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Circular Economy Strategies in Eight Historic Port Cities: Criteria and Indicators Towards a Circular City Assessment Framework

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Abstract: The circular city is emerging as new concept and form of practice in sustainable urban development. This is a response to the complex and pressing challenges of urbanization, as highlighted in the New Urban Agenda (NUA). The concept of a "circular city" or "circular city-region" derives from the circular economy model applied in the spatial territorial dimension. It can be associated with the concept of a "self-sustainable" regenerative city, as stated in paragraph n.71 of the NUA. This paper aims to develop an extensive form of "screening" of circular economy actions in emerging circular cities, focusing on eight European historic port cities self-defined as "circular". The analysis is carried out as a review of circular economy actions in the selected cities, and specifically aims to identify the key areas of implementation in which the investments in the circular economy are more oriented, as well as to analyze the spatial implications of the reuse of buildings and sites, proposing a set of criteria and indicators for ex-ante and ex-post evaluations and monitoring of circular cities. Results show that the built environment (including cultural heritage), energy and mobility, waste management, water management, industrial production (including plastics, textiles, and industry 4.0 and circular design), agri-food, and citizens and communities can be adopted as strategic areas of implementation of the circular city model in historic cities, highlighting a lack of indicators in some sectors and identifying a possible framework for "closed" urban metabolism evaluation from a life-cycle perspective, focusing on evaluation criteria and indicators in the (historic) built environment.

Keywords: circular economy; circular city; urban circular economy; port cities; historic cities; built environment; indicators; evaluation; urban metabolisms

1. Introduction

The circular city is emerging as new concept and form of practice in sustainable urban development in response to the complex and pressing challenges of urbanization, as highlighted in the New Urban Agenda (NUA). These challenges include climate change, increasing inequalities, and deployment of natural capital [1]. Circular city strategies can contribute to achieving the Sustainable Development Goals (SDGs) of the United Nations Agenda 2030 for Sustainable Development, in particular SDG11 (on safe, inclusive, resilient, and sustainable cities) and SDG12 (on sustainable production and consumption) [2].

The concept of a "circular city" or a "circular city-region" derives from the circular economy model applied in the spatial territorial dimension. It can be associated with the concept of a "self-sustainable" regenerative city [3,4]. As stated in paragraph n. 71 of the NUA, contemporary cities need to strengthen "*the sustainable management of resources, including land, water (oceans, seas and freshwater), energy, materials,*

forests and food, with particular attention to the environmentally sound management and minimization of all waste, hazardous chemicals, including air and short-lived climate pollutants, greenhouse gases and noise, and in a way that considers urban–rural linkages, functional supply and value chains vis-à-vis environmental impact and sustainability and that strives to transition to a circular economy while facilitating ecosystem conservation, regeneration, restoration and resilience in the face of new and emerging challenges" [1].

The circular economy model has been defined as an economic model which is "regenerative by design", with the aim to retain as much value as possible of products, parts, and materials [5], focusing on the life-cycle of materials to "close-the-loop" by recovering all wastes as a resource for new productive cycles. This principle has been also presented as the "cradle-to-cradle" approach, where all materials and products are recovered and regenerated at their end of life. A relevant increase of the overall economic system productivity is expected by applying a circular economy model to current linear production–consumption patterns, "decoupling growth from resources consumption" through the reuse and thus prolongation of the life cycle of materials and products, "designing out waste". This allows for the achievement of more output with less input, achieving the Factor 10 model [6], intending to critically reduce the amount of input and to increase the productivity by 10 times as compared to current production models by applying innovative and advanced technologies able to reduce the need for raw materials, freshwater, fertile soils, and non-renewable energy sources for production aims.

1.1. The Concept and Implementation of Circular Economy in Cities and Regions

The conceptualization of the circular economy has been deeply explored in the last decade, with more than 100 definitions in the literature [7], potentially identifying the model as the "new sustainability paradigm" [8]. However, the implementation of the circular economy in practice requires a global multi-level and multi-scale approach for developing innovation in policies, governance, business models, and financing systems [9,10]. According to the definitions proposed by de Jesus et al. [11], the scale of implementation of a circular economy can vary from micro (the company level) to meso (industrial districts or the whole urban system) to macro (national policies).

At the meso level, the experimentations of "closed-loops" range from industrial synergies [12,13] to eco-town/eco-city development [14–16], to the recent concepts of the "circular city" and "circular city-region" [17–22].

Currently, Japan, China, and Europe can be recognized as the most innovative environments for developing the circular economy at the urban and regional scales.

As reported by Guo et al. [23], "Germany is often entitled as a forerunner of CE due to the enactment of its 'Closed Substance Cycle and Waste Management Act' in 1996", while Japan established a series of laws and regulations that related to waste management and recycling, starting with the Basic Law for the Promotion of the Creation of a Recycling-Oriented Society in 2001 [16,23,24]. Port cities in Japan extensively experimented with the model of industrial symbiosis [25]. China learned from the German and Japanese strategies. The National Development and Reform Commission of China (NDRC) started the first circular economy pilot projects in 2005, involving 178 pilot entities including 105 enterprises, 37 industrial parks, and 36 industrial regions [23,26]. In 2009, the Circular Economy Promotion Law of the People's Republic of China went into force in China's legislation. In 2015, the NDRC started another program more focused on cities, including 25 cities and 26 counties.

The Japanese model of industrial symbiosis has been applied also in Europe, particularly in the cases of Dunkerque in France, Kalundborg in Denmark, and other industrial port cities [27]. Chinese and European cities are leading the way in which the circular city concept is defined and applied, but while Chinese cities are influenced by top-down national policies, European cities strategies are

more bottom-up and place-based as they are developing different approaches based on their specific resources and local challenges. Many European cities have produced strategic policy documents to transition towards a circular city/city-region model, involving consulting companies and stakeholders such as businesses and civil society organizations.

The action of "reusing" wastes, water, energy, products, and in the spatial dimension even entire buildings, sites, and landscapes that lay in a state of abandonment, takes a particular importance for emerging circular cities and regions. In fact, the action of "reusing things" and sites implies not only a technical knowledge and capacity, but also a high level of governance and social and technological innovation to identify new value chains and new use values for objects/buildings/sites or parts of them, and to enable their effective reutilization from a technical point of view.

1.2. Objectives and Organization of this Paper

This paper aims to develop an extensive screening of circular economy actions in emerging circular cities, focusing on eight European historic port cities self-defined as "circular". The analysis is carried out as a review of circular economy actions in the selected cities, and aims specifically to identify the key areas of implementation in which the investments in the circular economy are more oriented, and to analyze the spatial implications of the reuse of buildings and sites, proposing a set of indicators towards the development of a monitoring framework for the implementation of the NUA through circular economy in cities.

Section 2 presents the methodology applied to identify a set of circular cities and to select relevant indicators that could constitute a baseline for circular cities performance monitoring framework. The results of the screening phase are presented in Section 3, highlighting the areas of implementation/investment in the circular economy, the specific actions undertaken in each of the cities and the possible criteria and indicators to be applied for ex-ante and ex-port evaluations. Section 4 discusses the results of this study identifying a possible framework for circular city implementation based on theoretical and practical aspects as emerged from this study. Finally, Section 5 drafts first conclusions and ways forward for further research.

2. Methodology

The specific aim of this work is to identify a set of applicable monitoring indicators based on a theoretical and empirical analysis of circular cities implementation in seven selected historic port cities. The indicators represent a proposal towards a structured monitoring framework for the implementation of the NUA, taking into account §71 which is focused on the concept of circular economy in cities and regions.

Since the research and practice with respect to circular cities are still in an early stage of development [28], it has been considered appropriate to apply a methodology based on a mixed deductive and inductive approach, following four main steps from general and theoretical frameworks to practice, and back through feedback loop/generalization of findings (see Figure 1):

(1) Review of studies on concept and practice with respect to the urban circular economy and circular cities/city-regions, and identification of key areas of implementation;
(2) Selection of cities and screening of circular economy-specific actions/projects and areas of implementation;
(3) Analysis of circular city strategies in eight historic port cities/Analysis of spatial implications of circular economy actions in the selected cities, particularly focusing on the reuse of buildings and sites;
(4) Selection of applicable key performance indicators to monitor the implementation of circular cities in the perspective of the NUA §71.

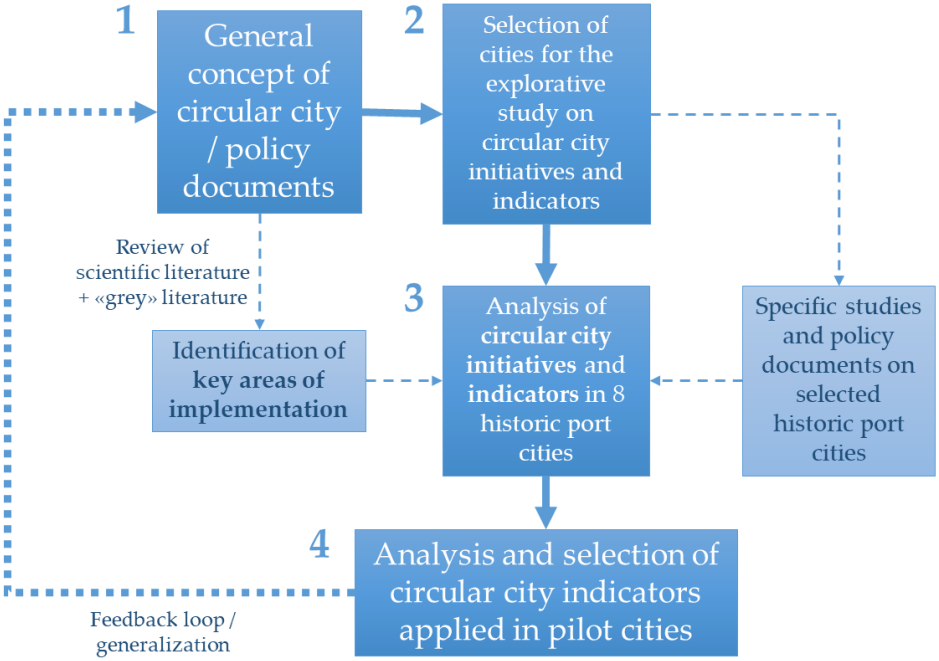

Figure 1. Methodological steps of the research: a mixed deductive and inductive approach.

3. Results: Circular City Strategies, Key Areas of Implementation, and Indicators in Eight Historic Port Cities

3.1. Review of Studies on Urban Circular Economy and Circular Cities/City-Regions

3.1.1. General Studies on the Circular Urban Economy

The circular economy model has been debated and applied in different ways in the last few years, with an exponential growth of scientific studies on the topic starting from 2014 [29–31]. European cities and regions are starting to apply the circular economy at the urban scale, also following a series of policy documents of the European Commission: "Towards a circular economy: A zero waste programme for Europe" [32] and "Closing the loop—An EU action plan for the circular economy" [33].

Focusing on cities and urban/territorial dimension, the recently developed Urban Agenda for the EU aims at the implementation of the NUA in European cities and regions, following the Pact of Amsterdam [34], and has established a specific "Partnership on Circular Economy", developing two orientation papers for the implementation of circular economy in cities and regions [35,36].

The European Spatial Planning Observation Network (ESPON) started a series of projects and studies which define the territorial implementation of the circular economy concept with demonstrative case studies. The study on "Pathways to a circular economy in cities and regions" [22] highlights the food, mobility, and built environment sectors as key areas which can be estimated to undergo a prospective reduction in greenhouse gas emissions of 48% by 2030 and 83% by 2050 as compared to 2012 levels, linking with the European Environment Agency (EEA) study on "Circular Economy in Europe" [37]. The ESPON (European Spatial Planning Observation Network) research project "CIRCTER—Circular Economy and Territorial Consequences" gives a territorial definition of a circular economy: *"A circular economy is one characterized by higher regenerative capacity. This quality expresses itself through territorially-bound enablers like local food systems, local waste-to-resource circuits, community-driven collaborative schemes, industrial symbiosis networks, etc. More often than not, these initiatives are characterized by high levels of territorial specificity, meaning that they cannot be extrapolated to other territorial contexts without major structural adaptations"* [38]. The recent synthesis report [39] identifies the waste management and waste prevention as the key areas in which European cities should orient investments to implement the circular economy at territorial level, while the bioeconomy could be implemented particularly

in rural regions. Also, remanufacturing and industrial symbioses should be developed in industrial areas, particularly industrial regions in decline, as in many European post-industrial port cities. Finally, the ESPON CIRCTER project conclusions highlight that the EU Strategy on circular economy should be integrated with the post-2020 Territorial Agenda.

A collection of experiences and experimentations of circular economy in cities and regions have been reported by ESPON [22], followed by the EUROCITIES report on circular cities which includes experiences in Almere, Amsterdam, Birmingham, Brussels Capital region, Dusseldorf, Genoa, Ghent, Ljubljana, London, the Lyon metropolitan region, Munich, Oslo, Strasbourg, Turin, and Utrecht, with varying scales and areas of implementation ranging from local food systems and food waste management to industrial ecology and industrial symbioses experimentations, materials recycling, and broader strategic plans for circular economy involving businesses and institutions [40]. Cooperation, innovation, and participation are identified as key dimensions of implementation of circular cities [41]. Starting from these experiences, EUROCITIES states that *"the transition towards a sustainable, low carbon and resource efficient economy is vital to our efforts to futureproof our cities and improve quality of life for citizens"* [42].

The Ellen MacArthur Foundation (EMF) has mainstreamed the concept of circular economy globally in the last years [43–47]. In 2017, an initial exploration of opportunities and constraints in the application of the circular economy at the urban scale has been developed, resulting in the identification of five key areas of implementation: built environment, energy systems, urban mobility system, urban bioeconomy (food, wastes, water, soils), and local closed production systems [18]. Recently, a study by the ARUP company and EMF developed a project guide for "circular economy in cities", which highlighted buildings, mobility, and products as key urban systems in which circular economy opportunities can be unlocked [17].

European applied studies on circular economy in cities and regions are growing in number and frequency. The EU Horizon 2020 R2pi project (2016–2019), focused on circular business models, recognizes six sectors of implementation: building construction, electronics, food, plastic, textiles, and water. Also, the Horizon 2020 CLIC project (2017–2020) includes cultural heritage and landscape regeneration and adaptive reuse as drivers of a circular economy in cities and regions.

Finally, the scientific literature on circular cities is varied and constantly growing. The concepts of eco-cities [48,49], (low-to-) zero carbon cities [12,50,51], zero waste cities [52], resource-efficient cities [53–55], regenerative cities [4,56–59], resilient cities [60–64], sharing cities [65–68], and smart cities [15,69–73], as well as food and food waste management in city-regions [58,74–77], can be all linked and integrated in the broader concept of the "circular city".

3.1.2. Closed Urban Metabolisms Assessments

At territorial level, the concept of "closed" urban metabolism is assumed as a key aspect to plan and monitor the circular city and city-region [53,58,74,75,78].

Specific studies on circular cities have been also developed to map actions and projects towards the circular economy in different cities [19,20,79–82] and evaluate the performance of urban circular economies [23,26,83,84].

Urban metabolism is a concept introduced in urban studies since 1965 by Wolman, and further explained as "*the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" (cited by Beloin-Saint Pierre et al. [85]). An urban metabolism model typically combines anthropic activities (e.g., transport, energy consumption) and their related urban infrastructure (e.g., roads, buildings). Moreover, some studies consider urban metabolism beyond the city boundaries perspective, including aspects such as copper and nitrogen flows [85]. Variable scopes, strategies, and modelling methods can be adopted to analyse urban metabolisms, which relate mainly to industrial ecology and ecological economics. Six main methods have been identified in the scientific literature to assess urban metabolisms: flow analysis, energy assessment, foot-prints, input-output analysis, network analysis, and life-cycle assessment (LCA) [85].

These methods employ different types of indicators, at different geographic scales and through various approaches depending on the objectives and users of the assessments, as well as on the availability of data, which seems to be the main issue to perform complete and comparable urban metabolism assessments. A scientific agreement or consolidated practice is still far to be found in this field of research. This study on circular city indicators aims also to contribute to the identification of viable indicators for circular city "closed" metabolism assessments.

3.1.3. Areas of Implementation of the Circular Economy in Cities and Regions

Built environment. One of the sectors that is more rapidly developing in relation to circular economy in cities is the building construction sector [5,86–88]. Buildings and construction contribute close to 40% of the emissions causing climate change [89]. Thus, many cities and organizations are focusing on the building construction sector as a key area of implementation of the circular economy [90].

Energy and the electric circular city. Also, the energy sector has been addressed as one of the fundamental sectors to implement circular economy [45]. The recent study by the ENEL (Ente nazionale per l'energia elettrica—Italian National body for electric energy) focuses on the optimization in the energy sector, "realizing a fully developed vision of the city as a living ecosystem, where wastes of subsystems are used as input for other subsystems (e.g., district heating systems based on industrial heat recovery)" [91]. Kennedy et al. [92] quantify energy and material flows for the world's 27 megacities, while Stewart et al. [93] propose the "electric" city as a possible solution for more sustainable and circular cities.

Industrial production: plastics and textiles, Industry 4.0, and re-localization of productions through distributed systems. The circular economy is mostly applied in industrial production, focusing on the most polluting industrial sectors such as plastic [94] and textile [95] manufacture.

As shown in the following sections, many cities and institutions are implementing circular economy actions by supporting large industries towards the transition to circular production-consumption patterns. In the same time, a different circular model of production in cities is emerging, enabled by digital fabrication technologies: the "cities of making" or "Fab Cities" (cities of fabrication) [96]. The Fab City movement strives for "locally productive, globally connected self-sufficient cities" [97]. The project of Fab City includes civic leaders, makers, urbanists, and innovators, working on "changing the paradigm of the current industrial economy where the city operates on a linear model of importing products and producing wastes", to a new circular urban economy based on distributed local production through small-scale manufacturing infrastructure and globally connected knowledge hotspots through distributed data. A focus on the design of products already in view of their dismantling, refurbishing, recycling, and reuse is integral part of a circular economy, stimulating designers and makers to rethink industrial production [98].

Citizens and communities: the role of institutions and social business, relationships and cooperation models. Finally, it is necessary to point out the fundamental role of citizens and communities in driving the shift of paradigm from a linear to a circular economy. Cities are made both of non-living assets such as buildings, roads, open spaces, products, and digital infrastructure, and of living assets such as people (and nature). Although the supply of innovative products and services can be boosted towards circularity, many authors [99–101], institutions [102], and civic movements [103,104] argue that without a cultural shift towards sustainable lifestyles and responsible consumption the efforts to achieve a full circular economy risk to remain ineffective. In this perspective, the role of social enterprise and more generally of purpose-oriented businesses is raising attention as a way to link social and business value in a "full" circular economy [10,105–109].

A synthesis of the literature review of most relevant studies on the urban circular economy, circular cities, and related areas of implementation is provided in the Table 1 below.

Table 1. Sectors of implementation of a urban circular economy.

Sectors/Cities	Main References
Built environment	[5,86,88]
Cultural Heritage	EU Horizon 2020 CLIC project (Circular models Leveraging Investments in Cultural heritage adaptive reuse) [110,111]
Energy and mobility	[91]
Waste	[18,38,39,54]
Water	EU Horizon 2020 R2Pi project (the Route to Circular Economy) [112]
Industrial production	
Plastics	[94]
Textiles	[95]
Industry 4.0 and Circular Design	[96–98]
Agri-food	[38,39,58,74,76,77]
Citizens and communities	[102]

The following sections collect and analyse specific circular economy actions in selected European port cities, highlighting the sectors in which cities are investing more based on the overview provided in the Table 1, and finally reviewing the indicators currently used to monitor the performance of these circular cities.

3.2. *Selection of Cities and "Screening" of Circular Economy-Specific Actions/Projects and Areas of Implementation*

The European Circular Economy Stakeholder Platform of the European Union is working to collect circular economy strategic plans at national, regional and local level throughout EU countries [113]. The platform includes plans and projects developed in 13 countries (see Table 2).

Table 2. Circular Economy strategies collected by the European Circular Economy Stakeholder Platform.

Level	Country/Region or City	Title	Year
National	The Netherlands	A Circular Economy in the Netherlands by 2050	2016
	Finland	Leading the Cycle—Finnish Road Map to a Circular Economy 2016–2025	2016
	Scotland	Making Things Last: A Circular Economy Strategy for Scotland	2016
	Germany	The German Resource Efficiency Programme II: Programme for the Sustainable Use and Conservation of Natural Resources	2016
	Italy	Towards a Model of Circular Economy for Italy—Overview and Strategic Framework	2017
	Portugal	Leading the Transition: A Circular Economy Action Plan for Portugal	2017
	Greece	National Action Plan on Circular Economy	2018
	Luxemburg	Luxembourg's National Waste and Resource Management Plan	2018
	France	Circular Economy Roadmap of France: 50 Measures for a 100% circular economy	2018
	Slovenia	Roadmap towards the Circular Economy in Slovenia	2018
Regional	Spain/Catalonia	Strategy of the Government of Catalonia: Promoting Green and Circular Economy in Catalonia	2015
	Belgium/Brussels-Capital Region	Brussels Regional Programme for Circular Economy	2016
	Finland/Päijät-Häme Region	Päijät-Häme Roadmap Towards a Circular Economy	2017
	Spain/Extremadura	Extremadura 2030—Regional Government of Extremadura	2017
	Belgium/Flanders	Circular Flanders Kick-Off Statement	2017
City	United Kingdom/City of London	London's Circular Economy Route Map	2017
	The Netherlands/City of the Hague	Circular The Hague: Transition to a Sustainable Economy	2018
	Slovenia/Municipality of Maribor	Strategy for the Transition to Circular Economy in the Municipality of Maribor	2018
	France/City of Roubaix	Roubaix's Circular Economy Route Map	2019

Three criteria have been identified for the selection of cities, with the aim of reviewing circular economy strategies and actions at the city level:

- Countries in which a specific circular economy plan has been developed at national level;
- Historic port cities;
- Cities in which a specific circular economy plan or industrial symbiosis/industrial ecology plan for the port area has been developed.

Starting from the experiences of industrial symbioses in port cities in Japan, China, and Europe [25], eight European port cities have been selected in the countries in which a circular economy plan has already been developed.

According to the above criteria, the following cities have been selected for this study (see Table 3): Amsterdam, Rotterdam, London, Antwerp, Hamburg, Marseille, Lisbon, and Porto.

Table 3. Selected cities for the analysis of urban circular economy actions.

Country	City	Main References on Official Circular Economy Plans
The Netherlands	Amsterdam	[114,115]
	Rotterdam	[25,116–118]
United Kingdom	London	[119,120]
Belgium	Antwerp	[121–125]
Germany	Hamburg	[126–130]
France	Marseille	[131–135]
Portugal	Lisbon	[136,137]
	Porto	[28,138]

The following section analyses circular economy projects and actions in the selected cities, highlighting the sectors in which investments are directed.

Circular Economy Indicators and Their Implementation at the Urban/Territorial Scale

The relative fuzziness of the circular economy concept, especially in its potential application in cities and regions, leads to difficulties in identifying shared methods and tools for its evaluation and monitoring, which in turn results in fragmented implementation [139–141]. Recent research efforts in systematizing existing indicators of circularity at the micro, meso, and macro levels have resulted in a taxonomy of 55 indicators sets [139], of which 19 are developed at the scale of cities, regions, and nations. Only the Evaluation of Circular Economy Development in Cities (ECEDC) is explicitly related to the urban scale, while the Evaluation of Regional Circular Economy (ERCE), Measuring Regional CE-Eco-Innovation (MRCCEI) and Regional Circular Economy Development Index (RCEDI) are related to the regional scale, and the National CE Indicator System (NCEIS) was developed at the national scale, which is out of scope of the present study. Within the lower level indicators, the Building Circularity Indicators (BCI) framework is specifically focused on the building construction industry. Moreover, a recent statistical analysis of 63 metrics for the circular economy [140] highlighted that existing frameworks are highly fragmented in scope and scale, and could be potentially mixed to be used in complementarity in order to achieve greater completeness and complexity of circular economy monitoring and performance evaluation. In general, studies on the circular economy indicators highlight a lack of coherence, completeness, and applicability of indicators, the latter mainly due to lack of data in this field. Thus, the present study aims to contribute to the identification of actionable indicators which have been already used in circular cities, and which include the key strategic sectors of a circular city, focusing on the built environment.

The following section reports the detailed analysis of circular economy actions and indicators in the city of Amsterdam to show the methodology of the analysis conducted.

3.3. Analysis of Circular Economy Strategies in Historic Port Cities: The Example of Amsterdam

The city of Amsterdam started the initiative of a circular innovation program within the Amsterdam Smart City initiative, creating a specific department for the circular economy (amsterdamsmartcity.com/circularamsterdam). Many initiatives are ongoing to reduce the polluting emissions and the consumption of materials [142]. The Netherlands already recycles 98% of building materials and Amsterdam is certainly a leader in this activity. Several companies are specialized in waste management systems deriving from demolition and construction [143]. Currently, one-third of the total waste produced in Amsterdam is incinerated to generate electricity and heat [114].

A key role is played by the AEB company, a world leader in the sustainable conversion of waste into energy, precious metals, and reusable raw materials. The AEB recycles about 61,400 tons of materials annually (especially ferrous and non-ferrous metals), reducing CO_2 emissions by approximately 172,500 T/year [144]. It represents the principal supplier of sustainable energy, sufficient for 320,000 families.

The port of Amsterdam is active in promoting the circular economy. The residual heat of the only coal-fired plant is currently transported into the city Amsterdam. There are 18,000 households which are using this heat, and the residual heat will be used to make asphalt [145].

Regarding the built environment, the Circl building is a demonstrative project of circular building, an experimentation towards the standards for future circular constructions. The use of Building Information Modelling (BIM) technologies for assessment of materials flows is the fundamental innovation of this project, supporting the cataloguing of all materials employed. The isolating material of the walls contains clothing fibers, while that of the roof was made with 16,000 pairs of old jeans. The panic exit devices were made with some old handles of other buildings. On the roof, photovoltaic panels and a garden for water recovery have been set up. All the bricks and the tiles come from recycled material.

Also, the regeneration project for Buiksloterham along the waterfront is an example of a postindustrial district reuse. Harbors are transformed in a residential neighborhood with green buildings. The empty land will be developed into a natural area, and different companies will produce energy from biomass.

The port of Amsterdam is investing in vapour recovery systems and a launder emission system to reduce emissions [145]. A platform enables companies to exchange ideas and residual products. The port authority uses active management on closing loops of companies and gives various training sessions regarding recycling. It has an active waste management plan and many recycling companies are located in the port. The port of Amsterdam even has an energy plant, which converts waste into energy. In 2011, the port managed 1.65 tons of biomass, and this figure is expected to rise to 13.5 tons in 2020.

Some textile companies are invested in the circular economy principles, like Mud Jeans, that rents out jeans for some months, or the Fashion Library, that rents out dresses. Others companies promote initiatives to make this sector sustainable with the support of some fashion institutes.

Table 4 collects different projects in the city of Amsterdam and in particular in the port area. To collect the information, desk research was conducted using scientific and practice literature, with some information collected through interviews with local professionals.

Table 4. Amsterdam circular economy projects.

Sector	References	Example Projects/Initiatives
Built environment	[142,145–149] Circle-economy.com Amsterdamsmartcity.com Portofamsterdam.com materialsexperiencelab.com	Circl Building, Buiksloterham, De Ceuvel, material passports, use of bio based materials, material stock areas, regulations for new buildings, dredged sand used as a building material, heavy ashes used as a filling material for the construction sector

Table 4. *Cont.*

Sector	References	Example Projects/Initiatives
Energy and mobility	[20,142,150]	Photovoltaic panels, power plants, wind energy production, district heating, the Amsterdam Smart City initiative, the Alliander Smart Grid, reduction of CO_2 emissions
Waste	[143,150] thewastetransformered.com portofamsterdam.com	The AEB Amsterdam's mid-term strategy until 2020, the AEB Amsterdam's mid-term strategy until 2035, the Household Waste Plan, recovery of waste after incineration, waste used to produce biogas, animal feed from waste, and the Obtibag research project (a study of a new system for the reuse of waste)
Water	(Bastein et al., 2016) thewastetransformered.com	Reuse of rainwater for toilets, sewage sludge used as manure, Water net (a wastewater treatment plan), the RWZI society collection of wastewater for treatment, energy produced from the processing of water
Industrial production		
Plastic	(Circle Economy, 2011) unenvironment.org theguardian.com worldenvironmentday.com bin2barrel.com amsterdamsmartcity.com	Port of Amsterdam promotion of strategies for the reuse of plastics to create fuel for ships, BinBarrel promotion of the reuse of plastics in the port area, an incentive programme for families that reuse plastics, the Amsterdam Smart City initiative, the Circular Amsterdam initiative
Textile	materialsexperiencelab.com circleeconomy.com	Circle Fashion Tool (company), the Beyond Green Amsterdam Fashion Institute, The Dyecoo circular industry, the Sympany Fashion industry, Mud Jeans, the Fashion Library, the Sustainable Fashion Industry initiative (a digital platform to share data about the fashion industry)
Industry 4.0 and Circular Design	fab.city/fab-city-campus-in-amsterdam.com	The Fab City initiative (Fab Lab Amsterdam, Waag society, Metabolic, Pakhuis de Zwijger)
Agri-food	[142,146,150] amsterdamsmartcity.com	The Amsterdam Smart City initiative, the Circular Amsterdam initiative
Citizens and communities	(Circle Economy, 2011) amsterdamsmartcity.com circleeconomy.com	Associations that provide advice about the circular economy, social start-ups in the circular economy, the Healthy Urban Living initiative, regional cooperation, end-user involvement in co-creation of innovative solutions, social entrepreneurship, the Pakhuis de Zwijger Foundation, the AMS Institute, the Construction Green Deal, the Circular Area Buikloterham, the Metro Region Amsterdam, an industrial park, The Ceuvel Sustainable Community, the Amsterdam Smart City initiative, the Circular Amsterdam initiative, sharing economy legislation, Free Zone Living Labs

A review of the indicators applied to monitor the circular performance of different projects and actions in the city of Amsterdam has been realized, with results shown in the Table 5 below.

Table 5. Indicators applied in Amsterdam to monitor the circular economy in different sectors.

SECTOR	INDICATOR
Built environment	Number of houses in 2040 = 70,000 % of useless waste reused in the port area: 99.0% Number of companies that reused waste in the port area = 24
Energy and mobility	Number of electrical cars = 28,889 (2016) % of car sharing 2018 = 37.6% % of traffic reduced = 32% due to the use of bikes

Table 5. *Cont.*

SECTOR	INDICATOR
Textile	Collected textile waste per person = 17 kg/year (materialsexperiencelab.com)
Waste	Kilograms of processed waste = 500,000 Kilograms of compost extracted = 9000 (www.thewastetransformered.com) % of domestic waste = 17.7% (Geemente Amsterdam, 2015)
Plastic	Number of families that access incentives for the reuse of plastics = 700
Agri-food	Production of KWh from waste = 900 Kwh (amsterdamsmartcity.com); Tons/years of organic waste = 900,000 tons

3.4. Circular City Strategic Sectors and Related Criteria and Indicators

3.4.1. Sectors of Implementation of Circular Urban Economy in the Selected Cities

According to the analysis performed in this study, the built environment, energy and mobility, waste, and plastic industry sectors are the most relevant for the circular economy strategies in the selected cities. Amsterdam and Lisbon were revealed to be the most active and vibrant circular cities, investing capital and effort into all identified sectors of the urban circular economy.

Industry 4.0 and circular design initiatives have been developed in Amsterdam, Rotterdam, and Lisbon; however, this sector is emerging as very relevant for circular city strategies and has the potential to receive more interest from different stakeholders in the near future. This result does not mean that in London, Antwerp, Hamburg, and Marseille the local Industry 4.0 enterprises, Fab Labs, and digital fabrication networks are not active—the organizations active in this sector are not yet explicitly contributing to the circular economy, as per the results of this study.

Moreover, the role of citizens and communities, including third sector as social enterprise and civic associations, appears to be very relevant in driving the transition towards a circular city and more and more central in the implementation of all other strategies in different sectors, influencing the demand of circular and sustainable goods and services.

The following Table 6 gives an overview of the sectors in which the eight selected circular cities are investing. The last column shows the "frequency" of implementation of each circular economy sector in all investigated cities.

Table 6. Comparison of circular economy projects per sector in the selected cities.

Sectors/Cities	Amsterdam	Rotterdam	London	Antwerp	Hamburg	Marseille	Lisbon	Porto	Frequency
Built environment	•	•	•	•	•	•	•	•	8/8
Energy and mobility	•	•	•	•	•	•	•	•	8/8
Waste	•	•	•	•	•	•	•	•	8/8
Water	•	•	•				•	•	5/8
Industrial production									
Plastic	•	•	•	•	•	•	•	•	8/8
Textile	•		•		•	•	•	•	6/8
Industry 4.0 and circular design	•	•					•		3/8
Agri-food	•	•	•	•			•	•	6/8
Citizens and communities	•	•	•	•		•	•	•	7/8
Frequency	9/9	8/9	8/9	6/9	5/9	6/9	9/9	6/9	

The analysis of all indicators emerged from reports on circular city strategies has identified 78 synthetic indicators in the nine sectors of implementation.

As reported in Table 7 and Figure 2, a focus in the sectors of energy, particularly in port areas (24%), waste, agri-food including agri-food waste (waste: 14%; agri-food 17%; total 31%), and built

environment (18%) can be noted. The industrial sector, including plastics (13%) and textiles (8%), is represented in total by 21% of all the indicators analysed.

Table 7. Number of indicators per sector from the analysis of circular city reports.

Sector	Number of Indicators	Percentage
Built environment	17	18%
Energy and mobility	22	24%
Water	1	1%
Waste	13	14%
Plastics	12	13%
Textiles	7	8%
Industry 4.0 and circular design	0	0%
Agri-food	16	17%
Citizens and communities	5	5%
Total	93	100%

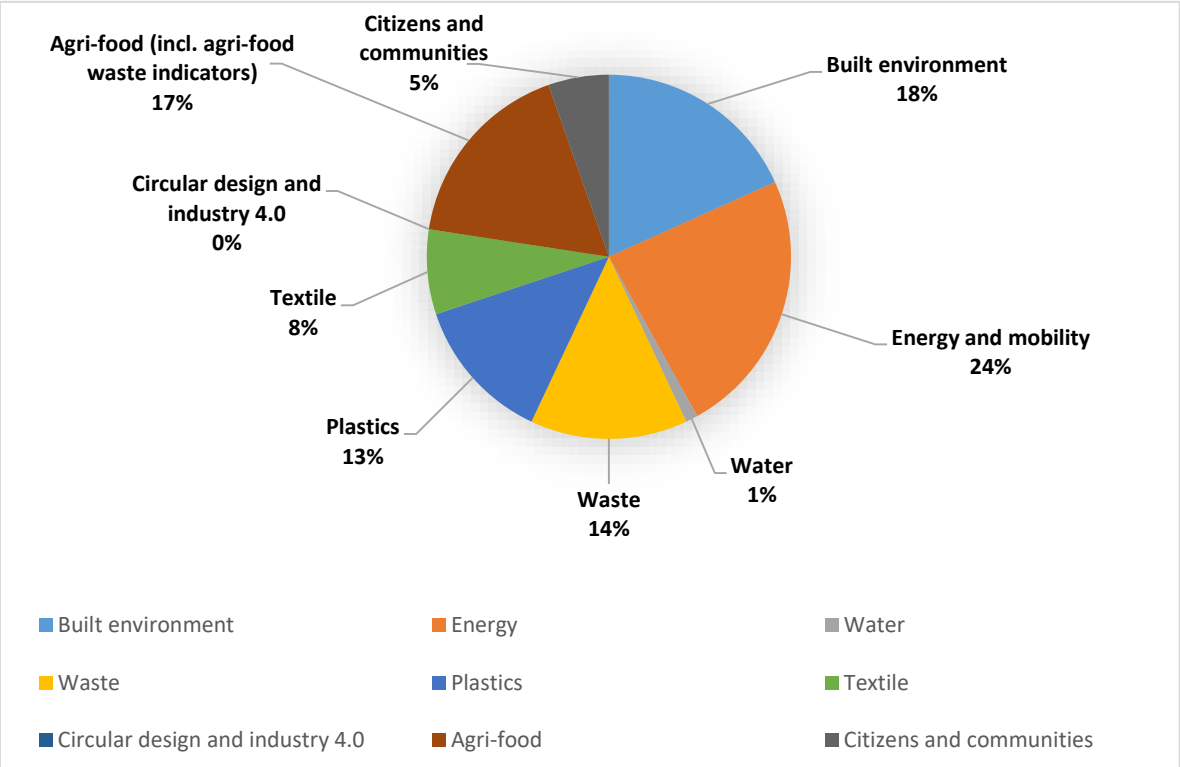

Figure 2. Number of indicators emerging from the analysis of circular city reports.

The spatial dimension is mainly represented by strategies and projects related to the built environment. The following section focuses on the 17 synthetic indicators in the built environment sector which emerged from the reports on circular cities, identifying criteria and a possible set of indicators for the assessment of circular city implementation.

3.4.2. Criteria and Indicators of Circularity in the Built Environment Sector

Analysing particularly the indicators in the built environment sector, a synthetic set of criteria and indicators can be identified. Table 8 synthesizes the indicators used in the eight selected cities to describe the impacts of circular economy strategies in the building construction sector.

Table 8. Criteria and indicators of circularity in the built environment sector.

Criteria	Number	Indicators *(Synthesized/Adapted from Circular City Reports)*	Frequency
Reuse of old buildings	1	Number of existing buildings reused	2
Retrofitting	2	% of retrofitting	1
Circular design of buildings	3	Number of new buildings designed to be dismantled and recycled	1
	4	Number of new green houses	3
	5	m^2 of green roof and green areas	2
Redevelopment of degraded areas	6	Ha of areas redeveloped	1
	7	% of very degraded buildings	1
Waste avoided in the construction sector	8	% of demolition waste	1
	9	% of waste reused	1
	10	Tons of avoided waste construction	2
	11	m^3 of recycled concrete used	1
Circular business models	12	Number of companies that reuse waste	1
Greenhouse gas emissions avoided	13	CO_2 emissions avoided (tons/year)	1
Water consumption avoided	14	% of water use reduction in buildings	1
Energy efficiency	15	% of energy reduction in buildings	1
Renewable energy	16	Number of housing units heated through renewable sources	1
	17	m^2 of houses/offices heated through renewable sources	1

Focusing on the built environment sector, it is possible to identify four specific strategies in circular cities:

- Circular design of new buildings
- Dismantling of old buildings
- Refurbishment of old buildings
- Reuse of old buildings (incl. adaptive reuse of cultural heritage)

The reuse of heritage buildings and sites is particularly relevant in historic port cities, where the strategy of dismantling and circular design of new buildings can be rarely applied. As highlighted in recent studies on circular economy metrics [140], only few circular economy metrics generally assess CE elements that are related to the maintenance of value, such as retention, value change, and longevity, although these are recognized as key objectives of a circular economy in almost all theoretical studies. This lack of focus in a key element of circularity applies also to the building construction industry, where theoretical studies focus more on circular design and dismantling, than refurbishing and reusing to maintain building value over time. The following section focuses on the adaptive reuse of heritage assets as a possible strategy for the circular city implementation, highlighting a set of specific adaptive reuse projects in the selected historic port cities.

3.4.3. Adaptive Reuse of (Historic) Buildings and Sites as Key Strategy for Circular Cities Development

The adaptive reuse of old buildings, and especially of cultural heritage buildings/sites, is recognized to enhance the attractiveness of abandoned or degraded areas while also enhancing relationships and circularity between waterfront/port areas and historic city centres.

An overview of cultural heritage adaptive reuse projects in the circular cities analysed is here proposed in order to highlight the potential of adaptive reuse strategies in the context of circular port-city regeneration.

In the city of Amsterdam, an example of the reuse of cultural heritage is Westergasfabriek, a nineteenth-century factory on the outskirts of central Amsterdam which halted operations in the 1950s. In 1981 the site was rezoned as recreation space (www.archdaily.com). The entire area in which the industrial complex was born has been recovered; the two historic gas holding structures adjacent to the Cité des Artistes complex have become frame displays of aquatic plants, fish, and reflective water. In this area, there is a channel that has been recovered as a central element of a new square, intended as a recreational space for the community. The urban regeneration intervention in the GWL neighborhood, which occupies an area central urban area in Amsterdam, is characterized by attention for issues related to environmental sustainability and maintenance. The transformation of the water treatment plant into an area with residences, commercial spaces, and culture, has resulted in one of the first ecological neighborhoods in Europe, having been designed to be a car-free zone in a pedestrian area.

An example of reuse of cultural heritage in Rotterdam is the "HAKA-building boasts", an industrial building located on the river. It was an old factory converted into offices with an auditorium, boardroom, kitchen spaces, and an exhibition area. All the interior spaces have been created with materials coming from demolished buildings and other reused materials. For example, the colorful walls were built from 8000 kg of old clothes, while the doors were made by recycled materials coming from other buildings. Van Nelle Fabriek is a UNESCO World Heritage site situated on the waterfront. It is an old factory that manipulated products coming from tropical countries like tobacco, tea, and coffee. This building is the symbol of a functionalist architecture, realized in steel and glass and converted into an office building. Another important example in Rotterdam is the Venlo project, which comprised the sustainable transformation of an old educational building. In the process of this project, a materials passport was developed. All the materials used for this building came from the demolition of other buildings; the residual products were subsequently processed into new products and materials such as an acoustic wall made of old doors, and the use of recycled textiles for the soft fabric finish (www.c2c-centre.com). Many examples of adaptive reuse of the industrial heritage can be identified in the port area. The Heysehaven neighborhood was transformed in a research, design, and manufacturing campus and university college.

The city of London includes four World Heritage Sites, over 1000 conservation areas, 19,000 listed entries for historic buildings, 150 registered parks and gardens, and 160 scheduled monuments. The re-use of historic buildings in the city of London is constantly growing. There are many examples of English heritage reconverted. King's Cross is one of the mostly well-known examples, where the train station shed and range buildings have been adapted and re-used with new commercial functions. The Tate Gallery is an old industrial building (an ex power plant) from 1981. In the year 2000 it was reconverted in a contemporary museum, which contributed to the entire revitalization of the district. The University of Art was designed for a former industrial building, and the University of Birmingham was designed for the Bramall music building. The Turbine Hall at London's Tate Modern is a well-known museum which was originally a power plant.

The city of Antwerp invests in the valorization of cultural heritage, considered a creative sector able to produce positive impacts on tourism. Along the port area there are many historic buildings that the municipality aims to recover to create new relationships between the city and the waterfront. The "Port House" was designed by Zaha Hadid in the Eilandje quarter as a fire station, but nowadays it is a symbol of the port area with its 110 meters of glass extension. The architectural project is a tribute to the diamonds history production of Antwerp, recalled on the glass surfaces of the building. Another example of adaptive reuse is the MAS Museum, situated on an old dock. It has been redeveloped with the aim to integrate it with the city through the use of materials: the glass recalls the strong relationship of the city with the river. The MAS is considered a catalyst for the entire neighborhoods, the new

cultural symbol of the city. Moreover, the Kanaal building, an old malting distillery, was converted into new apartments, galleries, offices, restaurants, and an auditorium.

In Hamburg, an important example of cultural heritage adaptive reuse is the Elbphilharmonie. It was formerly a cocoa factory and is an old building that now is crowned with a gleaming silver construction made from 2200 glass panels. It represents a center of social and cultural activities. The new functions include a chamber music hall, restaurants, bars, a panorama terrace with views of Hamburg and the harbor, apartments, a hotel, and parking facilities (www.elbphilharmonie.de). Also, the Mövenpick Hamburg is an old building reconverted into a hotel in the historic center. The reuse of the Warehouse in the port area (a UNESCO site since 2015), once used for the storage of the coffee, tea, chocolate, and spices, has been reused with new functions such as museums, coffee shops, and restaurants. Another example is the Energy Bunker of Wilhelmsburg, Hamburg, an old bunker from World War II converted into a power plant using renewable forms of energy, with a large heat reservoir. It feeds the renewable power into the Hamburg distribution grid.

In the city of Marseille an example of adaptive reuse of cultural heritage is La Friche de la belle de Mai. It is a former tobacco warehouse reconverted in an area for cities services; in fact the 45.000 m^2 are nowadays filled with offices and urban parks (www.lafriche.org/fr). The docks of Marseille are the trendiest buildings in the city; they represent the symbol of the city's renaissance. In the historic industrial buildings, which were once used for the storage of materials, companies, and commercial activities are now present. Le silo d' Arenc is another historic building that was reconverted in 2011 into an auditorium with 1800 seats and some offices in an area of 4500 (www.attente-silo-marseille.fr).

In the city of Lisbon, the restoration of the Baxia-Chado district is the most well-known example of regeneration and reuse of historic buildings. A mapping of protected areas was elaborated, with the aim of giving new functions for these neighborhoods' regeneration. In particular, the project for Baixa Chiado provided an area dedicated to universities, new residential housing and a commercial area. The aim of the project was to regenerate the neighborhood through a sustainable model, enhancing economic and social values after the fire that destroyed the entire area. The Chiado neighborhood is placed in a strategic position between the port and the historic center that ends with the St. George's castle. For this reason, it was chosen to include functions related to its touristic/commercial/cultural vocation. Another example in Lisbon is the historic buildings along the Praça do Comércio, in the waterfront area, that has been converted into hotels, restaurants, coffee shops, shops, and offices. Along the waterfront, the Central Tejo is an old power plant converted into an electricity museum.

In Porto, the adaptive reuse of the Matadouro slaughterhouse by architects Kengo Kuma and the OODA company was intended "to reactivate, reinvent, and engage the local history and memory of the city", reconnecting 20,500 square meters of the abandoned slaughterhouse with the city, re-establishing the site's importance in the city's cultural, business, and social network (see: www.dezeen.com). The Porto AXA Building is an adaptive reuse project which has generated positive economic, social and cultural in the surrounding area. The building is now a core element in the new urban space syntax, in a context of intense urban dynamics, touristic flows, and leisure and cultural activities [151]. Moreover, the adaptive reuse of the Miss'Opo building in the historic downtown transformed an abandoned textile workshop into a creative medley of a guesthouse, café, bar, shop, and art gallery. The project involved a team of architects, planners and local residents, turning an abandoned and empty space into an attractive place for residents and visitors, also enhancing the overall economy of the city [152].

4. Discussion: Towards a Framework for Circular City Implementation in Historic Cities

This study has been conducted adopting a mixed deductive and inductive approach to identify strategic areas of implementation of circular cities, and identifying a set of indicators to evaluate and monitor their performance. The findings highlighted that in all cities analyzed, cultural heritage adaptive reuse represented an important strategy to address the implementation of circular economy in the historic built environment. In fact, some of the evaluation criteria and indicators identified are

specifically related to "reuse of old buildings", "retrofitting", and "redevelopment of degraded areas", which are coherent with the circular economy principles of reuse, refurbishment, and repurposing. Moreover, it is important to note that urban planning rules and regulation generally foresee higher preservation status in historic urban areas, compared to other parts of the city, which makes difficult the implementation of other strategies such as dismantling and re-design following circular principles.

The findings of this study can be generalized to start developing an evaluation framework for the implementation of the NUA through the development of circular cities and city-regions. However, it must be noted that the indicators identified, as presented, indicate the beginning of a path towards a circular economy, but in themselves cannot (yet) represent the actual degree of circularity achieved by the urban area considered. The limitation of this study is related to the empirical approach which is useful to identify common areas of implementation and to analyze the general trends in the use of indicators, but it has not the ambition to represent an exhaustive overview of indicators for the circular city implementation. However, some generalizations can be drafted:

- The circular city model can be implemented in historic port cities adopting the strategic areas identified in this study: built environment (including cultural heritage), energy and mobility, waste management, water management, industrial production (including plastic, textiles, Industry 4.0 and circular design), agri-food, and citizens and communities;
- Indicators in the water management sector, Industry 4.0 and circular design, and citizens and communities are less explored or not explored at all, indicating partly the lack of recognition of these areas as strategic for the implementation of the circular economy in cities and regions, and partly the difficulty in data collection, probably due to lack of data availability;
- The adaptive reuse of cultural heritage can represent a key strategy for the implementation of the circular economy in historic cities; the criteria and indicators within the built environment sector which emerged in this study can be adopted in a wider evaluation framework for the monitoring of the NUA, since these indicators have already been implemented in some cities and they can be reliably assumed as "actionable" indicators.

Thus, a general evaluation framework can be drafted starting from the findings of this study, adopting the approach of "closed" urban metabolism in a life-cycle perspective. Figure 3 synthesizes the proposal of evaluation framework for the monitoring of the NUA (with particular reference to § 71) structured in a life-cycle perspective with the objective to "close" urban metabolisms.

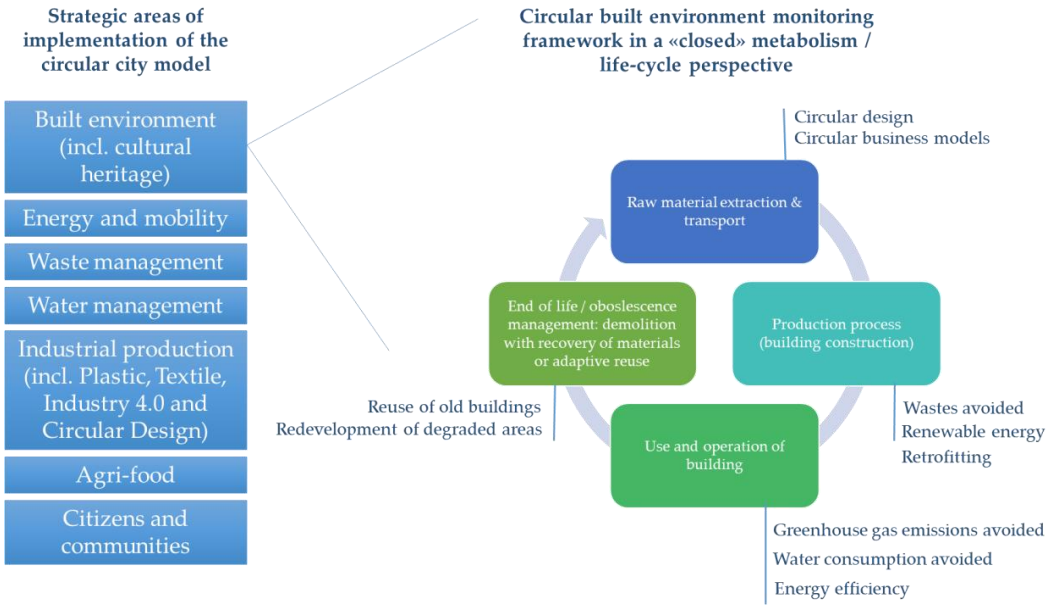

Figure 3. Strategic areas of implementation of the circular city model: a focus on circular built environment in a "closed" urban metabolism/life-cycle perspective.

As shown in Figure 3, a first set of applicable ("actionable") indicators has been identified in this paper, grouped into general criteria of circularity in the built environment. This study aims to contribute to the ongoing scientific debate and to circular cities' practice by indicating a possible pathway for the implementation of circular economy in the spatial/territorial dimension, proposing a framework, and identifying a first set of indicators for the monitoring of the circular city from a "closed" urban metabolism perspective.

5. Conclusions

Circular cities can be seen as regenerative and self-sustainable systems [3]. The transition to "full" circularity in cities and territories requires a high level of innovation in all key sectors of production identified in this study, including society and local communities embedding the social capital of a city/region that should be continuously regenerated, along with the human capital, natural capital, and man-made capital [153]. The urban landscape represents the tangible manifestation of the linear or circular functioning of the city as a system of people, materials, energy, knowledge, infrastructure, and nature. In the landscape it is possible to recognize past and present values and behaviours, liveability, and identity of the city/region.

In the territorial dimension, empty/abandoned/degraded spaces represent hidden areas of collective consciousness, places that are not visible and not attractive, but that can represent resources for regeneration and self-sustainability of cities and regions bringing to new light/life their actual and potential values through a creative act of re-design for new uses. Real estate is a fundamental aspect to be taken into account when adopting circular strategies of regeneration. In fact, real estate values are drivers of urban regeneration and can activate circular processes of value creation and value sharing/redistribution in abandoned and degraded urban areas.

The transition towards circular urban economies requires a cultural paradigm shift leading to innovation in all sectors and changes in governments organization, business strategies, and educational structures (determining the supply of new products and services) as well as civil society (the "demand" side). The third sector, which includes social enterprises, foundations, and civic associations, appears to be very active in the organization of a circular city, also stimulating a new demand of circular products and services and thus opening new market niches for innovative products. This is linked to cooperation and synergies between different actors, which are key to activate territorial symbioses, inspired by the experiences of industrial symbioses in many port areas [25,27].

In self-sustainable systems, cooperation is a fundamental aspect [3], enhanced by differentiation and uniqueness which lowers the levels of competition creating multiple niches for innovative products and services that can be complementary to each other. For Zeleny [3,154] the model of the self-sustainable city is in the Czech Republic: the industrial city of Bata designed around productivity and innovation which is able to regenerate its human and social capital over time, as well as its built and natural capital.

This study aimed to review the strategies of circular port cities, highlighting the areas of implementation and the specific projects and actions towards enhanced productivity in multiple dimensions: economic, social and environmental productivity through optimization of materials and energy flows, "products as a service" systems, reuse, recycling, and refurbishment, re-localization of production, and regeneration of abandoned buildings or entire urban areas.

This study reviewed the indicators currently applied to monitor the performance of circular strategies in terms of reduction of waste, material extraction, freshwater consumption, and in the general reduction of negative environmental externalities of production and consumption systems. However, as highlighted by Lemille [10], the reduction of negative social externalities should be embedded in the circular economy model, and thus appropriately monitored through relevant indicators. To evaluate the circular city and orient and monitor its progress towards self-sustainability, circular urban metabolism assessment can be introduced, as in the experience of the De Ceuvel project in Amsterdam, to design urban regeneration and its "closed-loop" functioning.

The review of projects and indicators of circular city conducted in this study highlights the lack of measures and assessments that go beyond the "materials and energy" dimensions in circular urban economy, embedding other dimensions related to the culture of cooperation, synergies, and symbioses that are key to the self-sustainability of urban and territorial systems.

The results of this study underline the existence of an open field of research related to the assessment of the circular city, through enriched urban metabolisms assessment that could take into account the economic, social, environmental, and cultural self-sustainability and self-regeneration capacity of circular cities and regions. Criteria and indicators, as well as methodologies for urban metabolism assessment, are still to be developed in their full potential, orienting and monitoring progress towards more desirable "circular" cities.

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