citizens' quality of life. The second generation was smart cities governmentled using information and communications technology (ICT) for smart governance, a decision- support tool, and a more resource efficiency management. The last and more recent generation includes smart cities, people-centered or citizen co-creation cities that embrace citizen participation through all the decision processes, enabling citizens as sensors, public participation, and volunteer geographic information.

In our conceptual framework, we apply the concept of smart city-user driven to urban systems' metabolism at the urban place-scale, which means that we support all the metabolic processes of an urban place using technology to identify its users' real needs. By applying urban smartness to the complex urban metabolisms' dynamics, we support holistic and sustainable urban growth. Starting the smartization of urban metabolic systems, we provide the most cited definitions of the smart city concept to present and highlight the main features of urban smartness. Thereafter, we relate urban smartness to urban sustainability, and last, we demonstrate how sustainable smart urban metabolism allows us to tackle urban challenges.

Ahvenniemi et al., (2017) state that there are two consecutive main smart city literature strands. The first strand discusses mainly how modern technologies in daily urban systems contribute to a better quality of life, reducing environmental impacts. The second strand adds the human capital to the technical and environmental aspects of a city. A smart city is developed based on "*a holistic understanding that smart cities bring together technology, government, and society*" [30]. Harrison et al., (2010) define a smart city as an "*instrumented, interconnected, and intelligent*" city. A smart city is instrumented because it uses various appliances (sensors, meters, surveillance cameras) to capture and integrate real-life data. It is also interconnected because it integrates this acquired information into a platform that allows access to multiple services. Ultimately, a smart city is intelligent because it includes complex analytics, modeling, optimization, and visualization services for better operational decisions [31]. Caragliou et al., (2011) as the most cited work applied to the second part of smart cities literature, define a city as smart "*when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and high quality of life, with a wise management of natural resources, through participatory governance*" [32]. Angelidou, (2014) provides a first and clear view on the strategic choices that should be considered when mapping out a smart city strategy using the definition "smart cities are all urban settlements that make a conscious effort to capitalize on the new information and communications technology (ICT) landscape in a strategic way, seeking to achieve prosperity, effectiveness, and competitiveness on multiple socio-economic levels" [33]. Zanella et al., (2014) mention that a smart city aims to make better use of the public resources, increasing the quality of the services offered to the citizens while reducing the public administrations' operational costs [34].

Summarizing the key attributes of the aforementioned smart city definitions, we perceive the smart city concept as the coupling of government, society, and the strategic investing in technology and ICT, resulting in socio-economic growth. A smart city is prosperous, competitive, and effective, establishing prudent management of resources and high-quality user services. We can say that overall, the smart city literature examines the relationship between the concepts of smart city and sustainability [35–37]. After conducting a bibliographic coupling analysis on the infometric cluster of literature that links the smart city concept and sustainability, Peponi and Morgado, (2020) highlight that, a city to be truly smart, it must be sustainable as well through all three pillars of sustainability. The three pillars of sustainability; economy, society, and environment has been conceptualized as three successive sustainable development models (Figure 2). In the first model, the three pillars exist independently, as three interlocking rings, where sustainability is placed at their intersection. Human society is separate from the environment implying the reliance on technological fixes to address sustainability issues. The second model of the three nested rings (or Russian doll model) places the economy at the center as a social construct contained within society. The natural environment is the outermost ring since it provides the life support systems for surviving. The last model of the dual nested rings removes the unnecessary separation between human economy and human society. In this way, human society's dependency (including its economic activities) on the environment is recognized and taken into account, leading to a more integrating approach to analyze the dimensions of sustainability [38].

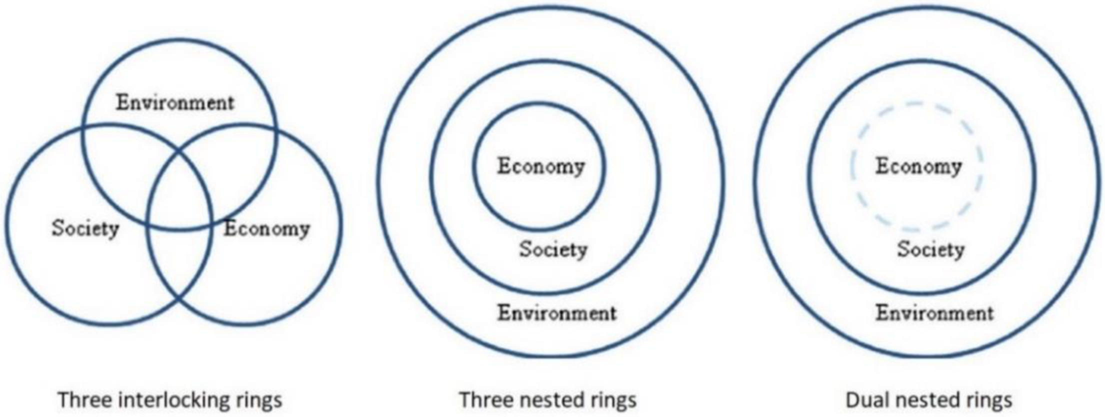

Figure 2. Conceptualizations of sustainable development [38].

Designing, planning, and managing the complexity of urban places by adopting the smart-sustainable urban metabolism approach, technology contributes to networking the urban systems, facilitating their metabolic synergies, within the urban place and beyond. Information and communications technology (ICT), and urban Internet of Things (IoT) are applied to the operation of urban infrastructures (buildings, transportation systems, electric systems, etc.), and services (smart traffic monitoring, smart waste management, e-governance, etc.), enhancing their efficiency while promoting social, cultural, economic and environmental sustainability.

3.2.3. Urban places as Regenerative complex systems.

In the previous subchapters, we demonstrated how the urban metabolism approach integrated with urban smartness allows us to face current urban challenges promoting urban sustainability. As urbanization continues to grow and urban dwellers' affluence to increase, the pressure on local and global rural areas increases, resulting in increased resource intensity, waste production, and environmental pollution. The so-far linear urban metabolism of "take, make, consume, and dispose" could be reformed to circular to eliminate negative implications of wasteful urbanization. This metabolic circularity in urban systems protects the environment and natural resources not only by sustaining them but by regenerating them instead. In this subchapter, we demonstrate how the regenerative design of urban metabolic processes tackles urban challenges overpassing the limitations of other circular metabolism concepts, ensuring sustainable growth for future generations.

Lyle in 1996, first expressed the idea to replace the linear flows of a city with cyclical in the field of development and design. According to Lyle, (1996) this change to circular flows at sources, consumption centers and sinks, it is related to the rebirth of life itself, and therefore to the hope for the future [39]. (Re)-designing urban metabolisms under circularity is the basis of different schools of thought such as regenerative design, looped, and performance economy, cradle to cradle (C2C), industrial ecology, close supply chain (or closedloop supply), biomimicry, blue economy. These aforesaid concepts have inspired the circular economy (CE) a new business model for a sustainable economy and a healthy environment [40,41]. Although CE is still a non-consolidated concept, difficult to describe and comprising diverse areas, such as sustainable production-consumption systems; closedloop supply chains; and product-service systems [42]. The Ellen Macarthur Foundation in 2015 put forward a definition of CE as "*one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" [43] (Figure 3).

Although the concepts of restoration and regeneration appear of high importance and used widely within CE, as Morseletto, in his work in 2020, affirms, "*are rarely denied or explained*". Notably, the concept of regeneration appears as "a symbolic/evocative term with little practical application in the context of circular systems except in the case of certain agricultural practices. Until new developments intervene, regeneration does not seem to apply to the economy as a whole, and because of this, it might be abandoned as a guiding principle of the circular economy" [44]. In the same line, Geisendorf and Pietrulla, (2018) after reviewing the CE concept, summarize that CE needs to be a regenerative system, but instead, most of the studies have been focused on waste management using a limited interpretation of the 3Rs principles (reduce-reuse-recycle) although these principles propose wider options [41]. Faraud, (2017) as well points out that CE appears to be limited mainly under the umbrella of waste, and by narrowing the focus on flow circularity leads to a different type of linear analysis [45,46]. Naboni et al., (2019) advocate that regenerative design, even that it goes far from just the limitation of the environmental impact of the built environment to climate change adaptation and improvement of human health, its implementations to urban scale are rare [47].

Scholars agree that the circularity of the metabolic processes need a regenerative design to ensure that urban growth can be sustained in longer terms. Nevertheless, we empirically know that there is still a long way to go as there is a lack of specific metrics, indicators tools, and methodological workflows capable of putting in practice regenerative design concepts.

We advocate that to create an urban place as regenerative complex system, we need to focus on the holistic regenerative design of the metabolisms of the social, cultural, technological, and ecological systems of urban places. A part of regenerative design studies supports that understanding the relationships between ecosystems and human society is the key to truly regenerative design, ensuring maximum wellbeing for both [48–50]. By treating urban systems as complex open ecosystems, incorporating ecosystem processes and services, we plan and design their metabolic processes in a holistic and regenerative way, overpassing circularity limitations as system boundary limits (see limits, challenges, and CE barriers in [51,52]). Through this regenerative paradigm, the relationships between urban places and the natural systems that they depended on are enhanced and restored, reaching the goals of the three dimensions of sustainability.

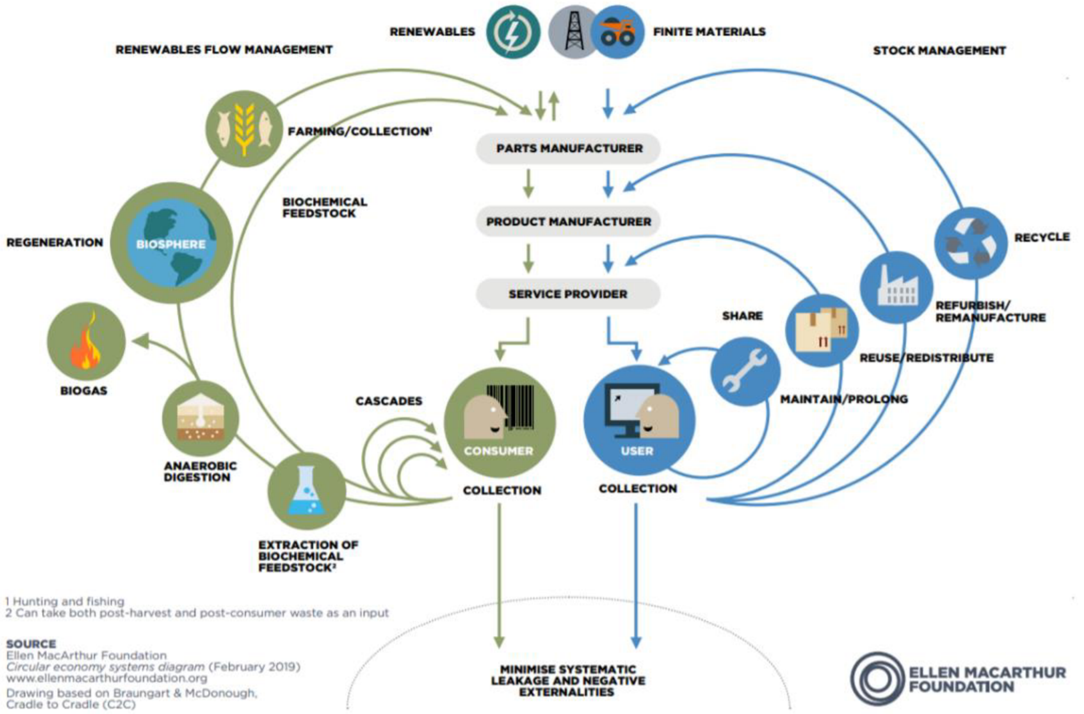

Figure 3. Butterfly diagram of systematic circular economy.

3.3 Smart and Regenerative Urban Places (SRUP): A new conceptual framework.

In the first part of our conceptual analysis we demonstrated that urban places to be smart, they need to be sustainable simultaneously through all three pillars of sustainability. As well as, regenerative designed urban places are truly sustainable in longer terms through restoration, revitalization, and improvement of their environment, people, and communities. Both smart city and urban regeneration concepts have been proposed and applied by scholars attempting to achieve sustainable urban growth and, therefore, to equip cities to meet modern urbanization challenges. In this second part of our conceptual analysis, we synthesize the conceptual framework of Smart and Regenerative Urban Places (SRUP), interconnecting the two aforementioned concepts under the broader framework of sustainability. We propose SRUP conceptual framework as a response to the limits of urban smartness and urban regeneration approach to achieve sustainability unilaterally. We conceptualize smart and regenerative urban places as the intersection of two rings (smart, regenerative concept) depicted in Figure 3. These rings appear with the same diameter since we treat the concepts as having equal importance, but without being homocentric because they are not the same concept. We place the sustainability concept in the intersection of smart and regenerative rings as being their interconnection factor. Sustainability does not cover the entire interconnection area since, in our understanding, smart and regenerative urban places are not just sustainable. This way, we built a cat-eye shaped diagram to depict our novel integrated and holistic conceptual framework at urban places scale, as shown in Figure 4.

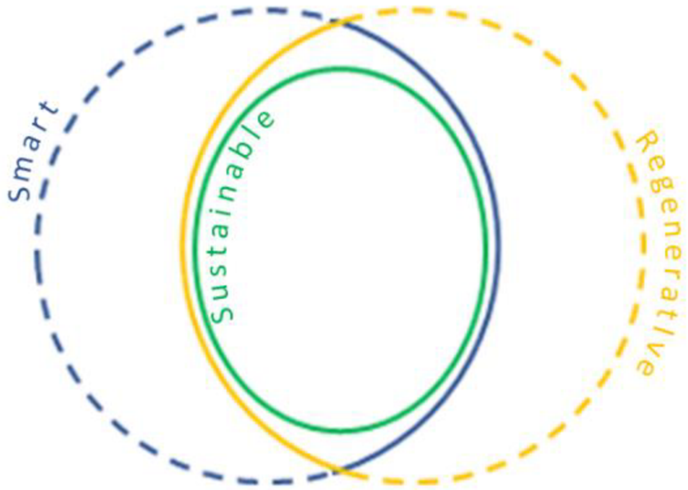

Figure 4. Cat-eye diagram of smart and sustainable urban places (blue for smart + yellow for regenerative = green for sustainable).

In Table 1, we summarize the aspects of our integrated conceptual framework. The table is designed to provide information by reading its columns vertically starting from the top left corner. In the first column, we see the concepts that constitute our novel framework SRUP (see previous subchapters). The second column mentions the spatial and temporal scale at which the framework is set. In the third column, we found the main dimensions of urban places to be measured and assessed, in the fourth column the stakeholders involved, and the principles of SRUP we adopt are summarized in the fifth column. In this way, specific characteristics are given to urban systems, as shown in the table's sixth column under SRUP framework. Examples of urban metabolic processes corresponding to main dimensions under the implementation of SRUP are presented in the table's seventh column. The table continues with the overall goals we attempt to achieve by applying this conceptual framework.

Adopting a systematic thinking approach and accepting the organic analogy of urban places as living organisms, we plan and design the metabolic processes of the social, cultural, technological, and ecological systems of urban places in a smart and regenerative way. Considering these systems as open and interdependent in permanent interaction within and beyond the boundaries of an urban place, we perceive urban places' planning and design as circular, ongoing [8], and co-evolutionary [53]. Conceptualizing smart and regenerative urban places, we face the complexity of the urban systems holistically by applying advanced technologies and real-time data-driven approaches in conjunction with urban ecology principles.

From the urban ecological point of view, understanding and mimicking organisms, their behaviors, and whole ecosystems (including their functions and services), serves as a paradigm of planning and designing an urban system able to return to the thriving state before exposed to hazards. Zari et al., (2012) integrate ecosystem services into the built environment and identify the six most suitable ecosystem services for regenerative design (Table B1, Appendix B) [54]. Accordingly, an urban place is designed to provide habitat for species, purify the air, water, and soil, and regulate the climate mitigating greenhouse emissions. Moreover, we argue that a regenerative designed urban place contributes to soil formation and fertility through careful cycling of biodegradable waste and recycling non-biodegradable wastes, produces renewable energy, and supports rainwater collection wastewater recycling and reuse.

Nowadays, an abundance of technologies transforms almost everything into a data source. Using these technologies in urban lifeline systems allows us to have access to a huge amount of data, from a variety of sources, at an unprecedented rate and with veracity, in other words, big data. Therefore, big data, along with advanced algorithms for spatial data analysis and the access to high computing power coupled with ecosystem services analysis, enable us to manage the complexity of urban living more efficiently. Therefore, we cannot have urban solutions of 'one size fits all'. Different neighborhoods show different systems behaviors and therefore need different solutions. Comparing high-density residential old neighborhoods with newly developed neighborhoods, we can see the differences and the need to develop and apply tailored solutions. In the first case, the buildings are old located in medieval parts of the cities and maybe on high slopes. They are built based on different transport systems, having narrow streets and sidewalks. Most of these urban places face challenges regarding; domestic garbage collection, building energy efficiency, accessibility, lack of green public spaces, citizens vulnerability to natural hazard as heat, cold waves, floods, and contagious diseases, among others. The new neighborhoods in the new part of the city have new energy-efficient buildings and an underground waste collection system. They are planned to have broad sidewalks with arrays of trees and green spaces promoting healthier lifestyles. Social facilities are located within walking distance promoting environmentally friendly mobility. Our point is that we can provide different actions and measures fitted to different places at a low-scale level to solve their unique problems with knowledge-based actions due to Big data and ecosystem analysis.

Far from just limiting the negative environmental impacts of urbanization and a zero waste-oriented approach, the SRUP design focuses on positive environmental benefits. It fosters health and, at the same time, improves the quality of life of the inhabitants and the companies, tourists, researchers, entrepreneurs, and all the urban tissue of the urban places. By learning from ecosystem processes, we apply this knowledge to smartizating and regenerating the exploitation of natural resources, the human and social capital, the economy, mobility, governance, and how they interact with each other. Therefore, we are able to design safe and secure, attractive and liveable, and more creative urban places.

ICT-based urban monitoring and surveillance systems embedded with artificial intelligence, business intelligence, machine learning algorithms, and image processing techniques to manage and analyze real-time data support urban places' security and safety [55]. Along with regenerative-based solutions, it powers our ability to conduct urban risk assessment specifying potential hazards and vulnerabilities, seeking to strengthen the urban place's resilience, security, and safety related to natural and socio-economic hazards.

An urban place that grows smarter and regenerative is attractive for all to live and work. Smart and regenerative urban design and planning limits the use of resources, it tackles bureaucratic issues by offering high quality of services, and it promotes a usercentric approach by engaging citizens in the city's functioning. At the same time, it enables economic growth to attract investors and businesses due to the quality and efficiency of the provided infrastructure that facilitates commerce and reduces friction. In addition to this, while fully equipped, smart cities should provide a dashboard showing economic, social, and environmental performance. Jointly, it contributes to leverage economic ICT based companies and startups, avoiding brain drain and keeping the young workforce (talent) from leaving.

Recognizing the affective attachment that individuals have with a place, we aim to plan and design in a smart and regenerative way liveable urban places enhancing the communities' quality of life and individual wellbeing. This affective attachment is built through the experience of the individuals. It is measured by the degree of their overall satisfaction and wish for residential stability in the place [56]. To strengthen this affective bond of individuals with the place, we enhance the quality of the environment (residential and natural) of the place according to users' needs, the place identity [57], and territoriality. Building smart, blue and green infrastructure, we focus on urban happiness and health contributing to the place's overall liveability.

In line with Sepe, (2014) the creativity of an urban place is related to the identity capital and innovation of the place [58]. Enhancing and developing the unique characteristics of a place through cultural, artistic productions, research, technological, and ecological smart regeneration, we strengthen their competitiveness and effectiveness. Therefore, combining all the characteristics of smart and regenerative urban places mentioned above, urban places are able to face long-standing urban challenges related to environmental justice, social equity, poverty, emergency management, provision and consumption of amenity services, urban ecosystems under pressure, efficient use of energy, renewable energy development, infrastructure provision, sustainable transport, delivery of life support services including water, sanitation, education, health.

Close collaboration with key stakeholders is required to implement this conceptual framework and extend the knowledge and practical evidence from it. Stakeholders can be local and regional government, public-private companies operating in the field, local communities, and private companies, and NGO's. Equally important is the need to develop legislation that allows synergies (economic and technical) between all the systems of an urban place. As well as activities that shorten the distance and, at the same time, strengthen the link between academia and stakeholders that can implement the measures and implement new policies, is critical.

Table 1. An integrated conceptual framework for smart and regenerative urban places as complex systems (SRUP).

Concepts	Scale	Dimensions	Stakeholders
Smart city	**Spatial**: Urban Place	Social	Local government
Regenerative urban planning and design	**Temporal**: Coevolutionary existence of relationship	Cultural	Local communities
		Technological	NGO's
		Ecological	Public and private companies

Principles	Characteristics	Processes (examples)	Goals
Holistic thinking	Open interdependent systems	Amenity services	Safety and Security
Systematic thinking	Complex systems	Wastewater recycling and reuse	Quality of life
Real-time data-driven approach	Open access to public data	Recycling of non-biodegradable wastes	Liveability

Urban ecology-Metabolic approach	User-centric approach	Cycling of biodegradable wastes	Attractiveness
Smartizating and Regenerating the exploitation of natural resources, human-social capital, economy, mobility, and governance	Living systems	Dashboard showing economic, social, and environmental performance	Competitiveness & effectiveness
3D sustainability	Mimicking ecosystems	Ecosystem functions and services	Creativity
	Circular metabolisms		Economic growth
	Social equity		Zero-Waste
	Environmental justice		

3.4 Smart and Regenerative Urban Places: Main Challenges and Discussion

In this Subchapter we discuss the limitations/challenges of urban smartness and regenerative design to sustainable urban growth in perspective of previous studies, and how we address these challenges though an integrating conceptual framework under urban metabolism approach.

One of the critical processes included in the proposed conceptual framework coming from the regenerative design subconcept, is the ecosystem service analysis. As Zari, (2012) points out, the analysis of ecosystem services is a promising but long-term approach to meet sustainability goals [54]. However, simultaneously, it increases the potential for accuracy while creating a measurable design based on the urban place's physical reality rather than some anthropogenic activity or political trend. Therefore, integrating the ecosystem analysis with the smart city concept, we conceptualize new digital services with an overall goal to improve the quality of life and work of citizens and companies.

Despite all the benefits coming from this conceptual integration, we identify a few fundamental challenges. As mentioned in the previous subchapter, a large amount of spatial data is obtained from various sources constantly within urban places. Therefore, besides having access to a large volume of data, it is crucial to assess meaningful data that we can analyze and turn into knowledge. Maintaining and improving the quality of this data is fundamental mainly for two reasons. Firstly, the overall quality of a model (especially an analytical model) depends not just on the policy guidelines and recommendations but also on the data quality. Secondly, the overall realism of an operational research project relies on data quality as well. In synthesis, data curation is critical for the quality and realism of project deliveries, in general. Efficient data storage and processing facilities, as well as computational intelligence algorithms, are required to extract valuable information from the datasets to plan, design, and manage smart and regenerative urban places. The IoT and the cloud computing services available nowadays are possible ways to overcome this challenge [59].

A further challenge related to data privacy, protection, and sharing is how to build trust that the use of data for smartness and efficiency is not putting at risk individual privacy and personal control in data collection and management and city's sovereignty. In smart and regenerative design, data circulates openly accessibly through the metabolic processes of an urban place with the responsibility of companies and governments. Revealing the full value of data as a common good and engaging citizens' participation in the design, we encounter this ethical challenge of smart city concept [60]. The citizens have an empowering role in the design process of an urban place. Through collaboration with governments, citizens are involved in the decision-making process identifying priorities, strategies, and goals regarding matters of public relevancy. Citizens are crucial stakeholders to generate valuable ideas to meet social needs and, at the same time ICT users [61].

Another critical issue regarding the human capital dimension is focused on consumer behavior. Gallaud and Laperche, (2016) mention that the mass consumption model in the postwar era promotes consumer behavior based on high rates of household consumer equipment and highly equipped cars [40]. Adding to this trend, companies promote behavior based on equipment replacement, building products with low-quality materials, and making it hard for consumers to find inexpensive spare parts. Moreover, by advertising the idea of products fast renewing to maintain the benefit of last technological developments, the consumption increases. With planning and designing smart and regenerative urban places, the essential scope is saving, restoring, and regenerating resources. Therefore, it is safe to say that consumption behavior needs further evolution towards a smart and regenerative consumer's behavior.

The aforesaid consumption behavior is closely related to the growing challenge of ewaste. The increased demand of electronic equipment either for household use or at city level, results in shortages of raw materials necessary for its production. Through urban mining processes, rare metals coming from electronic and electrical waste are reclaimed and reused to produce new equipment to support the needs of smart city concept. In many cases, where urban mining occurs informally, it results in serious health hazards, security risks, and environmental pollution due to the toxic substance realized through reclaiming processes. Applying our proposed framework of smart and regenerative urban planning and design, we can face this e-waste challenge, focusing not only on recycle but avoiding e-waste disposal to landfill and incineration sites at first place via circular metabolisms. Life cycle assessment coupled with urban metabolism supports the smart and regenerative e-waste management practices estimating the environmental impact of the e-waste treatment performing end-of-life scenarios.

A topic of significance under discussion is the cost-effectiveness of adopting smart and regenerative places. Transforming an urban place into a smart and regenerative requires time and money to invest in ICT infrastructure, to build an integrated master planning of control methodologies of big data [59] and circular metabolisms. In addition, it is difficult to monetize the benefits of this transformation especially benefits from ecosystem services and the positive socioeconomic impacts.

Considering these, local governments and decision-makers, and urban planners need to develop business models that could attract public funding and private financing to make this transformation of urban places viable and financeable. Moreover, they need to engage all urban agents so the concept of public place as a place of all and for all, be assimilated and leverage the sense of responsibility across the community. The holistic design of an urban model that we suggest involves all stakeholders, it is based on knowledge adopting good practice and guidelines, and therefore, it contributes to further cost savings. For example, through smart lighting, which uses renewable energy, we save energy costs. Using smart technologies in administrative procedures manpower costs can be saved as well as savings in public funds related to urban security and city maintenance, cost reduction for maintenance and waste collection and treatment services are also.

3.5. Conclusions

The world as we used to know it is going through significant changes. Urban areas are growing and expanding, covering more space than rural areas, increasing resources' consumption, energy demand, and generate waste. This unbalanced relationship between urban areas and nature leads to social, economic, and environmental challenges that urban areas, in all their complexity, are critical to face and ensure sustainability in urban growth. Based on a literature review, we verified that the smart city concept is related to urban sustainability, and the regenerative design studies embrace sustainability to maintain a healthy state of urban systems and move one step further by allowing the urban systems to flourish and evolve. We also verified that the concepts of urban smartness and urban regeneration had been studied separately in the pathway to reach sustainability. In this part of the thesis, we have proved that we cannot fully understand the complexity of urban areas without a holistic and integrative systematic approach. Therefore, having demonstrated the importance and the role of each concept of our interest, we integrated them via sustainability principles, highlighting the symbiotic and mutually beneficial interconnection. We conceptualized the novel framework of smart and regenerative urban places (SRUP) under the urban metabolism approach to encounter the current challenges of urban complexity, supporting the idea that an urban place to be truly regenerative needs to be smart and vice versa.

We perceive the relationship between the urban systems (social-cultural-ecological-technological) as open and co-evolutionary at the urban place scale. Focusing on urban places, besides their spatial and human aspects, we emphasize the sense of safety, security, and identity. In other words, we reflect the attachment bond that inhabitants have with the place they live in as a mix of cultural and physical features that make this place unique, authentic, offering a sense of security and safety to its inhabitants. Giving a coevolutionary context in our framework, we highlight the need for continually maintaining and improving, in an integrating way, the relationship between the human and natural capital. Our holistic framework goes beyond sustainability, transforming urban places into truly smart and regenerative by combining advanced technologies and ecological principles. In this way, we re-design the urban place's metabolisms so as to be attractive and liveable, competitive and effective, and innovative with a higher goal to restore the health of natural resources recognizing the value of ecosystem services and the cost of their loss.

To implement this innovative conceptual framework requires investments and collaborations between businesses and the government engaging public participation in the process. Complex systems, such as urban areas' dynamics, are full of uncertainty and therefore demanding for an integrative systems approach, and at the same time a holistic perspective of the whole instead of focusing on single parts. All actors should be engaged with the urban place dynamics, building a more systemic worldview, and adopting a more participatory attitude in the decision-making process. All in all, combining all the characteristics of smart and regenerative urban places mentioned above, urban places are able to face long-standing urban challenges, e.g., environmental justice, social equity, poverty, emergency management, provision and consumption of amenity services, urban ecosystems under pressure, etc. As the main problems to our model implementation, we have noticed that there is a lack of meaningful eco-geo-urban data at a high-resolution scale, produced systematically in time and space, as well as tools to analyze them and build evidence-based knowledge. Our next step is to evaluate the smart and regenerative performance in all the dimensions of selected urban places under study. Initially, we will define a set of variables representing the principles and characteristics of a smart and regenerative urban place. Using these variable and advanced methods, we will measure and assess the study areas' metabolic processes. A protocol agreement, regarding access to data, with a local stakeholder, has already been established and signed.

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Chapter 4

Based on: Peponi, A., Morgado, P., & Kumble, P. (2022). Life cycle thinking and machine learning for urban metabolism assessment and prediction. Sustainable Cities and Society 80, 103754.

4. Life cycle thinking and machine learning for urban metabolism assessment and prediction.

The real-world urban systems represent nonlinear, dynamical, and interconnected urban processes that require better management of their complexity. Thereby, we need to understand, measure, and assess the structure and functioning of the urban processes. We propose an innovative and novel evidence-based methodology to manage the complexity of urban processes, that can enhance their resilience as part of the concept of smart and regenerative urban metabolism with the overarching intention to better achieve sustainability. We couple Life Cycle Thinking and Machine Learning to measure and assess the metabolic processes of the urban core of Lisbon's functional urban area using multidimensional indicators and measures incorporating urban ecosystem services dynamics. We built and trained a multilayer perceptron (MLP) network to identify the metabolic drivers and predict the metabolic changes for the near future (2025). The prediction model's performance was validated using the standard deviations of the prediction errors of the data subsets and the network's training graph. The simulated results show that the urban processes related to employment and unemployment rates (17%), energy systems (10%), sewage and waste management/ treatment/recycling, demography & migration, hard/soft cultural assets, and air pollution (7%), education and training, welfare, cultural participation, and habitat-ecosystems (5%), urban safety, water systems, economy, housing quality, urban void, urban fabric, and health services and infrastructure (2%), consists the salient drivers for the urban metabolic changes. The proposed research framework acts as a knowledge-based tool to support effective urban metabolism policies ensuring sustainable and resilient urban development.

4.1 Introduction

It can be argued that urbanization and globalization are accelerated by technological advancements. These are often, the main drivers that influence and change the spatial and functional structure of the urban areas today. These two main drivers -urbanization and globalization-appear interdependent in how their influence upon urban systems, resulting in the increase of the global urban population. Specifically, the urban global population has grown rapidly from 751 million (30% of the world's population) in 1950 to 4.2 billion (55% of the world's population) based on recent data from 2018 and it is projected to reach 6.7 billion (68% of the world's population) by 2050 (United Nations (UN) 2018). It has been well documented that much of the world's economic activities are now concentrated in urban areas, generating 80% of the global gross domestic product (GDP) (Ferrao & Fernandez, 2013) while simultaneously demanding nearly 75% of energy consumption (UN-Habitat, 2021) to support this activity. Therefore, urban areas are now responsible for metabolizing or consuming a vast proportion of natural resources in support of their inhabitants' needs, generating a high rate of pollution and waste, and stress upon society. On the other hand, urban cores areas facilitate research and development, economic and social development while simultaneously providing the necessary infrastructure to support health care and well-being by employing a variety of advanced technologies.

As part of the context of urban metabolism, an urban core area can be seen as a complex ecosystem requiring a neverending exchange of materials, energy, and information between its processes/systems and as a consequence must expand beyond its boundary in order to function and grow. This means that urban core areas require more "space" to survive than they typically encompass, perhaps suggesting that they lack efficiency. Thus if one were to make urban sustainability, a priority, one must find ways to cope with the environmental, social, and economic challenges initiated by the increased demand for more resource extraction and consumption, that generates excess waste production. By doing so, it is essential to understand, measure, and therefore assess the complexity of the different urban metabolic processes/systems and the services they deliver that are critical for human survival and well-being. Different methodologies have been proposed and applied to measure urban metabolism with the intention of creating a more sustainable society since 1965, when it was first introduced by Wolman. In subchapter 4.2, we provide a detailed analysis of the applied methodologies, highlighting their benefits and deficiencies. Summarizing the main shortcomings of these methodologies, we identify challenges related to the determination of the urban processes/systems' boundaries and the lack of an integrated and multi-impact approach, including the lack of the impact of the ecosystem services on urban sustainability.

Attempting to address the above-stated limitations, we propose an original methodology that assesses the multidimensional urban metabolic processes by coupling Life Cycle Thinking (LCT) with Machine Learning (ML) from an ecosystem services perspective. We build and assess a smart and regenerative metabolic scenario that can simultaneously assess the main drivers for changes in purchasing power per capita in our study area, the urban core of the functional urban area of Lisbon (UCL) indicating, in which *degree, where* metabolic changes will occur in the near future and the level of impact on the overall urban system. We accept that the urban metabolism is derived indirectly from GDP changes expressed in purchasing power per capita (IpC) when the analysis is at an urban core area scale as in our study area. The methodological approach applied in this part of the dissertation thesis is described in detail in the Research framework subchapter 4.3, followed by the Results subchapter 4.4. These subchapters have raised several hypotheses and issues that we summarize in Discussion subchapter 4.5. Finally, we highlight the main findings and novelty of our study in the Conclusions subchapter 4.6.

The objectives of this part of the dissertation thesis are based on five key methodological steps. They are 1) to identify the main limitations of previously applied methodologies of urban metabolism (UM), 2) to introduce a new and novel methodology that addresses these limitations and contributes to the extent of state-of-art thinking, 3) to create evidence-based knowledge from the multidimensional metabolic methodology under the perspective of ecosystem services 4) to identify the main drivers for urban metabolic changes; and 5) to predict metabolic changes for a near future. This newly developed methodology should be considered as a tool for optimizing planning and design, in support of critical policymaking by measuring and assessing urban metabolism and thus ensuring urban sustainability.

4.2 Background

The concept of urban metabolism (UM) has been evolved and adapted over time in response to scientific and technical changes. Based on the literature, the concept of UM appeared first using Material flow Analysis (MFA), then the Emergy (embodied energy) method influenced by the work of Odum, 1983 or occasionally the Ecological Footprint (EF) method, and most recently coupled with Life Cycle Assessment (LCA) (Goldstein et al., 2013). UM's first approach is related to Industrial Ecology incorporating tools of MFA to assess material, water, food, and nutrient fluxes and stocks within urban systems and the resulting outcomes to other systems in the form of pollution, waste, or exports (Sahely et al., 2003 as cited in Pincetl et al., 2012). MFA is based on the principle of mass balance (mass in = mass out + stock changes), where matter cannot either be created or destroyed. Zhang, 2013 supports that by directly adding the weight of different materials, the quality differences among these materials are ignored. Moreover, the role of energy flows that drive all material flows throughout the urban metabolic process is also ignored. Scholars attempting to understand metabolic processes thoroughly have combined MFA along with energy flow analysis (EFA), focusing on physical material and energy flows in urban ecosystems, under one analytical framework (MEFA) (Kennedy et al., 2011 as cited in Zhang et al., 2018).

Moving the focus beyond mass, UM's emergy-based accounting method (EMA) ensures that the emergy (solar energy) used directly or indirectly for the creation and flow of all products or services is accounted. Hence the qualitative differences of the materials and energy flows that were ignored previously are now highlighted (Pincetl et al., 2012; Zhang, 2013). The Emergy method, initially originated by Odum in 1988, is based on ecology, thermodynamics, and general systems theory fields, emphasizing the fundamental dependence of cities on ecological processes that can occur only due to solar energy. Emergy is measured in solar emergy joules (seJ) and emphasizes standard units for all materials, energy, nutrient, and waste flows in biophysical systems (Pincetl et al., 2012). The main challenge of this method and, therefore, its limitation relies on the difficulty of converting materials and energy flows of different units to the seJ metric (Pincetl et al., 2012).

In line with Goldstein et al. (2013), these first generations of UM methods fail to fully quantify the environmental impacts of larger-scale systems. In an attempt to face the limitations of the first generations of UM, in the last decade, authors have coupled UM with LCA assessing the environmental consequences of cities (Goldstein et al., 2013; Loiseau et al., 2014; Peuportier & Herfray, 2010) and various urban processes (Ramos & Rouboa, 2020). In general, life-cycle assessment (LCA) is a cradle-to-grave standardized method accounting the associated environmental impacts of products or services over their different life cycle phases. Pincent, 2012 states that LCA provides methodologies and tools appropriate to quantify the materials or UM, including processes generating inputs and outputs.

However, various shortcomings of LCA applications have been pointed out. Beloin-Saint-Pierre et al., (2017) in their review of the methodological choices of UM studies, found out that besides the fact that Life cycle modeling is essential for sustainability assessment, "the life cycle of complex system like UM is not clearly framed in most UM studies under review". Mirabella et al., (2018) reviewing the application of LCA at the city scale, affirms that "no applications of comprehensive LCA at urban scale exist to date", in other words, "no complete urban LCA studies exist so far". The conventional LCA methodologies provide only relative sustainability evaluation since they ignore ecosystem services' role in supporting human activities (Bakshi, Ziv & Lepech, 2015 as cited in Liu et al., 2019). Another essential deficiency relies on system boundary determination; the results may reflect the authors' subjectivity in system boundary, leading to errors or contradictory results. Moreover, LCA is data-dependent. Therefore, if the life cycle inventory is not complete may not return the total environmental impact of the process/product under analysis. As LCA uses a single standard approach ignoring multiple factors (environment, technology, and capital) that may affect the target process, its environmental assessment lacks a multi-angle approach (Wang et al., 2020).

Hybrid modeling approaches coupling different urban metabolism methodologies have been developed to cope with the shortcomings of the applied methods previously described. Authors have integrated Emergy and LCA to assess sustainability in urban systems under study (Cano Londoño et al., 2019; Li et al., 2020; Santagata et al., 2020) to reach maximum environmental benefits as well as the most cost-effective technologies according to the financial limits (Falahi & Avami, 2019). Wang et al., 2020 reviewed the EMA and LCA methods and suggested their coupling development to be based on three aspects; the aggregate emergy flow table, the indicator system construction, and indicator evaluation methods to exert the maximum functional advantages of each method. Westin et al., 2020 have combined MFA and LCA to identify environmental hotspots of urban consumption. García-Guaita et al., (2018) integrated MFA and LCA under UM approach for urban environmental evaluation. The main limitations of this study include a lack of local data and the absence of social and economic indicators in the analysis. Attempting to describe the links between the different variables of UM, authors have coupled the network approach (NE) with MFA, with ecological network analysis (ENA), Environmentally-Extended Input-output analysis (EE-1/O), and LCA (Berloin et al., 2017). This type of methodologies are data-driven, allowing comparisons and recognition of future trends. Urban systems' metabolic patterns have been studied using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting method relating fluxing and funds, and therefore offering applicable and coherent indicators (Rallo† and Zucaro, 2019; Perez-Sanchez et al., 2019). However, this method appears to be static, allowing the observation of a system's evolution but not its dynamics (Ginard-Bosch and Ramos-Martín, 2016). LCA has also been combined with agent-based models (ABM) make it suitable to evaluate the sustainability of complex systems through behavior-driven modeling (Marvuglia et al., 2018; Walzberg et al., 2019; Micolier et al., 2019). Baustert and Beneto, 2017 categorize the coupling of ABM and LCA based on the direction of the information flow as; *ABM-enhanced LCA* with the ABM to feed the LCA model, *LCA-enhanced ABM* opposite to the previous, and as *ABM/LCA symbiosis* when the information is looping between the two models (Marvuglia et al., 2018). Although there are already examples of using ABM for simulating LCA, there is still a long road to be made in order to make them more user-friendly and less computing expert-oriented.

4.3 Research framework

In our work, we couple Life Cycle Thinking (LCT) and Machine Learning (ML) adopting smart and regenerative urban metabolism to assess purchasing power per capita (IpC) changes driven by the multidimensional metabolic processes of our study area UCL (Figure 1). IpC indicator is a composite indicator drawn from the factor analysis calculation based on 16 variables selected by Statistics Portugal (Table C3, Appendix C). The IpC is the main factor resulting from the factor analysis, as it explains more than 45,6% of the 16 variables' total variation after rotation. The indicator explains the purchasing power expressed on a daily basis, in per capita terms using the figure of Portugal as a reference (STATISTICS PORTUGAL, 2017). Purchasing power by definition is "the quantity of goods and services that can be bought with a monetary unit," observing the real economic activity trends (production, consumption) globally concentrated in urban core areas as mentioned in the introduction. Therefore indirectly, it can give a perception of the flows of materials, energy, and information representing the holistic and multidimensional perspective of urban metabolism associated with the production of waste and environmental impacts.

We understand LCT as a systematic approach that offers a holistic vision of all generated impacts of an urban system, improving its multidimensional performance throughout its entire value chain. Adopting LCT to study urban metabolism allows coping with urban sustainability from both macro and micro scale points of view. UM requires large-scale data and life cycle assessment, as standardized methodology requires more detailed data (Maranghi et al., 2020). Coupling LCT with Artificial Intelligence (AI) and Machine Learning (ML) methods enables us to adopt a data-driven and bottom-up-based methodology capable of building knowledge from the systems dialectic in an iterative way. AI is the development of a certain type of computational technique that can perform tasks simulating human intelligence and behavior to solve practical problems (Goodfellow et al., 2016; Openshaw & Openshaw, 1997). AI is powered by ML. ML consists of algorithms that learn by example using historical data to predict outcomes and uncover patterns not easily identified by humans. The obtained knowledge can be used by ML algorithms to make predictions about future trends. ML is found in literature associated with different names such as; pattern recognition, statistical modeling, data mining, knowledge discovery, predictive analytics, data science, adaptive systems, and self-organizing systems (Domingos, 2015). ML algorithms based on the learning role fall into three categories; supervised learning, unsupervised learning, and reinforcement learning (Graves A. 2012; Sathya & Abraham, 2013). The supervised ML algorithms reveal insights, patterns, and relationships from a labeled (classified) training dataset (input-output pairs) using regression or classification techniques. On the contrary, unsupervised ML algorithms infer patterns from a dataset without reference to known or labeled outcomes. Reinforcement learning (RL) reflects ideas from psychology. The RL algorithms learn using trial and error and related reward interactions with their environment to find optimal policies without being taught by examples (Fu et al., 2014).

Artificial neural network (ANN) techniques have been extensively applied overall the last thirty years in several areas, e.g., medicine (diagnosis and decoding brain signals), security (face recognition), Linguistics (language recognition and translations), governance (decision support systems and smart cities), Banking and Insurance (loans and insurance attribution), Pharmaceutical (risk analysis), non-renewable resources exploration (prediction), advertising and marketing (customer profiling), remote sensing (automatic and semiautomatic analysis of satellite images), human and physical geographical studies (spatial data pattern & data relationships analysis), Landscape and urban planning (conflict management and urban growth simulation), and so forth (Bação et al., 2005; Fischer, 1998, 2006; Henriques et al., 2012; Openshaw & Openshaw, 1997; Venugopal & Baets, 1994). With the advent of big data, and more specific geoBig data, and the increased parallel computing, ANN methods, and techniques, also commonly known as the Neurocomputing field of studies, have gained more and more applicability across all types of scientific domains, ranging from art, social sciences & humanities to more philosophical and ethics studies. To the best of authors' knowledge, coupling LCT and ML to study urban metabolism changes has not been applied before.

Our research framework is understood from an ecosystem services perspective. Specifically, under the urban metabolism concept, an urban core area could be seen as an ecosystem where biotic components are in conjunction with abiotic components of their environment, developing circular and ongoing complex relationships. Studying the functional aspects of an ecosystem responsible for the flows of energy and the cycles of materials and the beneficial ecosystem services to human well-being, we are able to apply this knowledge for the design and planning of the urban environment. Therefore, maintaining the urban ecosystem services is the key to sustain urban places, reinforce system resilience, ensuring public health and well-being.

After defining the goal and the scope of our study, we start implementing our research framework by conducting the Life Cycle Inventory (LCI). The LCI is the first phase to implement a LCT methodology. By definition, LCI is the quantification of inputs (material and energy flows) and outputs (emissions to air, water, or soil) of a system under study. In this phase, all the processes involved in the life cycle of a product/ process/or system of processes have to be identified along with the data related to these processes, and their system boundaries need to be determined (Khanali, Mobli & Hosseinzadeh-Bandbafa, 2017; Nabavi-Pelesaraei et al., 2018). Doing the LCI, we identify the indicators representing the smart and regenerative urban metabolic processes, and we set their system boundaries by defining the dimensions and subdimensions. Last, we selected the related measures (Data components) to these urban metabolic processes and again classified them under the urban ecosystem services perspective. We use for case study the urban core of the functional urban area (FUA) of Lisbon, Portugal, and its administrative boundaries as overall system boundary to test the proposed methodology. Having finished the LCI, we couple it with ML to obtain evidence-based knowledge on the drivers and dynamics of the metabolic processes of our study area.

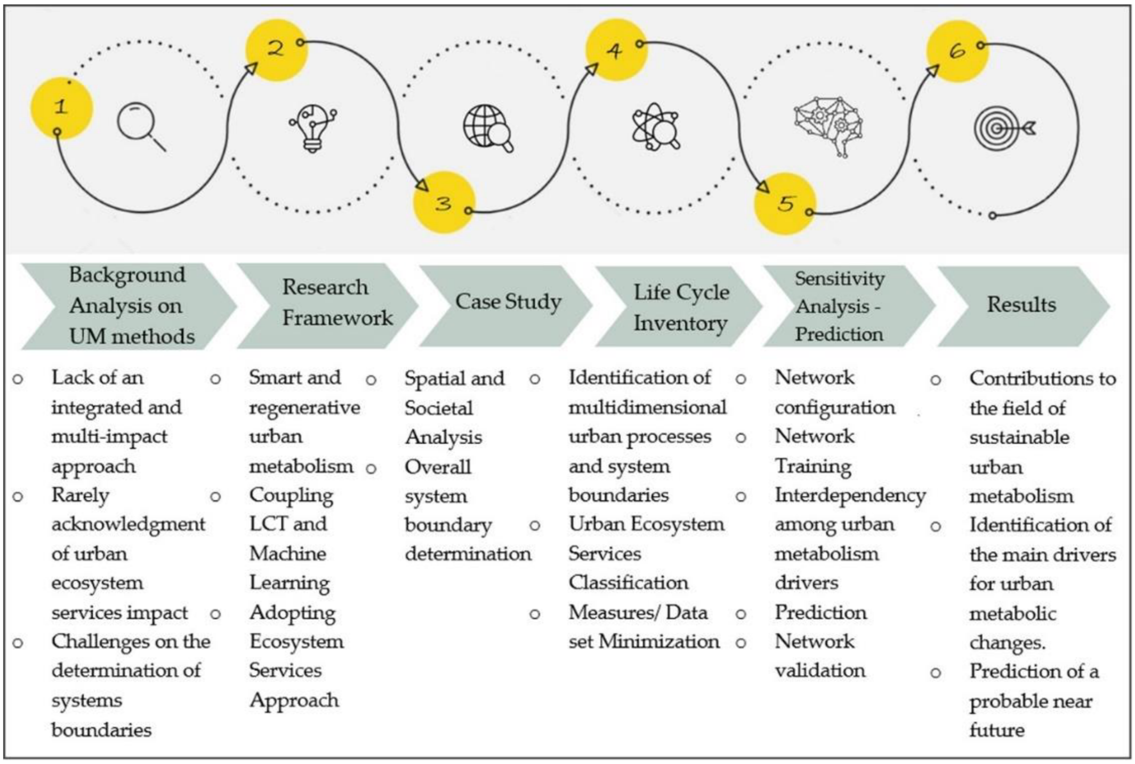


Figure 1. Research framework flow.

4.3.1. Case study

In this subchapter, we delineate our study area by setting the overall system boundary for our study and analyze it by conducting spatial and societal analysis. Hence, in our work, we use the urban core of the functional urban area (FUA) of Lisbon city to assess and predict its smart and regenerative urban metabolism. FUAs consist of densely urban zones with more than 50,000 inhabitants (Copernicus, 2018). Using the core area of Lisbon FUA (UCL), we delimit the area of strong metabolic influence of the city of Lisbon.

The UCL is located in the country's center, crossed by the Tagus River and it is met by the Atlantic Ocean to the west (Figure 2). The UCL, is divided into nine municipalities: Lisbon, Loures, Odivelas, Amadora, Oeiras, Cascais in the northern margin of the Tagus River and Almada, Seixal and Barreiro in the southern margin. The UCL covers approximately 1040 (1036.847397) square kilometers, of which 19% is classified as agricultural, 27.3% is covered by forest, natural areas, and urban green areas, and 51% by the built environment (Copernicus Programme, 2018). It has an annual average air temperature of 16,4◦C (Celsius), a maximum of 22 ◦C, and a minimum of 11,6° C and the annual precipitation of the region of Lisbon is 692,3 mm (Statistics Portugal (INE), 2018).

The total resident population of UCL is 1690,014 inhabitants (equal to 16% of the total population of Portugal), with a population density of 1629.9 inhabitants per square kilometer (Statistics Portugal (INE) 2011). The 49% of the total population of UCL constitutes the labor force almost equally divided by sex (24,19% male and 24,87% female). Nearly 14,5% of the population is classified as young people under the age of 15, while elderly people over the age of 65 make up account for 20% of UCL's population (Statistics Portugal (INE) 2011). The UCL has an aging index of 120 elderly per 100 young people. The percentage of the foreign population as the total resident population of the area is 9% (Statistics Portugal (INE) 2011).

The regional economic activities are based mainly on the tertiary sector, and the primary and manufacturing activities are low. In 2018, the tertiary sector contributed to 87.0% of the regional gross value added (GVA), the secondary sector (including construction) to 12.6%, and only 0.4% of the GVA comes from the primary sector (EC, 2021). The region of Lisbon comprises a science and tech hub concentrating the highest expenditure on Research and Development (R&D) activities, 1.62% of GDP whilst the national average is 1.35%. In addition, it concentrates the highest share of personnel and researchers in R&D, 16.6% per 1000 active inhabitants whereas the average for Portugal is a bit lower at only 11.1% (PORDATA, 2018). Looking at the index purchasing power per capita of UCL, we see that the municipality of Lisbon has the greatest purchasing power (219.6) in-country, with Portugal as reference value 100. Six to nine municipalities of UCL, including the municipality of Lisbon, have purchasing power above the national average and three (Loures, Seixal, and Odivelas) below (PORDATA 2018).

Finishing our analysis, we examine a couple more urban metabolism parameters related to energy and material flows. The total electricity consumption in the study area is 4198.2 kgwatt-hour per inhabitant, while the national electricity consumption is 4754.4 kWh/inhab. The municipality of Seixal has the highest consumption 7072.70 kWh/ inhab., following Lisbon with 6038.40 kWh/inhab. The overall waste selectively collected[9] of the UCL (not including the municipality of Odivelas) is 154 kg per inhabitant while the national average value is 103 kg/inhab. The municipality of Cascais has more than double the national value (250 kg/inhab.), following Almada with 191.5 kg/inhab. and Lisbon with 179.8 kg/inhab. (PORDATA, 2018).

Figure 2. Geographical position of the study area.

4.3.2 Life cycle inventory in urban ecosystem services perspective

Under the smart and regenerative concept, the metabolic processes are not just the linear consumption of energy and materials that generate waste, but instead, they are circular, ongoing, and co-evolutionary, eliminating waste by regenerating resources using technology (Peponi & Morgado, 2020). As urban cores are metabolic complex systems that exist through the interactions and interdependencies of all social-cultural-technological-ecological urban processes, a holistic, multidimensional

[9] Waste selectively collected in eco-points, door-to-door, recycling yards and special circuits of various materials and biodegradable urban waste selected for organic recovery the energy consumption (INE, 2018)

systematic network approach is essential to evaluate their urban metabolism.

The social dimension of an urban metabolism includes all urban processes related to urban governance, human capital, economic capital, and health system. The focus is to plan and design a smart and regenerative social structure that improves and even eliminates situations perceived as social problems (social exclusion, inequalities, poverty, limited health care access, and so on). The cultural dimension of urban metabolism contains processes related to the hard and soft cultural assets of the area under study, their accessibility, and public participation. The hard-cultural assets are publicly owned, and the soft-cultural assets are found within communities (e.g., artists and creative people), businesses (e.g., creative industry), and other stakeholders' groups. In the cultural dimension of urban metabolism, we include processes related to urban agriculture, highlighting its beneficial role in building community cohesion, providing a place where community members can come together, interact, and strengthen their bonds. The smart and regenerative cultural planning refers to the planning and implementation of strategies that highlight the unique hard and soft cultural assets of a place, boosting the local and regional competitiveness (urban art interventions, collaborative community projects and networks, urban culture inheritance, and the creation of the contemporary city culture). The technological dimension of urban metabolism lies in implementing advanced technologies in urban planning and design, which is required to solve the technical issues of supplying energy, water, materials, construction, planning, and design and do it while regenerating the urban metabolisms. Examples of this implementation are applying the Internet of Things (IoT) and the Information and Communication Technology (ICT) to support interconnection among heterogeneous systems, laser cleaning technologies, sensors for data collection, barriers to prevent floods, management, and disposal of the city's waste. The ecological dimension of urban metabolism refers to understanding and mimicking organisms and ecosystems (including their functions and services). By learning from ecosystem processes, we apply this knowledge to regenerate the exploitation of natural resources, the human and social capital, the economy, mobility, and governance and how they interact with each other.

Having defined the metabolic dimensions and subdimensions establishing the boundaries of their related urban processes, we identify their representative indicators as shown in Table 1. Adopting the ecosystem services perspective, we classify these indicators according to four well-known groups; provisioning services, regulating services, supporting services, and cultural services proposed by the Millennium Ecosystem Assessment (MA), 2005 classification system. Pedersen Zari, 2012 provides a list (Table C1, Appendix C) with the main ecosystem services of each category after conducting a comparative survey of the existing research. In line with this list, we classify the urban processes of a smart and regenerative urban ecosystem into these four categories, transferring the ecological knowledge to the built environment aiming to maintain the overall health and resilience of the urban ecosystem as a whole (Table 1). Therefore, the provisioning services offered by a holistic smart and regenerative urban ecosystem are related to the welfare, economy, social inventions, energy and water systems, and all urban ecological processes, including processes related to urban agriculture. The regulating services regulate environmental media or processes, such as pollination and dispersal, climate regulation, biological control decomposition, and disturbance prevention and moderation of extremes. Thus, the regulating services are provided by urban processes related to demography and migration, Healthcare services and infrastructure, urban agriculture, sewage and waste management, treatment and recycling, urban safety processes, and all urban ecological processes. Following the supporting services are these ecosystem processes and functions that support other services like soil formation, soil retention, renewal of fertility, quality control, nutrient cycling, habitat provision, and species maintenance. Therefore, the supporting services are provided by urban processes related to fertility and mortality, employment-unemployment rates, urban agriculture, mobility -accessibility, urban fabric, sewage and waste management, treatment and recycling, and all urban ecological processes. Finally, the cultural services are the services offered by the urban ecosystem responsible for covering cultural or spiritual needs, such as artistic inspiration, education, and knowledge, esthetic value, cultural diversity and history, recreation and tourism, creation of sense of place, spiritual and religious inspiration, relaxation and psychological well-being (Table 1, Table C1).

Table 1. Multidimensional metabolic analysis in the perspective of urban ecosystem services.

Dimensions	Subdimensions	Indicators of urban processes	Urban Ecosystem Services
Social	Urban Governance	Public participation and stakeholder engagement in decision making	Cultural services
	Human Capital	Demography and migration	Regulating services
		Fertility and Mortality	Supporting services
		Education and training	Cultural services
	Economic Capital	Welfare	Provisioning services
		Employment-unemployment rates	Supporting services
		Economy	Provisioning services
		Touristic attractiveness	Cultural services
		Social inventions	Provisioning services
	Health system	Healthcare services and infrastructure	Regulating services
Cultural	Cultural mapping	Hard/ Soft cultural assets	Cultural services
	Cultural Participation	Cultural participation	Cultural services
	Urban agriculture	Urban agriculture	All ecosystem services
Technological	Housing	Housing quality	Supporting services
	Mobility-Accessibility	Road network	Supporting services

		Railway	Supporting services
		Maritime transport	Supporting services
	Urban structure	Urban fabric	Supporting services
		Urban void	No ecosystem services
	Innovation	Research and development	Cultural services
	Utility systems and infrastructure	Sewage and Waste management/treatment/recycling	Regulating services/ Supporting services
		Energy systems	Provisioning Services
		Water systems	Provisioning Services
		Urban safety	Regulating services
Ecological	Habitat-ecosystems	Habitat-ecosystems	All ecosystem services
	Environmental protection	Environmental protection	All ecosystem services
	Environmental quality	Air pollution	All ecosystem services
		Air temperature	All ecosystem services
		Soil exploitation	All ecosystem services
		Water quality	All ecosystem services

We finish the life cycle inventory phase by building the dataset reflecting these urban processes and functions responsible for smart and regenerative metabolism and circularity of resources, information, and waste emissions in all dimensions for two different years (2011, 2018). The built dataset consists of 254 measures. These measures represent the biophysical characteristics of the ULC, for instance, land use and land cover, the UCL's socioeconomic profile, as population growth and density, economic prosperity, lifestyle practices, access to services, and quality of life.

Moreover, we include measures representing the material and energy flows, including energy, water, waste flows. Some of these measures could be used for more than one indicator/ urban process of different metabolic dimensions. Still, to avoid data redundancy, we chose to use them once to measure the urban process they represent more generally.

For our analysis, we set the year 2011 as the oldest year and the year 2018 as the most recent year to study the metabolism of ULC before the COVID-19 pandemic; 2018 was the year with the majority of the available data. When a specific dataset was not available for the target years 2011 and 2018, we chose the closest year to them available. The Census data were only available for the years 2001 and 2011. We retrieved statistical data from the Database of Contemporary Portugal (PORDATA), Statistics Portugal (INE), and the Urban Atlas land use and land cover (Copernicus Programme, 2012, 2018).

Overall, the built dataset consists of 4 dimensions organized in 15 sub-dimension, comprising 29 indicators and 254 measures, for two time periods focusing on the system dynamics over time and space (Table 2).

Table 2. Dataset for measuring smart and regenerative urban metabolism. (Where U.E.S. = urban ecosystem services, C.S.= cultural services, R.S.= regulating services, S.S.= supporting services, P.S.= provisioning services, N.S.= no services, A.S.= all ecosystem services.)

	Indicators	Data components/ measures	Timespan	U.E.S.
Social	Public participation and stakeholder engagement in decision making	Registered voters in the elections for the Local Authorities: voters and abstention	2009, 2017	C.S.
	Demography and migration	Resident population, according to the Census by major age group and sex:(0-14, 15-64, 65+)	2001, 2011	R.S.
		Annual population growth (Individual): (Natural increase, Migration net increase)	2011, 2018	R.S.
		Foreign population with legal resident status as a % of the resident population by sex (Proportion %)	2011, 2018	R.S.

	Population density (Ratio- Average no. of individuals/ Km²)	2011, 2018	R.S.
Fertility and Mortality	Crude birth rate - ‰	2011, 2018	S.S.
	Crude death rate - ‰	2011, 2018	S.S.
Education and training	Enrolled students in higher education by sex: (Males, Females)	2011, 2018	C.S.
	Enrolled students in pre-school, primary, lower secondary, and upper-secondary education by sex: (Males, Females)	2011, 2018	C.S.
	Schools in pre-school, primary, lower secondary, and upper-secondary education	2011, 2018	C.S.
	Teaching staff in pre-school, primary, lower secondary, and upper-secondary education	2011, 2018	C.S.
Welfare	Total dependency rate (Ratio - %)	2011, 2018	P.S.
	Proportion of buying power (Proportion - %)	2011, 2017	P.S.
	Purchasing power per capita - Index (number) - %	2011, 2017	P.S.
	Average monthly earnings of employees by the level of education and by sex: (Upper-secondary and post-secondary non-tertiary; Higher)	2011, 2018	P.S.
Employment-unemployment rates	Activity rate, according to the Census: by age group (25-34, 35-44) and by sex (total) (Rate - %)	2001, 2011	S.S.
	Unemployment rate, according to the Census: by age group (25-34, 35-44) and by sex (total) (Rate - %)	2001, 2011	S.S.
	Employment rate, according to the Census: by age group (25-34, 35-44) and by sex (total) (Rate - %)	2001, 2011	S.S.
Economy	Value of goods imported and exported by enterprises: (Imports, Exports) (€)	2011, 2018	P.S.
	Industrial, commercial, public, military, and private units (sqkm) (class 12100, urban atlas)	2012, 2018	P.S.
	Survival rate of Enterprises born 2 years before (Rate-%)	2011, 2018	P.S.
Touristic attractiveness	Guests in tourist accommodations per 100 inhabitants (Ratio - %- individual)	2011, 2018	C.S.

		Total incomes of tourist accommodations: total (€ - Thousands)	2011, 2018	C.S.
	Social inventions	Public Administration Retirement Fund: retirees and pensioners	2011, 2018	P.S.
		Social Security and Public Administration Retirement Fund pensions in total of the resident population aged 15 and over (Rate - %)	2011, 2018	P.S.
	Healthcare services and infrastructure	Inhabitants per doctor and pharmacist (Ratio)	2011, 2018	R.S.
		Pharmacies and mobile medicine depots	2011, 2018	R.S.
		National Health Service: beds in general and specialist hospitals	2011, 2018	R.S.
Cultural	Hard/ Soft cultural assets	Live shows: performances	2011, 2018	C.S.
		Live shows: box-office revenue (€ - Thousands)	2011, 2018	C.S.
		Cinema: screenings	2011, 2018	C.S.
		Cinema: box-office revenue (€)	2011, 2018	C.S.
		Museums: Number	2013, 2018	C.S.
		Art galleries and others temporary exhibition spaces (No.)	2011, 2018	C.S.
		Art galleries and other places for temporary exhibitions: exhibitions	2011, 2018	C.S.
		Cultural facilities: Number	2011, 2019	C.S.
		Town Council expenditure on culture and sports as a % of total expenditure: (Proportion - %)	2011, 2018	C.S.
	Cultural participation	Museums: total visitors (individual)	2013, 2018	C.S.
		Cinema spectators (No.)	2011, 2018	C.S.
		Live shows spectators (No.)	2011, 2018	C.S.
		Sports and leisure facilities (sqkm) (class 14200, urban atlas)	2012, 2018	C.S.

	Urban agriculture	Arable land (annual crops), Permanent crops, Pastures (sqkm) (classes 21000, 22000, 23000, urban atlas)	2012, 2018	A.S.
Technological	Housing quality	Licensed buildings by type of building work (New constructions- Extensions, alterations, and reconstructions)	2011, 2018	S.S.
		Buildings, according to the Census by type: Mainly residential - Mainly non-residential	2001, 2011	S.S.
		Conventional dwellings: total (Dwelling)	2001, 2018	S.S.
		Average bank valuation of flats by type: (Dwelling typology 2-berdoom, 3-bedroom) (Mean- €)	2011, 2018	S.S.
	Road network	Fast transit roads, other roads and associated land (sqkm) (classes 12210, 12220 urban atlas)	2012, 2018	S.S.
	Railway	Railways and associated land (sqkm) (class 12230, urban atlas)	2012, 2018	S.S.
	Maritime transport	Port areas (sqkm) (class 12300, urban atlas)	2012, 2018	S.S.
	Urban Fabric	Continuous urban fabric (S.L. > 80%) (sqkm) (class 11100, urban atlas)	2012, 2018	S.S.
		Discontinuous dense urban fabric (S.L. 50% - 80%) and Discontinuous medium density urban fabric (S.L. 30% - 50%) (sqkm) (classes 11210, 11220, urban atlas)	2012, 2018	S.S.
	Urban void	Land without current use (sqkm) (class 13400, urban atlas)	2012, 2018	N.S.
	Research and development	Employees in high technology sectors: by economic activity (research activities)	2011, 2018	C.S.
	Sewage and Waste management/treatment/recycling	Urban waste by type of destination t (tonne): (Landfill, Energy recycling, Organic recycling, Recycling)	2011, 2018	S.S. R.S.
		Urban waste selective collection per inhabitant (Ratio-kg/ inhab.)	2011, 2018	S.S. R.S.
		Urban waste collection per inhabitant (Ratio-kg/ inhab.)	2011, 2018	S.S. R.S.
		Dwellings connected to sewerage systems (Proportion - %)	2011, 2018	S.S. R.S.
	Energy systems	Electricity consumption per inhabitant by type of consumption kWh (kilowatt-hour) / inhab. - Ratio: (Street Lighting, State Buildings, non-Domestic, Domestic, Industry, Agriculture)	2011, 2018	P.S.

		Natural gas consumption per inhabitant (Ratio - Nm^3/ inhab.)	2011, 2018	P.S.
		Fuel sales for consumption t(ton): (Butane gas, Propane gas, Liquefied petroleum gas (LPG), Unleaded petrol 98, Unleaded petrol 95, Fuel diesel)	2011, 2018	P.S.
	Water systems	Water supplied/consumed per inhabitant (ratio- m3/ inhab.)	2011, 2018	P.S.
	Urban safety	Inhabitants per firemen (Ratio- individual)	2011, 2018	R.S.
		Crimes registered by the police: total and for some categories of crime: (Domestic violence against spouse or similar; Motor vehicle theft; Burglary in residence; Burglary in commercial or industrial building; Total)	2011, 2018	R.S.
		Deaths in road traffic accidents	2011, 2018	R.S.
		Injuries in road traffic accidents	2011, 2018	R.S.
		Pedestrian accidents deaths	2011, 2018	R.S.
		Pedestrian accidents	2011, 2018	R.S.
Ecological	Habitat-ecosystems	Urban Atlas (classes 3, 4, 5 including green urban areas)	2012, 2018	A.S.
	Environmental Protection	Expenditure by municipalities on the environment: by environmental management and protection domains (Euro-Thousands): (Protection of biodiversity and landscape; Protection against noise and vibrations; Waste management; Other areas)	2011, 2018	A.S.
		Expenditure of municipalities in environment as% of total expenditure (Proportion-%)	2011, 2018	A.S.
		Environmental Non-Governmental Organizations (ENGO): Number	2011, 2018	A.S.
	Air pollution	Annual mean concentration of PM10 particles (μg/ m^3); Annual	2013, 2018	A.S.
		Annual mean concentration of CO (8h) (mg/m3)	2014, 2018	A.S.
		Annual mean concentration of O3 (hourly) (μg/m3)	2013, 2018	A.S.

	Annual mean concentration of NO2 (VL=40 μg/m3) (ug/m3)	2013, 2018	A.S.
Air temperature	Annual mean air temperature (°C)	2012, 2018	A.S.
Soil exploitation	Mineral extraction and dump sites (class 13100, urban atlas) and Constructions sites (sqkm) (class 13300, urban atlas)	2012, 2018	A.S.
Water pollution	Quality for human consumption (Proportion %)	2011, 2018	A.S.

4.3.3 Urban metabolism sensitivity analysis and prediction

Coupling LCI and ML, we support the application of the smart and regenerative urban metabolism concept. The LCI under the ecosystem services perspective enables the smart and regenerative aspect of the system dynamics. ML allows us to capture the feedback effect coming from the different urban processes and system dynamics components. In this way, we encapsulate the circularity of urban metabolism, adopting a data-driven methodology. From the ML algorithms, we have used Artificial Neural Networks (ANN) to accomplish this task. ANN is an information processing technique that mimics the way in which a biological nervous system operates. It uses a variety of highly connected processing units that co-work to process information and generate meaningful results.

Specifically, in the STATISTICA software[10] environment, we developed an algorithmic representation of the urban metabolism of our study area, using the Multilayer Perceptron (MLP) a supervised algorithm of ANN, and create a network of 253 input units and one output unit (the dependent variable) where here represents the purchasing power per capita for the year 2018. MLPs are often identified as the most common neural network architecture that produces predictive models for one or more

[10] STATISTICA software is an advanced analytical package for data analysis, management, mining, statistics, ML, text analytics, data visualization. It can be used for predictive modeling, clustering, and classification. More details regarding the tools and applications of the software can be found on (StatSoft Inc., 2004).

dependent (target) variables based on the values of the predictor (independent) variables (Lievano & Kyper, 2006). MLP training procedure starts by setting a layered feedforward topology (input layer-hidden layer(s)-output layer). Then training algorithms using optimization functions set the network's weights and thresholds and update the network parameters at every iteration of the training aiming to minimize the prediction error[11] made by the network. Ultimately, a network is appropriately trained when it has learned to model the function that relates the input variables to the output variables. Therefore, it can be used to make predictions where the output is unknown (Lievano & Kyper, 2006). For explanatory or causal forecasting problems as of this study, the functional relationship of predictors and the dependent variable is of the form $y = f(x1, x2, \ldots, xp)$ where x1, x2,…,xp are p predictors and y the target variable (Zhang, Patuwo & Hu, 1998). Another important output that we can perform once the network is trained, is the sensitivity analysis on the network inputs. From this analysis, we can examine the inputs' interdependencies and obtain information regarding the variables of the data set that most affect the output of our analysis, or in other words the network's performance. To do so, sensitivity analysis rates the input variables according to the deterioration in network's performance that occurs if that variable is "unavailable" to the network. STATISTICA software has a missing value substitution procedure allowing forecasting where the value of one or more input variables v is missing. To define the sensitivity of a variable v, the network initially runs using a set of test cases, and the network error is accumulated. Then network runs again using the same test cases and replacing the observed values v with the estimated value by the missing value procedure and the network error is accumulated again. The variables are rated based on the ratio of the error with the missing value substitution to the original error; greater the ratio means greater the expected

[11] An error function combines all the differences between the actual outputs and the target outputs of all training cases and gives the networks error. For regression problems, the error function is usually the sum of the squared errors.

deterioration in error and therefore the network is more sensitive to the specific v input variable (StatSoft Inc., 2004).

To train the network, we typically divide the original data set into training, selection, and testing sets. The training set is normally the biggest in size and is used to learn the parameters of the model during the training process. The selection test or validation test is used to tune the parameters of the model (network configuration, regularization techniques, and so on) and eventually to select the "best" model. Finally, when the model has been trained, the testing set is used to evaluate its performance, ensuring that it can generalize well to unseen data.

We adopted an explorative approach to train our network, trying different sizes of hidden layers and units, learning algorithms and parameters aiming to find an affective network configuration for our study (Figure 3). Starting with the network's topology, we tested various approaches-rules of thumb suggested by the literature for choosing the number and the size of hidden units. One approach suggests that a hidden layer should never be more than twice as large as the input layer (Berry & Linoff, 1997). Another tested approach was that the number of hidden units should be 2/3 the size of the input units plus the output unit. We also tested the default configuration of STATISTICA software of one hidden layer with the number of hidden units equal to half of the sum of the input and output units. Another rule of thumb that we tied suggests that the second hidden layer has to be at least three times the size of the first hidden layer (Lippmann, 1987). Moreover, we also tested random sizes of hidden units, increasing or decreasing them according to the network's performance.

After setting the network's topology, we selected the linear approach to map the output variable using the identity activation function ($\gamma(c) = c$). This function takes real-valued arguments and returns them unchanged, supporting a substantial amount of extrapolation, although not unlimited (the hidden units will saturate eventually) (StatSoft Inc., 2004). We randomly assigned five out of nine (total) training cases to the training set, two to the selection set, and two to the testing set.

To start the training process, we followed a two-phased standard training procedure for MLPs. We used the Backpropagation learning algorithm for the first phase of 100 epochs. We tried different powerful algorithms for the second phase of 600 epochs Quasi-Newton (BFGS), and Levenberg-Marquardt, and the Conjugate Gradient Descent. The BFGS (Broyden–Fletcher–Goldfarb–Shanno) algorithm belongs to the Quasi-Newton methods. It is a local search optimization algorithm that approximates the inverse Hessian matrix. The approximation at first follows the line of steepest descent and later follows the estimated Hessian more closely. The BFGS's main drawback is that it needs O(n2) memory to store the inverse Hessian Matrix, making it impractical for most sophisticated ML models with millions of parameters. To decrease the memory cost, the Limited Memory BFGS (L-BFGS) extension can be applied to avoid storing the complete inverse Hessian approximation matrix (StatSoft, Inc. 2004); Goodfellow et al., 2016). The following tested optimization algorithm was the Levenberg-Marquardt (LM), a fast convergence algorithm for small networks, able to solve nonlinear least-square problems. LM combines the gradient descent and Gauss-Newton minimization algorithms. When the parameters of the network are far from their optimal value, LM acts more like a gradient-descent, and when the parameters are closer to their optimal value, it acts more like a Gauss-Newton (Gavin, 2019). The main disadvantage of LM algorithm is that can be very slow to converge when the network has more than ten parameters (Waterfall et al., 2006), and for flat functions can be lost in parameter space (Transtrum & Sethna, 2012). The last optimization algorithm tested was the Conjugate Gradient Descent that we eventually selected for the second phase of the training phase showing the best results for our network. The Conjugate Gradient Descent is an advanced optimization algorithm to train MLP recommended for networks with a large number of weights and/or multiple output units. The technical details on how the optimization algorithms carry out the network training process, how they update the network weights and minimize the prediction error are presented in the supplementary material.

For the first phase of training, we used a learning rate of 0.01 (initial and final) on each epoch. The learning rate is the amount that the weights are updated during the training; how far to move the weights in the direction opposite of the gradient. During the training, the backpropagation algorithm estimates the amount of error for which a node's weights in the network are responsible. Then the node's weight is updated based on learning rate-scaled error instead of the full amount of error. Using 0.01 learning rate, the weights of the network are updated 0.01 times the estimated weight error. To give faster training and better predictive accuracy to the network, we used a momentum value of 0.3. During the training, the gradient keeps changing direction and slower the process of training. Introducing the training momentum (a history of weights), the weights are adjusted to one direction smoothing the variations and making the training faster without losing information caused by highspeed convergence. We used the online type of training of Backpropagation that updates the weights of the network when each training case is presented. If all training cases are presented, and none of the stopping rules has been met, the process continues by recycling them. We shuffled the order of the presentation of the training cases at each epoch. The last parameter added for the first training phase was the Gaussian noise with a deviation of 0.1 to the output value on each training case. For the second phase of the training process no shuffle option was available since Conjugate Gradient Descent is a batch update algorithm that updates the weights once at the end of each epoch based on the average gradient of the error surface across all cases. For the same reason to avoid adding noise the learning rate and momentum are not available either (StatSoft Inc., 2004).

At the beginning of the training, we used the random-uniform method to initialize the network's weights normally-distributing small random values within a range of minimum and maximum values (0–1). We applied a pruning algorithm at the end of the training to prune neurons in input and hidden layers with fan-out weights below 0.05 since they don't significantly contribute to the network's performance. We also used sensitivity analysis with a ratio of 1.0 to perform input pruning. Considering that large weights make the network unstable, we applied a weight decay regularization to both training phases using a decay factor of 0.01. Overall, this parameterization road map forges the best network for the case study.

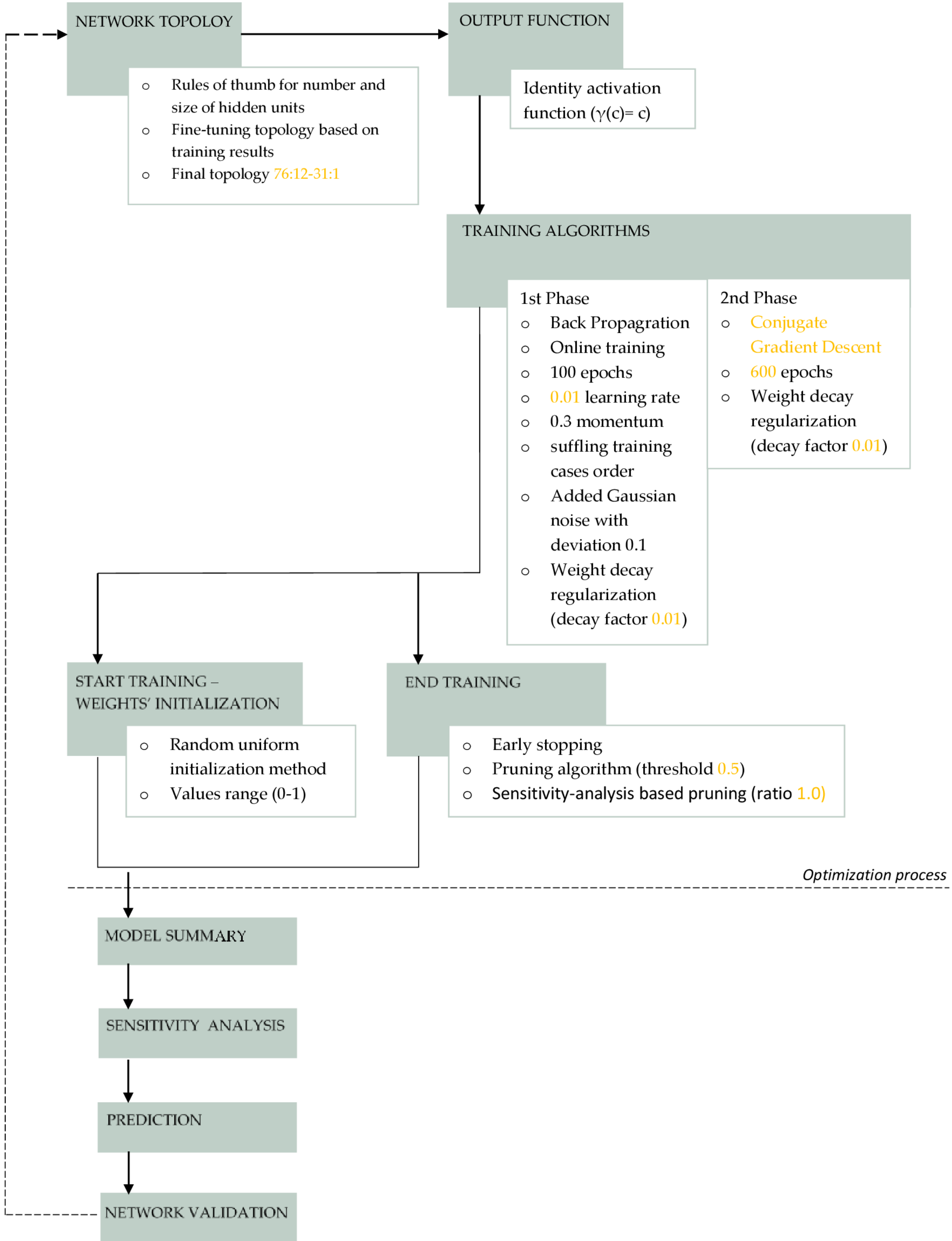


Figure 3. Flowchart of MLP network training.

After training more than 300 networks, we found the most effective model that generalizes well (Table 3). We trained the model with 76 input variables of the 253 having two hidden layers with 12 and 31 hidden units, respectively. Backpropagation with 100 epochs and Conjugate Gradient Descent (CG) were used to find the best network with the lowest selection error on the 593rd epoch of CG. The network's performance on the different data subsets used during the training process is shown in Table 3. The performance for regression networks like ours is the Standard Deviation Ratio. When the network's performance equals 1, the network performs as a simple average, and a lower ratio implies a better estimate. In Table 3, we can also find the network error on the subsets as the root mean squared (RMS) errors generated by the error function (sum-squared differences between the target and actual output values on each output unit). Based on a rule of thumb, when RMS error is greater or equal to 0.5, the model does not generalize well.

Table 3. Model summary.

Profile	Train Perf.	Select Perf.	Test Perf.	Train Error	Select Error
MLP 76:76-12-31-1:1	0.488857	0.837801	0.803547	0.216065	0.104959
	Test Error	Training/ Members	Inputs	Hidden nodes (1)	Hidden nodes (2)
	0.352127	BP100, CG593b	76	12	31

Another way to validate the model and assess its generalization ability in combination with the model summary is the graph of the training and selection errors on each epoch (Figure 4.). The training should stop when the training error curve and the selection error curve are close to each other. Flat lines or noisy values of relatively high error indicate that the model was unable to learn for the training dataset. The same applies when the training error curve continues to decrease at the end of the graph. In the opposite case, when the model has learned the training dataset too well (including noise or random fluctuations), while the training error curve continues to decrease through epochs and the selection error curve decreases up to a point and then starts to increase again. When the selection dataset does not provide enough information to evaluate the model's generalization ability, the selection error curve shows noisy movements around the training error curve even if the training error curve indicates a good fit. The selection dataset is unrepresentative also when the selection error curve is lower than the training error curve. On the other hand, when the training dataset is unrepresentative, both training and selection error curves show improvement, but there is a large gap between them. Our model's graph shows a good fit with the training and selection error curves to decrease to the point of stability with a very small gap between them.

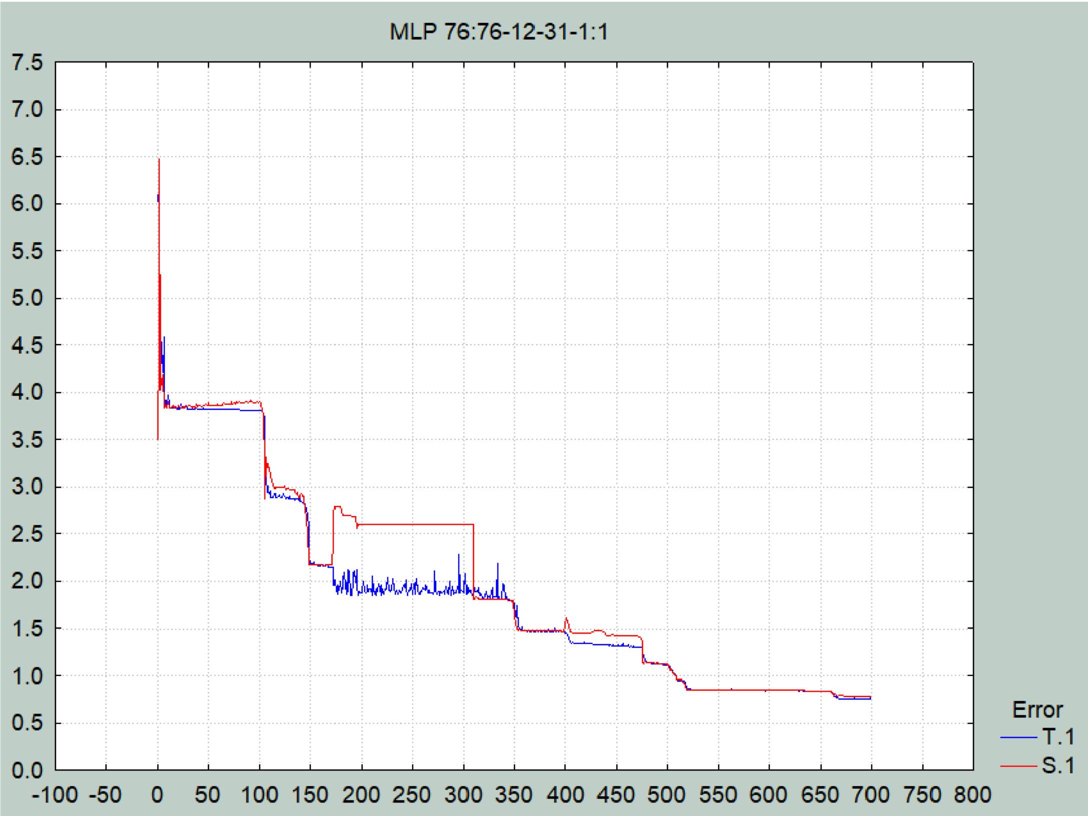
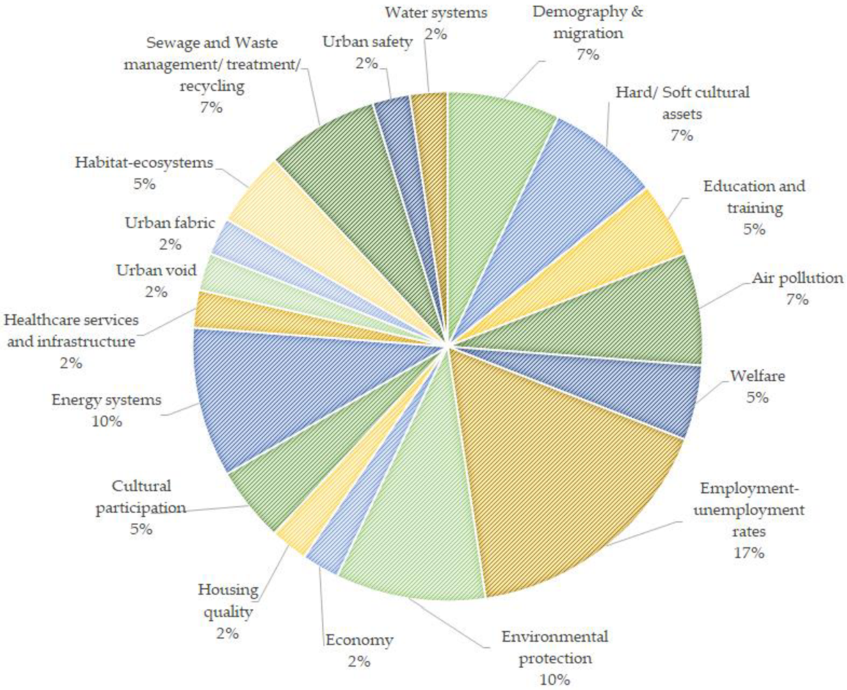


Figure 4. Network's training graph: training (T.1) and selection (S.1) error, axis(x) shows epochs, and axis(y) shows the error function.

4.4 Results

ANN - MLP network training provided us with two main outcomes. First, as a result of the sensitivity analysis, we obtained the main drivers representing the urban processes that most influence the predicted urban metabolism changes (the dependent variable) in terms of IpC changes. Second, we predicted where and to which degree these changes in urban metabolism will occur in the near future. In Table C2 (Appendix C), we present the output variables of our model's sensitivity analysis ranked by descendent order, from higher sensitivity (1) to lower sensitivity (76) based on their ratio. Focusing on the measures with a ratio of about one, we summarize the occurrence of the different data components/ measures (variables) per indicator (Figure 5). The summarized occurrence of the measures per indicator shows us to which urban processes the metabolic changes are more sensitive, examining holistically all the measures of the different metabolic dimensions of the study area. We see that the *Employment- unemployment rates* indicator measures have the greatest percentage of occurrence (17%) among the variables that most affect the network's performance. Second in place come the indicators Environmental protection, and *Energy systems* with 10% measures' occurrence. The indicators *Sewage and Waste management/treatment/recycling, Demography & migration, Hard/Soft cultural assets*, and *Air pollution* appear with 7% of measures occurrence followed by the *Education and training, Welfare, Cultural participation, and Habitat-ecosystems indicators' measures with 5%.* Last is the group of measures with 2% occurrence for the *Urban safety, Water systems, Economy, Housing quality, Urban void, Urban fabric,* and *Health services and infrastructure* indicators.



Indicators	Measures
Demography & migration	3
Hard/ Soft cultural assets	3
Education and training	2
Air pollution	3
Welfare	2
Employment-unemployment rates	7
Environmental protection	4
Economy	1
Housing quality	1
Cultural participation	2
Energy systems	4
Healthcare services and infrastructure	1
Urban void	1
Urban fabric	1
Habitat-ecosystems	2
Sewage and Waste management/ treatment/ recycling	3
Urban safety	1
Water systems	1
	42

Figure 5. Occurrence of data components/ measures per indicator with high sensitivity to urban metabolism changes (%).

The output of the sensitivity analysis shows evidence of the multidimensionality of a smart and regenerative urban metabolism. The most important measures (predictor variables) to urban metabolism changes cover all four metabolic dimensions, eleven out of fifteen subdimensions and eighteen out of 29 indicators (Table 4). Therefore, these indicators and related measures show a system-based representation of the interdependencies between different urban metabolic processes responsible for resource use, materials, energy and information circulation, waste production, and their associated performance throughout their entire value chain. These urban processes provide all urban ecosystem services benefiting human well-being.

Table 4. Important measures to urban metabolic changes under the perspective of ecosystem services.

Dimensions	Sub-dimensions	Indicators of Urban processes	Data components/ measures	Year	Code	Rank	U.E.S
Social	Human capital	Demography & migration	Resident population, according to the Census male 65+	2001	ml65_01	1	R.S.
Cultural	Cultural Mapping	Hard/ Soft cultural assets	Cinema: box-office revenue (€)	2011	cn_bxof11	2	C.S.
Social	Human capital	Demography & migration	Resident population, according to the Census female 65+	2011	fml65_11	3	R.S.
Social	Human capital	Education and training	Teaching staff in pre-school	2011	tch_pre11	4	C.S.
Ecological	Environmental quality	Air pollution	Annual mean concentration of NO2 (VL=40 μg/m3) (ug/m3)	2013	N02_13	5	A.S.
Social	Economic capital	Welfare	Average monthly earnings of male employees by Upper-secondary and post-secondary non-tertiary level of education	2011	ernml_upp11	6	P.S.
Ecological	Environmental quality	Air pollution	Annual mean concentration of PM10 particles (μg/ m^3); Annual	2013	PM10_13	7	A. S
Cultural	Cultural Mapping	Hard/ Soft cultural assets	Live shows: box-office revenue (€ - Thousands)	2001	lv_bxof01	8	C. S
Social	Economic capital	Employment-unemployment rates	Employment rate, according to the Census by age group (%) (35-44)	2011	empl3544_11	9	S. S

Ecological	Environmental protection	Environmental protection	Expenditure by municipalities on Protection against noise and vibrations (€ -Thousands)	2018	exp_noise18	10	A. S
Social	Economic capital	Economy	Industrial, commercial, public, military, and private units (sqkm) (class 12100, urban atlas)	2012	ind_ua12	11	P. S
Technological	Housing	Housing quality	Non-residential buildings, according to the Census	2001	tb_nrsd01	12	S. S
Social	Economic capital	Employment-unemployment rates	Unemployment rate, according to the Census male (%) (total)	2011	unmpl_ml11	13	S. S
Social	Economic capital	Employment-unemployment rates	Employment rate, according to the Census male (%) (total)	2011	empl_ml11	14	S. S
Cultural	Cultural participation	Cultural participation	Cinema spectators (No.)	2011	cn_spct11	15	C.S.
Technological	Utility systems and Infrastructure	Energy systems	Electricity consumption per inhabitant by type of consumption kWh (kilowatt-hour) / inhab. – Ratio: (street lighting)	2011	elc_strligh11	16	P. S
Social	Health system	Healthcare services and infrastructure	National Health Service: beds in general and specialist hospitals	2018	bed_hspt18	17	R. S
Technological	Utility systems and Infrastructure	Energy systems	Fuel sales for consumption t(ton): (propane gas)	2018	propn_18	18	P. S

Social	Economic capital	Employment-unemployment rates	Employment rate, according to the Census female (%) (total)	2011	empl_fml11	19	S.S.
Technological	Urban structure	Urban void	Land without current use (sqkm) (class 13400, urban atlas)	2012	ncuse_ua12	20	N.S.
Technological	Urban structure	Urban fabric	Continuous urban fabric (S.L. > 80%) (sqkm) (class 11100, urban atlas)	2012	cntufb_ua12	21	S.S.
Ecological	Habitat-ecosystems	Habitat-ecosystems	Urban Atlas classes 3,4,5 included urban green areas	2012	ecstm_12	22	A.S.
Ecological	Habitat-ecosystems	Habitat-ecosystems	Urban Atlas classes 3,4,5 included urban green areas	2018	ecstm_18	23	A.S.
Ecological	Environmental quality	Air pollution	Annual mean concentration of CO (8h) (mg/m3)	2014	CO_14	24	A.S.
Social	Economic capital	Employment-unemployment rates	Unemployment rate, according to the Census female (%) (total)	2011	unmpl_fml11	25	S.S.
Social	Economic capital	Welfare	Average monthly earnings of female employees by higher level of education	2011	ernfml_hgh11	26	P.S.
Social	Economic capital	Employment-unemployment rates	Unemployment rate, according to the Census female (%) (total)	2001	unmpl_fml01	27	S.S.
Technological	Utility systems and Infrastructure	Energy systems	Electricity consumption per inhabitant by type of consumption kWh (kilowatt-hour) / inhab. – Ratio: (agriculture)	2011	elc_agr11	28	P.S.

Technological	Utility systems and Infrastructure	Energy systems	Fuel sales for consumption t(ton): (fuel diesel)	2011	fueldsl_11	29	P.S.
Technological	Utility systems and Infrastructure	Sewage and Waste management/ treatment/ recycling	Urban waste collection per inhabitant (Ratio – kg/ inhab.)	2011	uw_clct11	30	R.S. S.S.
Technological	Utility systems and Infrastructure	Sewage and Waste management/ treatment/ recycling	Urban waste by type of destination t (tonne): (organic)	2018	uw_orgrcl18	31	R.S. S.S.
Social	Economic capital	Employment-unemployment rates	Employment rate, according to the Census by age group (%) (25-34)	2011	empl2534_11	32	S.S.
Cultural	Cultural participation	Cultural participation	Live shows spectators (No.)	2011	lv_spct11	33	C.S.
Social	Human capital	Education and training	Teaching staff in pre-school	2018	tch_pre18	34	C.S.
Technological	Utility systems and Infrastructure	Sewage and Waste management/ treatment/ recycling	Urban waste selective collection per inhabitant (Ratio – kg/ inhab.)	2011	uw_slctv11	35	R.S. S.S.
Technological	Utility systems and Infrastructure	Urban safety	Crimes registered by the police (motor vehicle theft)	2011	thfmoto11	36	R.S.

Technological	Utility systems and Infrastructure	Water systems	Water supplied/consumed per inhabitant (ratio- m3/ inhab.)	2011	water_cons11	37	P.S.
Social	Human capital	Demography & migration	Annual population growth (individual): (natural increase)	2018	grth_natu18	38	R.S.
Cultural	Cultural Mapping	Hard/ Soft cultural assets	Art galleries and other places for temporary exhibitions: exhibitions	2011	art_exh11	39	C.S.
Ecological	Environmental protection	Environmental protection	Environmental Non-Governmental Organizations (ENGO): number	2011	engo_11	40	A.S.
Ecological	Environmental protection	Environmental protection	Expenditure by municipalities on the environment (€ -Thousands) by environmental management and protection domains: (others)	2018	exp_oth18	41	A.S.
Ecological	Environmental protection	Environmental protection	Expenditure by municipalities on protection of biodiversity and landscape (€ -Thousands)	2018	exp_biolsc18	42	A.S.

The second output obtained from our model was the prediction with high accuracy of the urban metabolic changes in terms of IpC changes for the UCL for the year 2025. The year 2025 is calculated by adding to the present year (2018) the number of years (7) between the two time periods of the input data (2018, 2011). Looking at Table 5, we can observe that the degree to the UCL's urban metabolism at the municipality level either increases, decreases, or stays stable in 2025. In order to have a spatial visualization upon where the forecasting metabolic changes in 2025, we mapped the current metabolism of our study area (Figure 6) and the prediction results of the urban metabolism (Figure 7) at the municipality level.

Results show that Lisbon's metabolism decreased dramatically, followed by Cascais' and Almada's in 2025. On the other hand, Loures, Odivelas, and Seixal show an increased metabolism of the same class (Figure 6, 7). The municipality of Oeiras has one of the highest urban metabolism in 2018, and it continues to have for the year 2025. Amadora municipality does not show any significant metabolic changes for the near future, contrary to Barreiro's municipality that presents an intensive metabolism.

From our previous analysis, the main drivers of these metabolic changes are the urban processes related to the 42 higher ranks of higher sensitivity (Table 4). Therefore, those with decision responsibility can either stabilize, increase, or decrease the metabolism of the study area by activating these key metabolic drivers. Knowing the degree, the spatial distribution of the future metabolic changes, and the key drivers of change provides important information to link with potential urban development strategies related to urban governance. Provided by specific guidance coming from our model, we can enhance the relevant urban metabolic functions and services in a way to plan and manage resilient and sustainable urban development.

Table 5. Purchasing power per capita by municipality for the years 2018 and 2025.

Municipalities	IpC 2018	IpC 2025
Lisboa	219.6	172.1422
Loures	92.3	104.6195
Odivelas	89.3	104.1329
Amadora	100.6	100.6236
Oeiras	156.5	173.5109
Cascais	122.1	89.2158
Almada	108.7	91.0583
Seixal	89.7	106.8435
Barreiro	100	162.4113

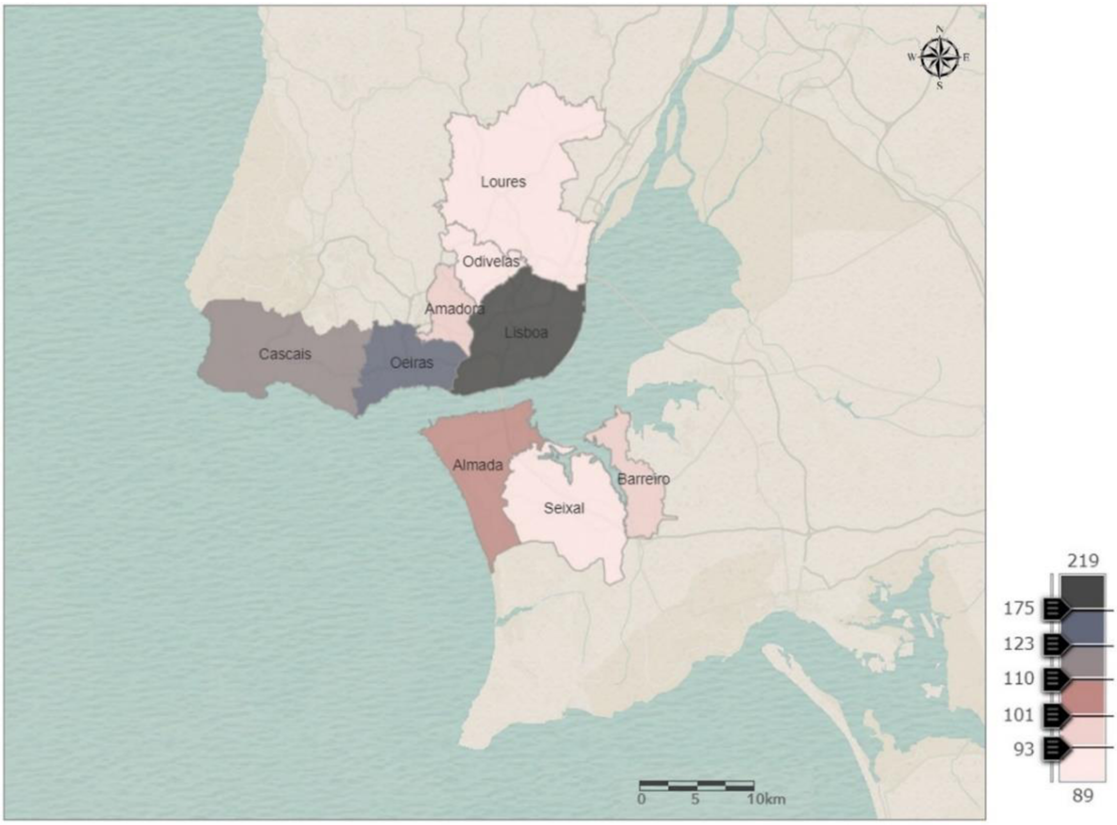


Figure 6. Urban metabolism per municipality for the year 2018.

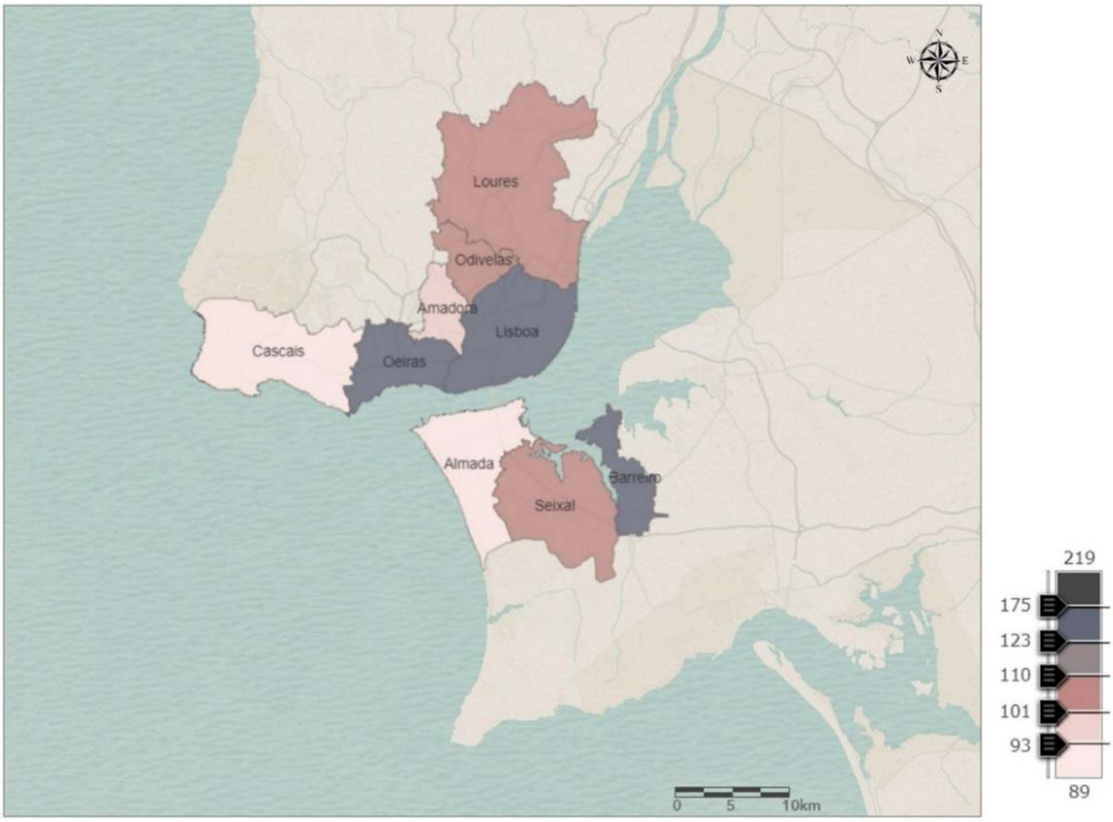


Figure 7. Urban metabolism per municipality for the year 2025.

4.5. Discussion

Urban cores are complex systems where various urban processes are responsible for resource use, flows of materials-energy-information, and waste emissions, establishing social, cultural, technological, and ecological relationships. Therefore, urban cores have their own metabolism, requiring a systematic approach that encapsulates its complexity and assess its sustainability. Adopting the concept of smart and regenerative urban metabolism, we describe the urban processes and their relationships as circular ongoing, co-evolutionary, focusing on eliminating waste by regenerating resources using technology. The urban processes represent different sub-systems of the urban system of which they are part. They are delimited by flexible and open boundaries that allow communication channels between the sub-systems and beyond the system boundary enabling their interdependence. In line with the UM framework, we treat the urban systems like ecosystems and the services offered by the different urban processes as ecosystem services. Natural ecosystems provide functions and services essential to human welfare and long-term survival. Studying the structure and services of ecosystems, we obtain guidance on how to achieve system resilience. In this way, we can build a research framework supporting a holistic understanding of how urban systems function, considering their multiple dimensions. Therefore, we can design a methodology able to capture the metabolic dynamics highlighting the impact of urban ecosystem services on urban sustainability.

We proposed a novel methodology that couples LCT and ML under ecosystem services perspective. LCT is the way of thinking of the consequences in the environmental, economic, and social dimensions of a product/process/system of processes throughout its entire life, meaning the effects on ecology, resources, and human health (Farjana, Parvez Mahmud & Huda, 2021). It facilitates the links between the different dimensions of urban processes aiming to reduce resource use, waste production and improve a process's socioeconomic performance through its entire cycle. The main limitations when applying LCT and mostly LCA at the city level are the definition of system boundaries giving insights into the fundamental urban dynamics, the appropriate functional units, and the use of data that capture the complexity of urban systems at micro and macro scales. Indeed, to measure and access UM at a local scale demands data with a high level of granularity produced and or collected systematically through time and space and with ground truth. Unfortunately, the type of multidimensional data meeting such requirements is scarce, affecting knowledge-based analysis due to uncertainty and data gaps.

Coupling LCT with ML, we are able to overpass/minimize these limitations, modeling a neural network of the different urban processes. ML algorithms have proven to be suitable for dealing with problems of data scarcity, where are uncertainty and unpredictable system dynamics. Although the demand for quality data at a local and even human scale still remains to be fulfilled, ML algorithms can work with data gaps and help the network perform better, enhancing its integrated systematic multidimensionality. For instance, while preparing the input dataset for implementing the proposed research framework at municipality level, we faced difficulties to encounter crucial data to measure important urban metabolic processes related to food consumption, construction materials, air quality measures at human scale, noise pollution, number of passengers transported by public transportation, domestic material consumption, number of people exposed to conditions beyond a critical threshold, among others.

Moving to the network training process's limitations, we must confront the general nonconvex case during the training. When training neural networks, ML traditionally avoids the general optimization problems by designing the objective function and constraints to guarantee that the optimization problem is convex. Although, even convex optimization comes with complications (Goodfellow et al., 2016). There are a few main challenges involved when optimizing convex functions—starting with the ill-conditioning of the Hessian matrix a common problem in numerical optimization where the Stochastic Gradient Decent (SGD) is "stuck" meaning that even very small steps of the gradient increase in cost function, the learning is very slow regardless a strong gradient (Goodfellow et al., 2016). Another important optimization issue is the convergence to a local minima when the training algorithm stops in a low point (the lowest of the surrounding terrain) rather than continuing to seek for the global minima, and therefore, it has not learned the entire training set. Plateaus, Saddle Points, and Other Flat Regions are common nonconvex optimization problems. In these points or regions on the landscape, the gradient is zero (very flat), which means it does not know which direction to move to optimize the model; therefore, the iterative algorithm is stuck mimicking local minima (Bishop, 1995).

An important task of neural networks is to have a final model that can perform well both on the training dataset and the unseen dataset (test dataset). When the predictive model has learned from the details of the training set (noise in the data) instead of the general behavior (the underlying function), it has overfitted the training dataset, and therefore, it is not able to perform the same with the testing set. Overfitting is a typical cause of poor generalization of the model, having high generalization error. A predictive model can underperform when it has learned too little from the training dataset and does not perform well on the testing dataset (underfitting).

In order to tackle these challenges while training neural networks, we looked for the optimum network topology (structure), and configuration we tried different training algorithms. We used regularization methods (parameters) to control the complexity of the network. Going through the literature, we noticed that there is not a consensus regarding the number of hidden layers and hidden units to be used, we tested the related rules of thumb. We trained the network using a two-phased MLP designed to address problems related to convergence to local minima and network overfitting. More precisely, the first stage is a light run on backpropagation in conjunction with a soft training rate in order to perform the raw convergence. This first stage could be sufficient to solve simple problems. Due to the complexity of the systems under analysis, the first phase is not enough. Therefore, we moved to the second more powerful training phase, using an extended run of conjugate gradient descent. As it benefits from the backpropagation performance first stage, this algorithm is less likely to bump into convergence problems.

We tried different learning rates for the first phase of training until finding the best for our network. If the learning rate is very low, the training process will take too much time with no significant updates to the weights. On the other hand, if the training rate is too high, it results in an undesirable divergent function behavior. We also added Gaussian noise to the output value on each training case to reduce the network's tendency to overfit. We used smaller weights and early stopping to reduce the problem of overfitting. We shuffled the order of the presentation of the training cases at each epoch, so the training algorithm to be less prone to stuck in a local minima. We applied a sensitivity analysis-based pruning algorithm, using a threshold ratio equal to 1.0. In this way, we excluded the input variables with sensitivity analysis below 1.0 to not compromise the network's performance since it most likely constitutes a by-product of overfitting.

We conclude that the network optimization process cannot be based on rules of thumb but by conducting an exploratory procedure consisting of fine-tuning the network parameters based on the previous training results. It is worth mentioning that the complexity of the network under study is based on the complexity of the dataset.

When the optimization process was successfully completed, we performed sensitivity analysis on the network's input to identify the most influential indicators and their related measures for the urban metabolism changes (Table 4, Table C2). It is essential to highlight that the rate of the indicators' sensitivities does not occur in an absolute manner; instead, it is measured considering the interdependencies between the input variables. Therefore, the obtained results regarding the importance of particular indicators concern the specific network considering the specific dataset used. The metabolic changes in this study are expressed in terms of purchasing power per capita (IpC) changes. As mentioned before, the IpC is a composite indicator provided by STATISTICS Portugal as a result of a factorial analysis using 16 variables. Using IpC for two time periods in our analysis it is important to say that there is a risk that the variation in IpC values could be a result of using associated variables that do not totally match between the different years or to use different reference periods for the associated data. For the purpose of this study, we assume that the IpC values of the two different years have been calculated using the same associated variables with the same year of reference. Knowing the key indicators causing metabolic changes, the degree of these changes, and their spatial location, one step further would be to qualitatively assess the metabolic changes. For instance, an increase in the urban metabolism in terms of IpC is predicted to happen in the municipality of Barreiro for the year 2025. What does this increase mean? that consumption and production in the area are going to increase due to increased migration? or due to individual earnings increase? or due to poor environmental protection policies that do not promote circular economy principles of reuse, reduce, recycle? Insights can be drawn by studying the dynamic changes of the key indicators as a result of the current study in the two different years of study (2011, 2018) individually and as a sum.

The proposed methodology can be applied to evaluate the multidimensional urban metabolism of urban areas and compare the metabolism of different urban areas at different levels; neighborhood-place; parish; municipality; metropolitan; country depending on the scale of the available data to be used for the analysis. The methodological framework and the proposed workflow are reproducible and can be used in different geographies to identify the main drivers for the urban metabolism changes, as well as to enable an alternative vision of the future. This approach contributes to both evidence-based policymaking and for professionals to adopt a new urban planning paradigm, more in line with the environmental and societal challenges cities are facing.

4.6 Conclusions

This study carries out a UM-LCT-ANN methodological framework from an ecosystem services perspective to overcome the limitations of previously applied UM methodologies and extend the state of the art of the subject. The proposed framework is applied to the urban core of Lisbon's functional urban area allowed us to obtain evidence-based knowledge on the complex metabolism of the different urban processes. The study results demonstrated the main drivers causing urban metabolic changes, and in which degree, and where. We were also able to forecast/predict urban metabolism changes for the near future, providing a data-based vision of how urban metabolism unfolds. Even though different urban processes require different dimensions and scales of analysis to measure and assess their metabolism accounting for the flows and storage of energy-material-information and their socioeconomic and environmental impacts, it is of utmost importance to design a framework that can be applied at various temporal and spatial scales. The proposed research framework has the ability to investigate the interdependencies of the urban metabolic processes of different dimensions holistically through time and space. Along with its main findings, we have shown that our methodology can be used as a tool to develop efficient policies for improving and fostering urban sustainability and contribute to a change of paradigm for urban planners and urban designers practitioners. Further research would be to build different scenarios based on experts, stakeholders, and local communities' visions, on how a city should be.

Supplementary material

Table S.A. Technical details of used algorithms.

Algorithm	Conceptual description	Mathematical description
Quasi-Newton (BFGS) (Broyden-Fletcher-Goldfarb-Shanno)	A powerful second-order training algorithm with very fast convergence but high memory requirements.	It is a batch-based algorithm that calculates the error gradient as the sum of the error gradients on each training case. It is formulated in terms of maintaining an approximation to the inverse Hessian matrix (H). The direction of the steepest descent is called *g, fi* is the weight vector on the ith epoch. *H* is initialized to the identity matrix, so that the first step is in the direction. On each epoch, a backtracking line search is performed in the direction: $d = -Hg$ The search direction is updated using the BFGS formula: $H_{i+1} = H_i + \frac{(x_{i+1} - x_i) \otimes (x_{i+1} - x_i)}{(x_{i+1} - x_i) \bullet (\nabla f_{i+1} - \nabla f_i)} - \frac{[H_i \bullet (\nabla f_{i+1} - \nabla f_i)] \otimes [H_i \bullet (\nabla f_{i+1} - \nabla f_i)]}{(\nabla f_{i+1} - \nabla f_i) \bullet H_i \bullet (\nabla f_{i+1} - \nabla f_i)} + [(\nabla f_{i+1} - \nabla f_i) \bullet H_i \bullet (\nabla f_{i+1} - \nabla f_i)] u \otimes \mathrm{u}$
Levenberg-Marquardt	An extremely fast algorithm in the right circumstances - low-noise	The Levenberg-Marquardt algorithm "is designed specifically to minimize the sum-of-squares error function, using a formula that (partly) assumes that the

	regression problems with the standard sum-squared error function.	underlying function modeled by the network is linear. Close to a minimum this assumption is approximately true, and the algorithm can make very rapid progress. Further away it may be a very poor assumption. Levenberg-Marquardt therefore compromises between the linear model and a gradient-descent approach. A move is only accepted if it improves the error, and if necessary, the gradient-descent model is used with a sufficiently small step to guarantee downhill movement". Levenberg-Marquardt uses the update formula: $\Delta w = -(Z^T Z + \lambda I)^{-1} Z^T{}_E$ where E is the vector of case errors, and the matrix of partial derivatives of these errors with respect to the weights is referred to Z.
Back propagation	A simple algorithm with a large number of tuning parameters, often slow terminal convergence, but good initial convergence. STATISTICA Neural Networks implements the on-line version of the algorithm.	STATISTICA software uses the on-line version of back propagation calculating the local gradient of each weight with respect to each case during training. Weights are updated once per training case using the following formula: $\Delta w_{ij}(t) = \eta \delta_j o_i + a \Delta w_{ij}(t-1)$ where η is the learning rate, δ the local error gradient, α is the momentum coefficient, o_i is the output of the i'th unit. Thresholds are treated as weights with o_i = -1.
Conjugate gradient descent	A good generic algorithm with generally fast convergence	Conjugate gradient descent is batch-based where the error gradient is calculated as the sum of the error gradients on each training case. The initial search direction is given by: $d_o = -g_o$

		Afterwards, the search direction is updated using the Polak- Ribiére formula: $$d_{j+1} = -g_{j+1} + \beta_j d_j$$ $$\beta_j = \frac{g_{j+1}^T (g_{j+1} - g_j)}{g_j^T g_j}$$

Source: StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com.

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Chapter 5

5. Conclusions

"The freedom to make and remake our cities and ourselves is,
I want to argue, one of the most precious
yet most neglected of our human rights."
David Harvey

5.1 Commentary on articles

This dissertation thesis aimed to build a conceptual framework and a methodological protocol to tackle the challenges generated by modern urbanization, ensuring urban sustainability and resilience. Modern urbanization takes the form of rapid, massive, unplanned, and uncontrolled urban expansion, leading to increased energy demand, natural resources exploitation, consumption, and waste production, resulting in social, economic, and environmental challenges. To this end, we need to understand the complexity of urban systems and balance their interrelation with the natural systems. This can be achieved by coupling the systematic, rational model in urban planning with the sustainability of ecosystems. Natural ecosystems provide functions and services beneficial to human wellbeing and long-term survival. Looking at the ecosystems' structure and services, we obtain knowledge on how to achieve system resilience. Using the urban metabolism framework, we include ecological principles in the planning and design of urban systems.

As mentioned in the introduction chapter, when properly planned and controlled, urbanization can be beneficial to urban sustainability transitions. While a growing body of empirical studies analyzes urbanization revealing its impacts (Noreen Noor Abd Aziz et al., 2012; Yunsong & Yi, 2016; Sheng et al., 2017; Wang et al., 2019; Anser et al., 2020; Haryanto et al., 2021), less attention has been given to the evolution of the various concepts of sustainable urban development. In the first published article (Chapter 3), we conducted a literature network analysis to study the evolution of the emerging concepts on sustainable urban development shedding light on the state of the art of smart and regenerative urban design under the urban metabolism framework. Using VOSviewer software, we constructed bibliographic network maps showing the relatedness of concepts, documents, key referenced works, and top influential authors.

Initially, we indicated three main research trends (clusters). The first research trend attempts to understand the urban processes and apply this knowledge to tackle urban challenges and problems. It seeks policies and strategies that support sustainable urban development, offering opportunities for urban regeneration involving different stakeholders. The second research trend studies urban systems and their negative environmental impacts under the urban metabolism framework at a regional scale of analysis. Under urban metabolism, the consumption of resources, the flows of energy and material within urban systems (i.e., water, transportation), and the resulting outcomes to other systems in the form of pollution, waste, or export products are modeled. The third research trend describes the inclusion of the "smart city" concept in urban planning and management at different scales of analysis. The smart city concept benefits the citizens by improving the overall quality of life, offering solutions, providing technological infrastructures for access to services and information.

We went one step further and we identified six key sub-research trends (6 clusters) and their interrelation. In short, the first sub-research trend studies socially, environmentally equitable, and sustainable communities for sustainable urban development. The second sub-research trend highlights the inclusion of ecological principles in urban planning through urban metabolism for a sustainable urbanized world. The third sub-research trend focuses on the urban metabolism evolution towards urban sustainability. The fourth sub-research trend discloses the smart concept meaning. The fifth sub-research trend offers a new economic paradigm: a socio-ecological systematic economy supported by technology and the sixth sub-research trend studies urban metabolism and regenerative urban design for future cities. After this analysis, we identified the most influential authors per sub-concept, and finally, we traced the origins of these key sub-research trends related to the urban growth and sustainable urban development literature under analysis.

Key findings of the literature network analysis indicate that urbanization/urban growth is multidisciplinary and interdisciplinary, integrating social, ecological, political, economic sciences, culture and arts, environmental, and computer sciences. In addition, obtained evidence shows that the smart concept and the regenerative concept for urban sustainability appear to be not connected or with no strong links.

In the second published article (Chapter 3) we attempted to fill this literature gap by conceptualizing Smart and Regenerative Urban Places (SRUP) able to face the urban complexity challenges. The proposed novel conceptual framework SRUP offers an integrated and expanded systematic analysis of the metabolism of urban places. We integrated urban smartness and regenerative design through sustainability principles, and we have demonstrated that an urban place to be truly smart needs to be regenerative and vice versa. We used the urban place as a scale of analysis offering the sense of safety, security, and identity, driven by the attachment bonds as a mix of cultural and physical features of its inhabitants. SRUP constitutes a paradigm shift from the mechanistic linear approach of permanent equilibrium to metabolic nonlinear approach out-of-equilibrium coupled with life cycle thinking (LCT). With life cycle thinking we highlight the multidimensionality of urban metabolism and the multi-impacts of different urban systems. We defined four dimensions; social, cultural, technological, and ecological of urban metabolism comprised of different urban systems/ processes. The relationship between the urban systems under SRUP framework is open, ongoing, and co-evolutionary. Given a co-evolutionary context, we highlight the need for continually maintaining and improving the relationship between human and natural capital in an integrating way.

Implementing SRUP requires investments and collaborations between different stakeholders and engagement of public participation in the process. Urban systems are complex systems characterized by uncertainty and found in permanent change. Therefore, an integrative and holistic approach is required to plan, design, and manage the different urban systems as a whole. Under SRUP conceptual framework urban places are able to face long-standing urban challenges, such as environmental injustice, social inequity, poverty, urban ecosystems under pressure among others.

In the third published article (Chapter 4), the goal was to implement the novel conceptual framework SRUP by developing and applying an original methodology able to capture, measure, and assess the complexity of the different urban metabolic systems/ processes and the services they deliver beneficial for human survival and well-being. The applied research phase of the dissertation thesis hands-on phase allows us to identify some key methodological limitations of applied research on urban metabolism framework, namely the lack of integrated multi-impact analysis, the rare acknowledgment of urban ecosystem services impact, and challenges on the determinations of systems boundaries (Bakshi et al., 2015 as cited in Liu et al., 2019; Ramos & Rouboa, 2020; Wang et al., 2020). Our proposed novel methodology addresses these limitations. It assesses the multidimensional urban metabolic processes by coupling life cycle thinking (LCT) with machine learning (ML) from an ecosystem services perspective. The ecosystem services perspective facilitates building a research framework that supports a holistic understanding of urban systems' functioning, deeming their multiple dimensions. Therefore, this new and novel applied research designed a methodology able to capture the metabolic dynamics including the impact of urban ecosystem services on urban sustainability. Adopting LCT we consider the economic, social, and environmental consequences of a product/process/system of processes throughout its entire life. LCT enables the interconnections between the different metabolic dimensions (social-cultural-technological-ecological) aiming to decrease resource use, waste production and to improve a process' socio-economic performance through its entire cycle.

As found in literature, the main limitations when applying LCT and mostly Life Cycle Assessment methodologies are the determination of system boundaries giving insights into the fundamental urban dynamics, the appropriate functional units, and the use of data that capture the complexity of urban systems at micro and macro scales. Coupling LCT with machine learning to model a neural network of the different urban processes, we were able to pass over and minimize such limitations. Moreover, by adopting our methodological protocol, it is possible to identify the main drivers responsible for urban metabolic changes and to forecast metabolic changes for the near future (2025), with a high degree of confidence.

As proof of concept, we applied our methodological protocol using the urban core of the Functional Urban Area (FUA) of Lisbon city to assess and predict its smart and regenerative urban metabolism. We build a Multilayer Perceptron (MLP) network of 254 data components that measure 29 indicators representing different urban 4-dimensional metabolic processes for two time periods. We selected the purchasing power per capita (IpC) as the dependent variable of the MLP network and the other 253 measures comprise the set of the independent variables. We classify these indicators and their measures according to the four well-known groups of the Millennium Ecosystem Assessment (MA), 2005 classification system (provisioning services, regulating services, supporting services, and cultural services). The simulated results show that the urban processes related to Employment-unemployment rates (17%), Energy systems (10%), Sewage and Waste management/treatment/recycling, Demography and migration, Hard/Soft cultural assets, and Air pollution (7%), Education and training, Welfare, Cultural participation, and Habitat-ecosystems (5%), Urban safety, Water systems, Economy, Housing quality, Urban void, Urban fabric, and Health services and infrastructure (2%), consists the salient drivers for the urban metabolic changes. The results of the most important urban processes causing urban metabolism changes provide all MA ecosystem services, they confirm the multidimensionality of urban metabolism and therefore the need to adopt a holistic systematic approach including the ecosystem services perspective for its sustainable planning and design.

Results of the study area's metabolism prediction show that Lisbon's metabolism decreased dramatically, followed by Cascais' and Almada's in

2025 (Figure 7, subchapter 4.4). In contrast, the municipalities of Loures, Odivelas, and Seixal present an increased metabolism of the same class. The municipality of Oeiras has one of the highest urban metabolisms in 2018, which remains for the year 2025. Amadora municipality does not appear to have any significant metabolic changes for the near future, contrary to Barreiro's municipality, which shows an intensive metabolism. Knowing the key indicators causing metabolic changes, the degree of these changes, and their spatial location, further research would be to assess the metabolic changes qualitatively. For instance, in the case of an increase in the urban metabolism in terms of IpC what it means in terms of consumption, production, individual earnings among other urban processes. Insights can be drawn by analyzing the dynamic changes of the key indicators as a result of the current study in the two different years of study (2011, 2018) individually and as a sum.

5.2. Contributions and perspectives

Revisiting our research hypothesis "*Adopting Life Cycle Thinking to study urban metabolism under ecosystem services perspective for the design of smart and regenerative urban places is the way to achieve sustainability and reinforce system resilience*", we may conclude that sustainable urban metabolism can be achieved through a smart and regenerative scenario of urban planning and design as has been proven in Chapter 3 and 4. For doing so, essential requirements that need to be met are initially to understand the urban metabolism of the multidimensional urban systems/processes as open, circular, ongoing, and co-evolutionary through a Life Cycle Thinking. Secondly, we need to perceive the urban systems like ecosystems and the services provided by the different urban processes as ecosystem services. On this wise, we re-design the urban place's metabolisms on the way to be attractive and liveable, competitive and effective, and innovative with a greater goal of the restoration of the health of the natural resources recognizing the value and the impact of ecosystem services on human well-being and survival.

Summarizing what makes this dissertation thesis pivotal to the urban metabolism studies are a) the integration of smart and regenerative concepts b) the multidimensionality of urban metabolic processes under LCT c) the use of urban place scale, d) the implementation of SRUP using machine learning methods and techniques, such as ANN. This dissertation thesis, from a scientific point of view, contributes to the state of art by filling the identified literature gaps on the concepts of sustainable urban development and on applied methodologies of urban metabolism. From the applied point of view, the developed methodological framework contributes to the need for more advanced methods able to tackle the challenges related to the lack of data and urban complexity challenges. Moreover, the methodological protocol makes it possible to identify the main drivers that cause metabolic changes and to forecast possible future metabolic changes, answering to where and to which degree. It provides evidence-based outcomes for policymaking and professionals to adopt a new urban planning and designing paradigm, able to tackle the environmental and societal challenges that cities are facing.

5.3 Directions for future work

Even though the goal of this dissertation thesis has been accomplished, the implementation of the methodological framework could provide more realistic results if we had access to data that cover all urban metabolic processes as defined in the conceptual framework, historical and data that have been produced systematically in time and space. Meaningful georeferenced data at a high-resolution scale help us to build evidence-based knowledge about the geographical variations and therefore to understand the geographical patterns and set customized geographical policy recommendations.

One of the main outputs of the methodological protocol implementation was the quantitative prediction of the metabolic changes for each municipality understudy for the year 2015. Due to the enormous time consumption that was required to train a learning network under the current circumstances (data issues), time did not allow us to pursue our research with a deeper analysis of the metabolic changes and provide a qualitative assessment of the predictions as mentioned in the previous subchapter. However, we recognize the scientific relevance of further research upon building scenarios for forecasting urban metabolic changes based on experts' knowledge, visions of different stakeholders, and local communities' needs and perceptions, and complete the life cycle thinking by conducting a life cycle assessment on these different scenarios.

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Appendix A

Table A1. Number of citations of documents per cluster based on the bibliographic coupling analysis (Doc.= documents, Cit.= citations).

CLUSTER 1 (60 Items)		CLUSTER 2 (47 Items)		CLUSTER 3 (40 Items)		CLUSTER 4 (40 Items)		CLUSTER 5 (31 Items)		CLUSTER 6 (10 Items)	
Doc.	**Cit.**	**Doc.**	**Cit.**	**Doc.**	**Cit.**	**Doc.**	**Cit.**	**Doc.**	**Cit.**	**Doc.**	**Cit.**
Arbaci (2012)	31	Alexandrescu et al. (2018)	6	Barles (2010)	86	Ahvenniemi et al. (2017)	77	Caputo et al. (2012)	13	Davoudia and Sturzakerb (2017)	10
Baba (2017)	2	Artmann (2014)	20	Basiri et al. (2017)	3	Al Nuaimi et al. (2015)	78	Dell`ollo et al. (2014)	10	Haghshenas and Vaziri (2012)	80
Bailey (2012)	30	Artmann (2014b)	28	Blecic et al. (2014)	10	Albino et al. (2015)	260	Farmani et al. (2012)	10	Li et al. (2017)	0
Barbour et al. (2016)	1	Barbosa et al. (2012)	135	Broto et al. (2012)	70	Angelidou (2014)	125	Grekousis et al. (2019)	0	Liu (2012)	30
Belanche et al. (2016)	34	Beck et al. (2013)	7	Chen and Chen (2019)	127	Batty et al. (2012)	372	Haapio (2012)	88	Moore et al. (2013)	56

Biddulph (2011)	29	Berta et al. (2016)	5	Chester et al. (2012)	33	Betz et al. (2016)	6	Hale and Sadler (2012)	12	Newton and Glackin (2014)	19
Blessi et al. (2012)	17	Bonafoni et al. (2017)	10	Chrysoulakis et al. (2013)	53	Bibri and Krogstie (2017)	58	Herrschel (2013)	26	Pojani and Stead (2015)	40
Bulkeley et al. (2016)	14	Breuste et al. (2013)	15	Conke and Ferreira (2015)	23	Caragliu et al. (2011)	576	Jansson (2013)	60	Thomson and Newman (2018)	4
Codecasa and Ponzini (2011)	16	Bridges (2016)	2	Cui et al. (2019)	0	Crivello (2014)	17	Jim (2013)	43	Van Timmeren et al. (2012)	6
Couch et al. (2011)	67	Chelleri et al. (2016)	2	Dijst et al. (2018)	4	Falco et al. (2018)	0	Kaur and Garg (2019)	1	Webb et al. (2018)	11
Cuthill (2010)	91	D'Al.isa et al. (2012)	32	García-Guaita et al. (2018)	1	Falco et al. (2019)	0	Rosa (2014)	43		
Deakin (2012)	11	Dierkes et al. (2015)	19	Goldstein et al. (2013)	42	Ejaz et al. (2017)	54	Rosa et al. (2017)	9		

Degen and Garcia (2012)	79	Francesch-Huidobro (2015)	8	Gonzalez et al. (2013)	47	Garau and Pavan (2018)	28	Leigh and Hoelzel (2012)	21
Dempsey et al. (2011)	27 5	Gaitani et al. (2014)	14	Huang et al. (2018)	0	Garau et al. (2016)	7	Lombardi et al. (2011)	40
Dempsey et al. (2012)	76	Girard (2013)	26	Inostroza (2014)	24	Gazzola et al. (2019)	0	MacLeo d (2013)	37
Dixon et al. (2011)	22	Grêt-Regamey et al. (2013)	48	Kennedy et al. (2011)	258	Gharaibeh et al. (2017)	32	Marsal-Llacuna and López-Ibáñez (2014)	8
Ergas (2010)	34	Guzmán et al. (2017)	20	Kılkış (2017)	0	Goodspeed (2014)	39	Mateo and Cunat (2016)	3
Eriksson (2010)	28	Kaika (2017)	32	Lehmann (2011)	28	Ibrahim et al. (2018)	6	Mavrakis et al. (2015)	11
Frantál et al. (2015)	28	Klopp and Petretta (2017)	22	Liang and Zhang (2012)	38	Lombardi et al. (2012)	158	Morimoto (2011)	10
González et al. (2013)	16 6	Lapenna and Toccafondi (2017)	0	Lin et al. (2014)	27	Macke et al. (2018)	8	Mörtberg et al. (2013)	17

Gray and Porter (2015)	19	Li et al. (2017)	17	Lund et al. (2015)	45	Manitiu and Pedrini (2016)	2	Oh et al. (2011)	5
Guimarães (2017)	2	Lu et al. (2016)	14	Meijer (2011)	18	March and Ribera-Fumaz (2016)	32	Peng et al. (2015)	32
Güzey (2016)	11	Marlow et al. (2013)	126	Mostafavi et al. (2014)	10	Marsal-Llacuna et al. (2015)	61	Pili et al. (2017)	51
Haas and Locke (2012)	0	McCormick et al. (2013)	144	Mostafavi et al. (2014a)	7	Martin et al. (2018)	11	Rogers et al. (2012)	34
Hodkinson (2011)	23	Medved (2016)	9	Niemi et al. (2012)	54	Martin et al. (2019)	0	Scott (2007)	31
Howley et al. (2009)	73	Nevens et al. (2013)	191	Pearson et al. (2010)	74	Mosannenzadeh et al. (2017b)	15	Shi et al. (2012)	43
Huston et al. (2015)	16	Newell et al. (2013)	41	Pincetl et al. (2012)	98	Palma Lampreia dos Santos (2016)	11	Song (2005)	55
Jung et al. (2015)	16	Perales-Momparler et al. (2015)	13	Rosado et al. (2014)	54	Pinna et al. (2017)	10	Strazzera (2010)	13

Keresztely and Scott (2012)	11	Pupphachai and Zuidema (2017)	13	Rosado et al. (2016)	12	Roche (2014)	36	Tyler et al. (2013)	25
Kort and Klijn (2013)	12	Radulescu et al. (2016)	8	Shahrokni et al. (2015a)	7	Shahrokni et al. (2015)	14	Yigitcanlar and Lee (2014)	60
Kriznik (2018)	2	Romero-Lankao et al. (2014)	24	Singh et al. (2011)	54	Shen et al. (2018	1	Zitti et al. (2015)	58
Larco (2016)	20	Sharma et al. (2010)	26	Voskamp et al. (2018)	8	Shin et al. (2015)	19		
Lee et al. (2014)	12	Simon et al. (2015)	19	Wachsmuth (2012)	46	Soyinka et al. (2016)	3		
Lees and Melhuish (2012)	12	Stredova et al. (2015)	7	Walker and Beck (2012)	14	Steenbruggen et al. (2015)	42		
Lim et al. (2013)	16	Tran (2016)	12	Xia et al. (2018)	3	Tranos and Gertner (2012)	48		
Lugosi, et al. (2010)	17	Uyarra and Gee (2013)	27	Yang et al. (2012)	19	Winters (2011)	97		
Malleson and Heppenstall (2013)	12	Van de Meene et al. (2011)	71	Yang et al. (2014)	24	Yigitcanlar (2015)	21		

Martí-Costa and Miquel (2011)	23	Wei et al. (2015)	36	Zhang et al. (2011)	56	Yigitcanlar et al. (2019)	0
McGuirk et al. (2016)	13	Willuweit and OSullivan (2013)	39	Zhang et al. (2014)	22	Zanella et al. (2014)	1065
Meerkerk (2013)	25	Yang and Wang (2017)	7	Zhang et al. (2018)	1	Zhang et al. (2019)	0
Mosannenzadeh et al. (2017)	9	Yigitcanlar and Teriman (2015)	46				
Obeng-Odoom (2014)	14	Yim et al. (2015)	3				
Pares et al. (2014)	12	Yin et al. (2014)	56				
Parés et al. (2012)	20	Yue et al. (2014)	26				
Park (2014)	2	Zhang et al. (2016)	3				
Rhodes and Russo (2013)	20	Zhao (2010)	121				
Sasaki (2010)	42	Ziervogel et al. (2016)	18				

Schuetze and Chelleri (2016)	13										
Shao and Liu (2018)	1										
Susilo et al. (2012)	39										
Tasan-Kok (2010)	25										
Tulumello (2016)	10										
Ulldemolins (2014)	22										
Uysal (2012)	23										
Van den Berg (2013)	22										
Vento (2017)	8										
While et al. (2010)	172										
Winston (2010)	43										

Zebracki and Smulders (2012)	1
Zhong (2016)	10

Table A2. Average citations and total link strength of authors per cluster based on bibliographic coupling analysis (T.L.S = total link strength, Avg. Cit.= average citations).

CLUSTER 1 (17 items)			**CLUSTER 2 (14 items)**			**CLUSTER 3 (13 items)**			**CLUSTER 4 (5 items)**		
Authors	**T.L.S**	**Avg. Cit.**	**Authors**	**T.L.S**	**Avg. Cit.**	**Authors**	**T.L.S**	**Avg. Cit.**	**Authors**	**T.L.S**	**Avg. Cit.**
Angelidou Margarita	125.38	62.50	Artmann Martina	10.00	24.00	Chester Mikhail	129.80	28.50	Davoudi Simin	89.33	7.00
Bisello Adriano	142.55	12.00	Carlucci Margherita	121.00	54.50	Chrusoulakis Nektarios	167.62	50.00	Moglia Mangus	142.00	68.50
Brandt Nils	103.81	10.5	Chelleri Lorenzo	21.75	7.50	Farzinmoghadam Mohamad	133.47	8.50	Newman Peter	292.25	6.33
De Facto Stefano	123.38	0.00	La Rosa Daniele	10.00	26.00	Gonzalez Ainhoa	167.62	50.00	Newton Peter	142.17	15.00
Evans James	147.39	5.50	Li Feng	57.00	10.00	Liu Gengyuan	98.75	29.50	Thomson Giles	292.25	6.33
Garau Chiara	93.90	15.00	Lombardi D. Rachel	136.50	37.00	Lopes Myriam	167.62	50.00			

Karvonen Andrew	147.39	5.50	Marti-Costa Marc	93.50	18.33	Lu Weisheng	43.00	2.00
Lazarevic David	103.81	10.50	Mcguirk Pauline M.	6.00	13.50	Mostafavi Nariman	133.47	8.50
Marsal-Llacuna Maria Luis	3.00	34.50	Pares Marc	90.50	16.00	Pincetl Stephanie	149.17	51.67
Masala Francesca	84.12	19.00	Porter Libby	87.60	29.50	Rosado Leonardo	16.63	33.00
Mosannenzadeh Farnaz	142.25	12.00	Rogers Chris D.F.	137.17	28.00	Spano Donatella	107.13	31.50
Nijkamp Peter	162.33	309.0	Salvati Luca	121.00	54.50	Yang Dewei	39.10	21.50
Pinna Francesco	84.12	19.00	Wang Rusong	45.00	36.50	Zhang Yan	105.35	27.00
Shahrokni Hossein	103.81	10.50	Zhang Xiaoling	64.00	17.33			
Tranos Emmanuil	166.71	45.00						
Vettorato Daniele	142.55	12.00						
Yigitcanlar Tan	45.11	27.00						

Table A3. References from obtained results as appear first in the text

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Appendix B

Table B1. Ecosystem services for the built environment (Zari, 2012).

Ecosystem service	Ranking criteria			Examples of existing design methods that could be potentially be used	Positive environmental implications
	Applicability to the built environment	**Ecological significance**	**Negative environmental impact caused by the built environment**		
Supporting services					
1. Habitat provision (including: provision of genetic information; biological; fixation of solar energy; and species maintenance)	Medium	High	High at a local scale	Revegetation; preservation of existing flora and fauna; urban wildlife sanctuaries; living walls; urban forests; green roofs and facades; wildlife corridors; green belts	Increased biodiversity; reduction of the urban heat island effect; sequestration of carbon; increased air, water and soil quality; remediation of some forms of water, air and soil pollution; possible protection from wind or wave surges; more adaptable ecosystems as the climate changes; reduction of storm water peak flows
2. Nutrient cycling (including: decomposition; soil building; and the provision of raw materials)	Medium	High	High at a regional scale/ global scale	Recycling and reuse techniques; cradle-to-cradle design; composting techniques; design for deconstruction; landfill mining; industrial ecology	Reduction of waste; reduced need for mining/ growing/production/transportation of materials and energy leading to reduction in greenhouse gas (GHG) emissions, waste and ecosystem disturbance; decreased use of energy; increased health of ecosystems and humans

Regulation services					
3. Purification	High	High	High at a local/regional scale	Living machines; phyto-remediation and bioremediation; filtration techniques; green roofs and facades; urban forests; constructed wetlands; composting techniques	Increased health of living organisms; increased terrestrial and marine productivity; reduction of air and water pollution; eutrophication reduction; remediation of polluted sites; reduced ozone damaging gas and GHG emissions
4. Climate regulation	High	High	High at a global scale	Storage of carbon in building structure; revegetation; design to enable behaviour change in energy use; renewable energy generation; passive solar design; non-high thermal mass infrastructure and landscaping; design to reduce reliance on fossil fuels	Mitigation of the causes of climate change; more adaptable communities; mitigation of the urban heat island effect; improved health of living organisms
Provisioning services					
5. Provision of fuel/energy for human consumption	High	Medium	High at a global scale	Design for renewable energy generation; cogeneration methods; design to enable behaviour change to	Reduced transport and energy generation related GHG emissions; more self-reliant and therefore robust urban environments; reduction of air, water and soil pollution; reduction of mining and drilling impacts

				reduce energy use; industrial/ construction ecology	
6. Provision of fresh water	High	High	High at a regional scale	Rainwater harvesting and storage; grey/ black water recycling; design incorporating water saving equipment; porous paving surfaces; water efficient landscaping	Reduction of water pollution; increased health of riparian systems; reduction of the urban heat island effect; increased quality of water; increased health of living organisms

Source: Zari, M.P. ecosystem services analysis for the design of regenerative built environments. *Build. Res. Inf.* **2012**, *40*, 54–64, doi:10.1080/09613218.2011.628547.

Appendix C

Table C1. Ecosystem Services (Pedersen Zari, 2012).

Provisioning services	Regulating services	Supporting services	Cultural services
Food: Human (land/fresh water/ marine) Forage	Pollination and seed dispersal	*Soil*: Formation Retention Renewal of fertility Quality control	Artistic inspiration
Biochemicals: Medicines Other	*Biological control*: Pest regulation Invasive species resistance Disease regulation	*Fixation of solar energy*: Primary production/plant growth (above ground, below ground, marine, fresh water)	Education and knowledge
Raw materials: Timber Fibre Stone Minerals	*Climate regulation*: Greenhouse gas (GHG) regulation Ultraviolet light (UV) protection Moderation of temperature	*Nutrient cycling*: Regulation of biogeochemical cycles Retention of nutrients	Aesthetic value
Fuel: Biomass Mineral Other	*Prevention of disturbance and the moderation of extremes*: Wind/wave force modification Mitigation of flood/drought Erosion control	*Habitat provision*: Refugium Nursery function	Culture diversity and history
Fresh water: Consumption Irrigation Industrial processes	*Decomposition*: Waste removal	*Species maintenance*: Biodiversity Natural selection Self-organization	Recreation and tourism
Ornamental resources	*Purification*: Water/air/soil		Spiritual and religious inspiration
Genetic information			Creating of sense of place Relaxation and psychological well-being

Table C2. Sensitivity analysis of input variables (authors) (Rt.= ration, Rnk= rank).

ml65_01	cn_bxof11	fml65_11	tch_pre11	NO2_13	ernml_upp11	PM10_13	
1.381698	1.327549	1.232948	1.139873	1.101623	1.100816	1.045264	Rt.
1	2	3	4	5	6	7	Rnk
lv_bxof01	empl3544_01	exp_noise18	ind_ua12	tb_nrsd01	unmpl_ml11	empl_ml11	
1.036905	1.028956	1.02440	1.01827	1.01532	1.01367	1.01254	Rt
8	9	10	11	12	13	14	Rnk
cn_spct11	elc_strligh11	bed_hspt18	propn_18	empl_fml11	ncuse_ua12	cntufb_ua12	
1.01199	1.01109	1.01082	1.00942	1.00843	1.00831	1.00818	Rt
15	16	17	18	19	20	21	Rnk
ecstm_12	ecstm_18	CO_14	unmpl_fml11	ernfml_hgh11	unmpl_fml01	elc_agr11	
1.00792	1.00692	1.00619	1.00604	1.00521	1.00435	1.00424	Rt
22	23	24	25	26	27	28	Rnk
fueldsl_11	uw_clct11	uw_orgrcl18	empl2534_11	lv_spct11	tch_pre18	uw_slctv11	
1.00407	1.00284	1.00177	1.00131	1.00118	1.00110	1.00087	Rt
29	30	31	32	33	34	35	Rnk
thfmoto11	water_cons11	grth_natu18	art_exh11	engo_11	exp_oth18	exp_biolsc18	
1.00081	1.00064	1.00037	1.00036	1.00035	1.00031	1.00020	Rt
36	37	38	39	40	41	42	Rnk
scrt_pens18	cn_spct18	fueldsl_18	inh_phrm11	fml0_14_01	empl2534_01	cn_src18	
0.99991	0.99957	0.99953	0.99953	0.99947	0.99934	0.99919	Rt
43	44	45	46	47	48	49	Rnk
bnk_dw218	empl3544_11	LPG_18	O3_18	dm_viol18	agr_ua12	ppldns18	
0.99907	0.99855	0.99775	0.99767	0.99757	0.99743	0.99729	Rt
50	51	52	53	54	55	56	Rnk
act3544_11	uw_clct18	firefght18	ppldns11	ernfml_hgh18	firefght11	NO2_18	
0.99711	0.99699	0.99689	0.99663	0.99622	0.99598	0.99556	Rt
57	58	59	60	61	62	63	Rnk
dw_swgstm18	butn_18	airtemp_18	CO_18	art_sp11	uw_land18	ml15_64_01	
0.99511	0.99143	0.99086	0.99038	0.98698	0.98338	0.97367	Rt
64	65	66	67	68	69	70	Rnk

exp_biolsc11	lv_perf11	elc_agr18	petr95_18	fml15_64_01	rd_ua12	
0.96218	0.93563	0.90899	0.81710	0.75047	0.70421	Rt
71	72	73	74	75	76	Rnk

Table C3. Associated variables for the calculation of the IpC indicator through factorial analysis (STATISTICS PORTUGAL, 2017).

Variables	Description
IRS	Personal income tax
Gross income	It's the reported income for taxes purposes
Value of domestic purchase through ATMs, per capita	The value is drawn by the location of the ATMs
Value of the payment transactions (services and special services) through ATMs, per capita	The value is drawn by the location of the ATMs
Value of domestic withdrawals from ATMs	The value is drawn by the location of the ATMs
Loans granted for housing purposes, per capita	The value is drawn based on the location of the real estate
Monthly earnings of full-time full-paid employees	The value is drawn by company location/municipality
Population living in places with over 5K inhabitants as a proportion of the resident population	Drawn from the Census
Number of cars sold according to the place of residence of owners, per capita	The value is drawn based on the location of the car owners
Companies' turnover according to their location, per capita	The retail market only, with exception of cars and motorbikes business)

Value of international withdrawals from ATM	The value is drawn by the location of the ATMs
Value of international purchases from ATMs	The value is drawn by the location of the ATMs
Municipal tax on onerous transfers of real estate, per capita	The value is drawn by the location of the houses
Municipal property (real estate) tax	The value is drawn based on the location of the real estate
Corporate turnover of catering business, per capita	The value is drawn based on the location of the real estate