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Digital Technologies for Urban Metabolism Efficiency: Lessons from Urban Agenda Partnership on Circular Economy

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Abstract: Digital technologies engaged in urban metabolism for efficiency provide policymakers, urban managers, and planners with useful instruments to collect, monitor, analyze, and evaluate the circularity of environmental, social, and economic resources to improve their effectiveness and quality. At present, the digital technology-based approach is strategic for circular cities engaged in the development of smart and sustainable actions in the fields of mobility, energy, environment, waste, telecommunications, and security. Through the 'Circular Resource Efficiency Management Framework' developed by the European Commission, this paper generates insights into the digitalization practices of the circularity of urban metabolism by analyzing the initiatives implemented by the municipalities of Kaunas, Flanders region, Porto, Prato, The Hague, and Oslo, which constitute the Partnership on Circular Economy (PCE) of the Urban Agenda of the European Union. The results of the analysis provide a wide range of practices such as real-time monitoring stations for water and energy consumption, digital cameras for controlling vehicle flows, web platforms for sharing goods and services, and tracking sensors for public transport, which aim to optimize the efficiency of the circularity of urban metabolic flows. This study increases the understanding and awareness of digital technologies in this paradigm shift.

Keywords: urban metabolism; smart urban metabolism; digitalization; circular city; circular economy; sustainability; urban development; city 4.0; smart city; urban sensors

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1. Introduction

The social, economic, environmental, and technological challenges of the current rate of urbanization and datafication place cities at the center of the theoretical and managerial debate on the circular economy and define them as the cornerstone for reversing the trend and promoting urban metabolism in a sustainable and digitalized manner [1–3]. In this sense, the negative consequences of the linear economy in cities are now evident to experts and public opinion [4]. Currently, about 55% of the world's population lives in cities that generate over 85% of global GDP [5,6]. Furthermore, cities are responsible for 75% of the consumption of global natural resources, 75% of global greenhouse gas emissions [7], and 50% of global production of waste [8]. Therefore, the development of innovative urban models that allows cities to create value by adhering to the principles of the circular economy is a fundamental requirement for a sustainable and digitalized urban transition [9]. On this point, the circular economy represents a great opportunity for cities around the world to meet the goals of the United Nations 2030 Agenda on Sustainable Development [10].

Nonetheless, capturing the advantages and opportunities of the circular economy requires that policymakers, urban managers, and planners integrate its founding principles into their urban strategies; for example, by moving from linear and short-term to circular thinking, such as codesign and cocreation of value [11,12] and from urban policies focused on the product to those focused on digital services [13]. In this sense, cities are characterized by an abundance of systemic and interdependent relationships between local authorities, citizens, universities, startups, research centers, trade unions, municipal utilities, companies, and nonprofit organizations, which design, develop, and redefine—through the use of shared and technological platforms—resilient and digitalized urban processes, products, and services [14–16].

Digital technologies, in particular those related to the concept of City 4.0 [11], such as sensors [17], real-time monitoring stations [18,19], digital cameras [20], real-time tracking systems [21,22], big data analysis systems [23], artificial intelligence [24,25], cloud computing [26], smart grids [27], Internet-of-Things (IoT) infrastructure [28], and other Information and Communication Technologies (ICTs) were identified as enabling factors of the circular economy in urban contexts. For example, their integration with the infrastructures that characterize the urban fabric such as roads, lamps, traffic lights, energy, and water distribution systems, surveillance cameras, buildings, public transport stops, vehicles, ports, airports, bridges, highways, rivers, lakes, and so on, allow cities to collect, monitor, analyze, and share data among the various stakeholders, improving urban products and services, their circularity, and their ability to increase the quality of life.

Therefore, this high concentration of social, economic, environmental, and technological flows, processes, and stocks creates opportunities to face future urban challenges in a circular manner, spreading disruptive practices, behaviors, and habits capable of fostering new models of urban governance and business [29–31]. In other words, the concepts of urban ecosystem [32,33] and living lab [34,35] in which it is possible to plan, elaborate, develop, analyze, and redefine forward-looking urban policies characterize the current scientific literature on cities. In this regard, the report [36] defines cities as "open innovation ecosystems based on a systematic user cocreation approach that integrates public and private research and innovation activities in communities, placing citizens at the center of the innovation".

To this end, it is essential to improve awareness, understanding, and knowledge of urban processes and operations [37], and reorient the urban metabolism [38,39] to support an emerging and fascinating idea of the city as an engine of circular economy and advanced urban technologies [40–42]. Therefore, the ambition is to configure the circular economy as a bridge between the built environment, the natural environment, and the digital environment [43–45].

According to the report [46], cities must strengthen "the sustainable management of resources, facilitating the conservation, regeneration, restoration, and resilience of the ecosystem in the face of new and emerging challenges". In this sense, the circular economy has the potential to simultaneously improve the economic, social, and environmental aspects, such as waste management [47], renewable energy sources [48], energy efficiency [49,50], water management [51], cultural and health issues [52,53], material flows [54], biodiversity [55], transport [56,57], land use optimization [58], air and noise pollution prevention [59], infrastructure [60], and economic growth [61].

Therefore, the circular economy integrated with advanced information and communication technologies offers numerous advantages to increase the efficiency and digitization of urban metabolism in terms of optimization of the circulation and enhancements of materials, waste, byproducts, emissions, energy, knowledge, data, information, and so on [62–64]. This increase in the qualitative and quantitative level of urban circularity requires a paradigmatic rethinking of the urban metabolism and role of resources within urban contexts [65,66].

In this context, the so-called 'circular city' is emerging as a crucial component of sustainable urban development to address the complex and challenging issues of circular economy in a scenario of rapid urbanization and datafication [67]. This innovative urban sustainability initiative increases the "added value" of urban metabolism [68], which, based on industrial ecology [69], integrates and reformulates urban social, environmental, economic, and technological infrastructures [70]. On this point, the report [6] defines the circular city as a complex urban ecosystem that uses and integrates circular economy technologies, smart city solutions, and other innovative urban development actions to reduce congestion, carbon emissions, pollution, and anthropogenic pressures, while ensuring better business opportunities, skills, jobs, air quality, and competitiveness.

In this regard, numerous circular city projects recently emerged. Therefore, this study elaborates a comparative assessment of Prato (Italy), Oslo (Norway), The Hague (The Netherlands), Kaunas (Lithuania), Porto (Portugal), and the region of Flanders (Belgium), the six cities that make part of the Urban Agenda Partnership on Circular Economy [71]. The cooperation also includes several European institutions, such as the European Commission (e.g., DR Regio, DG Env, DG Clima, DG RTD, DG Grow), the Council of European Municipalities and regions, Eurocities, Urbact, the European Investment Bank, and the Association of Cities and Regions for sustainable Resource management. Furthermore, the member states that joined the Partnership on Circular Economy (PCE) of the Urban Agenda are Finland, Greece, Poland, and Slovenia.

In this sense, the circular cities taken into consideration in the comparative assessment identified by the theoretical and managerial literature as paradigmatic examples of urban circularity demonstrate that an open and flexible urban governance is necessary and able to coordinate and support intersectoral cooperation during the planning, implementation, monitoring, and development of strategic actions towards a circular urban model [72,73]. In [74], authors underline the fundamental role of urban governance in disseminating circular economy principles in complex urban contexts, identifying several good practices that policymakers, urban planners, and managers can develop; for example, providing a long-term holistic vision, facilitating knowledge sharing and collaboration, creating support-schemes for businesses and citizens, and incorporating circular principles into procurement procedures and in the distribution of urban services and products.

On the other hand, the strategy of digitizing the circularity of urban metabolism through real-time monitoring stations of water and energy consumption, GPS tracking sensors and digital cameras to control and manage mobility, cloud computing platforms for sharing sensitive data and information between agencies, departments, divisions, utilities, etc., outlines a multitude of challenges and criticalities related to: (a) the quality of the data used [75]; (b) the degree of traditional and cyber security [76]; (c) the necessary integration of data and information of different types, provided by a wide range of stakeholders [77], and (d) the ability of policymakers, urban managers and planners to convert continuous and real-time feedback from stakeholders into forward-looking urban circularity strategies [11].

While these experiments are promising test-beds of innovation for circularity, they are still limited exceptions [78]. Moreover, many cities around the world do not yet have the industrial, technological, economic, social, and environmental structures suitable for such a paradigm shift [79,80]. Addressing and solving this combination of issues with a systematic and holistic approach is the challenge of policymakers, urban managers, planners, architects, and urban economists [81,82]. Such a challenge needs to integrate circular economy principles and technologies with methods that can guarantee progress towards an integrated and multifaceted urban circularity [83,84]. In this sense, the 'Circular Resource Efficiency Management Framework' implemented by the European Commission [85] aims to help policymakers, urban managers and planners, administrators, etc., who intended to develop a multidimensional and digital plan for the management of urban circularity, systematically integrating the identification of flows, the distribution of responsibilities between the stakeholders involved, the monitoring of interventions, and the evaluation of results.

Although there are several studies in the scientific literature on the role of the circularity in cities [40,86,87], most of them tend to focus on individual cities [88]. While authors of [41] compare the case studies of Amsterdam, Utrecht, and The Hague, highlighting the barriers and limits of the transition to urban circularity, the paper [67] mapped the cities of Amsterdam, Rotterdam, Glasgow, Haarlemmermeer, The Hague, and Barcelona. At the same time, authors of [89] analyzed cultural barriers to circularity at EU level. However, the existing literature on the use of Information and Communication Technologies (ICTs) and advanced digital infrastructure of cities remains conceptual and lacks a comparative assessment of several practical cases, in particular, how the implementation of digital technologies enables cities to develop circular urban models.

The proposed study identifies the need for research on the social, economic, environmental, and technological impacts of digital infrastructures on circular urban models, highlighting the need to identify digital technologies not only as enablers, but also as triggers factors. To fill these gaps, this study's aim is not only to investigate how technology allows for a more sustainable and digitalized circularity in Prato, Oslo, The Hague, Kaunas, Porto, and in the region of Flanders, taken as exemplary cases, but also to derive the main social, economic, environmental, and technological challenges, and the barriers and the enabling factors that characterize the digitization of urban circularity. Specifically, the study aims to answer two research questions on the role of digital technologies in circular cities: (1) which digital technologies use circular cities in their urban strategies, and (2) what kind of social, environmental, economic, and technological challenges do digital technologies pose, and what are the enabling factors to create value from better circularity?

Therefore, the paper is structured as follows. Section 2 provides an overview of the main digital technologies used in the urban metabolism management to facilitate the implementation of circular urban models. Section 3 introduces the methodological approach implemented. Section 4 provides a comparative analysis of the urban metabolism of the six circular cities of the Partnership on Circular Economy (PCE) taken as paradigm examples, highlighting the role of digital technologies in the development of urban circularity strategy. Finally, the last section includes discussion and conclusion.

2. Digital Technologies for Urban Metabolism

According to [90], urban metabolism represents a complexity of socio-technical and socio-ecological processes through which flows of raw materials, emissions, byproducts, energy, waste, people, information, data, and so on, characterize the city and the surrounding urban context and satisfy the needs of its inhabitants. On this point, the concept of urban metabolism was extensively examined in the literature [91–94]. In addition, advances in urban metabolism perspectives are proposed [95,96], different frameworks at the city level were implemented [92], several case studies in various region of the world examined [97,98] and, finally, demonstrated the relationship between the efficiency of urban metabolism and the sustainability of the city [99].

Nevertheless, the definition proposed by [90] requires the integration of digital technologies capable of facilitating the circularity of the social–ecological–technical processes. In this regard, authors of [100,101] observe how information and communication technologies (ICTs) occupy a central position in the urban metabolism of circular cities, underlining the determining role of technology in achieving urban resilience and sustainability.

Several scholars highlighted the fundamental role of the integration of advanced urban technologies, such as ICTs [43], sensors [11], IoT [22], big data analytics [102], cloud computing [103], artificial intelligence (AI) [25], augmented reality (AR) [104], real-time monitoring stations [105], digital cameras [106], actuators [107], real-time tracking systems [108], smart grids [109], Blockchain [110], 5G wireless communication [111], and social media platforms [112] with the physical infrastructures that characterize the urban context, such as roads, highways, airports, ports, bridges, rivers, lakes, buildings, public transport stops, vehicles, parks, and so on, to improve the efficiency and digitization of the urban metabolism. Hence, in light of the challenges related to the growing datafication and urbanization, the urban metabolism narrative has shifted from a linear approach (source–consumption–waste), characterized by the theory of the abundance of resources always available to models of smart urban metabolism [3], where real-time and digital monitoring, conservation, sharing, and reformulation of materials and products already in circulation is guaranteed and maximized to reduce the extraction of raw materials and the accumulation of waste.

Since the social, economic, environmental, and technological wellbeing of cities is dependent on their carrying capacity [113], the planning, monitoring, analysis, and redefinition of urban metabolism becomes relevant for the field of the circular economy [39]. In this regard, many cities around the world managed to exploit advanced technologies to provide sustainable and digital solutions useful for planning, monitoring, and analyzing urban processes [114–116]. In this sense, as explained by the authors of [117], citizens, entrepreneurs, local administrators, and so on, act as sensors by using mobile and stationary ICT devices, representing agents of urban change capable of developing new forms of participatory citizenship. Therefore, today, policymakers, urban managers, planners, municipal utilities, citizens, and technological companies and startups recognize the importance of digital urban infrastructures in various dimensions of urban metabolism to improve the efficiency of circularity, such as: (a) environment; (b) energy; (c) water and wastewater; (d) waste; (e) health; (f) safety and security; (g) education; (h) leisure; (i) economy; (j) mobility; (k) telecommunications, and (l) governance.

The technology in the environment dimension not only focuses on monitoring air quality, in particular CO_2 and GHG emissions through real-time monitoring stations [48,118], but also on surveillance and early warning systems such as digital cameras [106] and acoustic sensors [119] capable of providing alarms and messages via apps and social media platforms in the event of earthquakes, floods, and cyclones [120]. In this regard, the paper [25] describes artificial intelligence (AI) as a tool to safeguard our cities from the social, economic, and environmental consequences of climate change [121], loss of biodiversity [122], natural disasters [123], pandemics [124], unsustainable development [125], and so on.

Smart grid systems transformed the energy dimension of urban metabolism, facilitating the demand management to respond quickly during outages, shifting peak loads and failures [126]. In addition, the Internet of Things (IoT) integrated with sensors and actuators introduced a wide range of applications for consumers (e.g., remote monitoring) that encourage the use of alternative renewable sources to improve the efficient use of energy sources and to minimize the electricity costs [127]. In this sense, real-time price models (RTP) allow consumers, distributors, and producers to monitor the costs of energy consumption in real-time [128]. The paper [129] proposed a new strategy that can address the volatility of energy production costs based on real-time and long-term forecasts of the solar energy system and load demand to manage energy consumption optimally. Moreover, authors of [130] argue that the use of AI provides accurate estimates for generating energy maps that can be used for energy planning and modelling.

Digital technologies affecting water and wastewater in circular cities include solutions capable of improving the capacity of reuse through efficient and real-time quality monitoring systems located on the sewer pipes, rivers, lakes, and seas [131], and data sharing among urban stakeholders through cloud computing platforms [132]. Furthermore, real-time tracking sensors placed on public and private buildings allow urban administrators to identify possible losses or failures [133]. To this end, the installation of smart meters in buildings [134] and the development of apps for smartphones of fixed platforms [135] capable of providing actual consumption rate and those based on sustainable demand models can support water service management. The technology in waste management provides innovative solutions capable of analyzing and classifying waste in smart bins through code scanners [136] and tracking systems shared between municipal utilities, citizens, and policymakers via cloud computing platforms to optimize resources and time [137]. In this sense, the R principles that characterize circular economy [138,139], ranging from 3 R (Reduce–Reuse–Recycle) to 10 R (Refuse–Rethink–Reduce–Reuse–Re–pair–Refurbish–Remanufacture–Repurpose–Recycle–Recover) [140] applied to electronic waste (e-waste) represent a challenge for policymakers due to their difficult management and potential environmental impacts [141]. The same digital development is being observed in the healthcare dimension [142]. For instance, the implementation of ICTs changed the traditional relationships between patients and medical facilities, moving towards integrated e-health systems [143]. Furthermore, smartphones, social media platforms, and wearable devices provide enormous amounts of data useful for developing health programs remotely and sharing feedback and experiences to monitor health conditions in a more personalized and intelligent manner and reduce long-term health costs [53,144,145]. The paper [146] indicates that the use of cloud computing platforms capable of optimizing the vehicular flow of ambulances, emergency vehicles, and mobile clinics can minimize the number of visits to healthcare facilities, providing a completely interconnected perspective of healthcare. Safety and security management and control through satellite monitoring [147], CCTV surveillance [148], and the use of global positioning system (GPS) [149] do not only embrace traditional aspects such as the prevention of infringements, traffic accidents, deaths, etc., but they give rise to a multitude of issues related to the cyber environment as the level of technological security and the protection of personal data [150,151]. Regarding education, the COVID-19 pandemic highlighted a series of issues related to the inadequacy of the digital urban infrastructure [152]. For example, many cities failed to provide online education due to lack of adequate broadband connections or web traffic overload [153]. Furthermore, online education also highlighted and accelerated social equity issues related to the digital divide inherent among low-income and special-needs students, and perhaps those residing in marginalized urban areas [154]. From the leisure point of view, libraries, museums, public parks, sport facilities, and music halls benefited in terms of fruition by developing digital platforms (e.g., forums, social networks, blogs, etc.) able to increase user engagement [155]. For example, several tourist cities diversified their offer by providing virtual tours and 3D experiences through the support of augmented reality and artificial intelligence [156], capable of attracting tourists from all over the world. Internet of Things (IoT) structurally changed the economic dimension of cities [157,158]. Specifically, the employment and unemployment rate are experiencing a change in the type and quality of jobs [159]. For example, many companies use automated recruitment processes assigning other tasks to human resources departments [160]. Therefore, many of the products and services offered by human workers are now revolutionized or replaced by technology [161], radically transforming the industrial and manufacturing sector towards models of industrial hubs [162], industrial clusters [163], incubation centers [164], and science parks [165]. The dimension of mobility was profoundly transformed by digital solutions such as sensors and real-time monitoring stations positioned on roads, vehicles, traffic lights, bridges, buildings, and so on. [56,166,167]. In addition, public transport equipped with electronic payment systems [168], urban areas mapped in real time by interactive graphics [169], radar systems to detect critical events [170], and multimodal mobility (e.g., car sharing, bike sharing, carpooling, ride sharing, etc.) aim at optimizing vehicular circularity within urban contexts [171]. The next challenge for policymakers, urban managers, and planners is to integrate the autonomous vehicles—produced by the most important car manufactures and already being tested in various cities around the world—into the urban and regulatory fabric [172,173]. Nowadays, citizens, companies, and local authorities operate in a fully networked urban environment through mobile and fixed devices without limitations of time, place, and typology [174]. Therefore, by combining these factors with the rapid and pervasive spread of high-speed broadband [175], the quality of information is developed through higher image resolution [176] and greater personalization to meet specific needs and preferences [177]. In this regard, the role of information and communication technologies enabled urban governance to collect, integrate, analyze, and interpret data on a plethora of circularity dimensions [178]. In this sense, data-based urban management allows better governance as policymakers, urban managers, and planners can make informed decisions and formulate appropriate policies [179]. On this point, AI and machine learning technologies, which allow for the collection of real-time urban data, provide a deeper and more detailed comprehension of how circular cities evolve, adapt, and respond to various conditions [180]. To integrate Big Data, AI, and machine learning, new approaches such as Blockchain technology can improve the urban circularity [72]. The paper [181] argues that Blockchain can significantly contribute to the circular economy in cities by enabling distributed, secure, and digitalized urban governance, supporting systemic, and holistic cooperation between machines, Big Data, and humans. In fact, through Blockchain technology, the Big Data generated by the urban stakeholders are permanently saved and made accessible through shared platforms and dashboards [182–184], allowing citizens to acquire greater knowledge and awareness of urban processes, and therefore, to provide opinions and feedback [185].

However, the intensive and widespread use of digital technologies for urban circularity highlights a wide range of challenges related to the social, economic, environmental, and technological dimensions of urban metabolism [186]. From an economic point of view, the considerable costs of designing, installing, integrating, maintaining, and reprogramming advanced digital technologies undoubtedly represent an obstacle for poorly organized or less developed cities [187]. In this regard, the search for funding for the implementation of digital technologies is crucial for the cities involved in the transition of urban circularity [188]. Specifically, the European Structural and Investment Funds (ESIF), which include regional funds (ERDF) and agriculture and rural development funds (EAFRD), and Smart Specialization Strategies (RIS3) contribute significantly to the dissemination of circular and digital initiatives in Europe [189–191]. At the same time, policymakers, urban managers, and planners developed several partnerships with universities, research centers, startups, nonprofit organizations, technology companies, and so on, to encourage the experimentation of urban digital technologies through tax relief, incentives, or technical advice [192].

From a social point of view, the obstacles to urban circularity are mainly related to the highly departmentalized and nonintegrated bureaucratic governance structure, which prevents any digitalization strategy [193]. For example, in many cities around the world, the urban metabolism decision-making process still takes place in silos, where the policies of agriculture, water, waste, mobility, energy, health, telecommunications, education, etc., are considered separately by agencies, departments, divisions, cabinets, interdepartmental committees, municipal, regional, and state-owned utilities, and so on, neglecting a multidimensional and holistic perspective [194]. The balance of data and information governance between stakeholders operating within urban circularity, such as municipalities, research centers, universities, companies, citizens, nonprofit organizations, utilities, etc., represents a challenge for policymakers, urban planners, and managers [195]. In this regard, the literature on circular cities emphasizes participatory and fluid urban governance models capable of proactively involving stakeholders in the planning, monitoring, and evaluation circularity performance through continuous suggestions, feedback, proposals, ideas, and recommendations. At the same time, the active involvement of stakeholders provides a greater sense of belonging and a greater commitment to the decision-making process, further legitimizing the digitalization of urban metabolism [196].

However, there are several behavioral, psychological, and motivational barriers to the digitalization of circularity of urban metabolism [197]. Firstly, resistance to change and the maintenance of the status quo can lead policymakers, bureaucratic apparatuses, and entrepreneurs to maintain their power of influence, rejecting any innovation in the decision-making process [198]. Furthermore, the lack of: (a) confidence in digital technologies [199]; (b) motivations or incentives to codesign or cocreate circular urban policies [200]; (c) awareness of the importance of user participation and monitoring [201]; (d) certainty in the use of digital devices due to security and privacy issues [202], and (e) familiarity with fixed and mobile digital platforms [203] are factors that discourage users from actively participating in the digitalization of the circularity of urban metabolism.

Thus, to capture and address the systemic improvements in the efficiency of the urban circularity, digital technologies must enable the creation, integration, and dissemination of value within cities through urban model innovations [204]. In this sense, the 'Circular Resource Management Framework' elaborated by the European Commission [85] provides a detailed and smart description of the mapping, monitoring, and evaluation phases of resources to acquire comprehensive and accurate information on the metabolism of circular cities. Specifically, the sustainable and digital framework proposed as an instrument for managing urban circularity integrates the phases of: (a) identification of the urban metabolism, necessary to inventory and prioritize urban flows; (b) intermediation with stakeholders to catalog the different flows between the stakeholders involved, and (c) monitoring of interventions and evaluation of resource efficiency. Subsequently, we examined and described how digital technologies that characterize the 'Circular Resource Efficiency Management Framework' contributed to the circular economy of the six cities (Prato, Oslo, The Hague, Porto, Kaunas, and Flanders region) participating in the circular economy partnership (PCE) promoted by the European Commission.

3. Methods

This study is based on a qualitative methodological approach characterized by a literature review of digital technologies that catalyze the circularity of urban metabolism and a detailed analysis of circular cities that compose the Partnership on Circular Economy (PCE) elaborated by the Urban Agenda of the European Commission to develop an exhaustive overview of the digitalization strategies of the circularity of urban metabolism. The methodological process is illustrated in Figure 1.

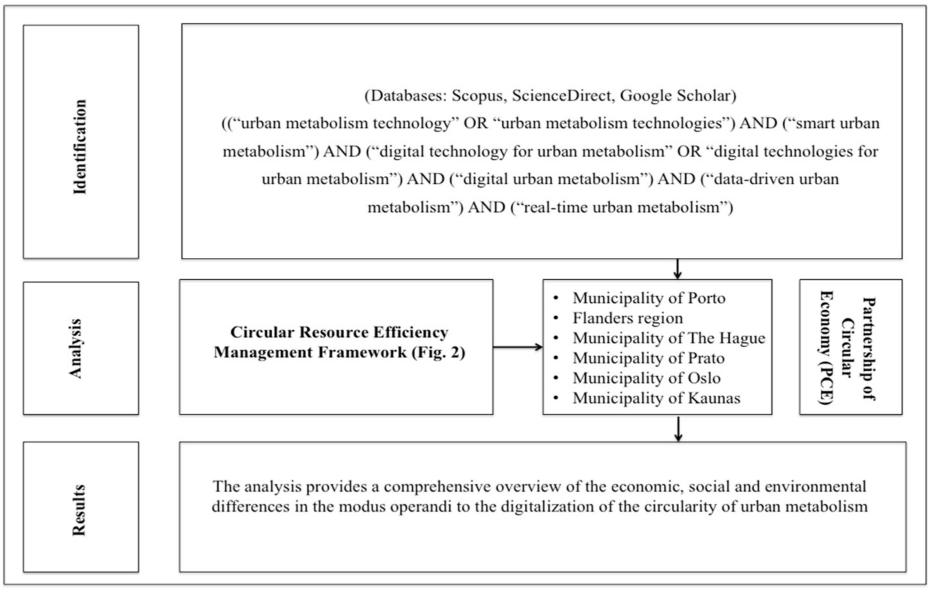

Figure 1. Methodological approach. Source: authors (2021).

Firstly, the search question, keywords, and search databases are identified. Regarding the research objective and question, the study aims to identify the digital technologies that favor the circularity of urban metabolism, and subsequently, to highlight and analyze the different approaches used by the six cities engaged in the circular transition promoted by the Partnership on Circular Economy (PCE) of the European Commission. Hence, to develop a detailed literature review on digital technologies on urban metabolism, the study integrates journal articles, books, conference proceedings, and grey literature such as urban reports and master plans. To do this, ScienceDirect, Google Scholar and institutional websites were used as search databases. Regarding the keywords, they include: ((“urban metabolism technology” OR “urban metabolism technologies”) AND (“smart urban metabolism”) AND (“digital technology for urban metabolism” OR “digital technologies for urban metabolism”) AND (“digital urban metabolism”) AND (“data-driven urban metabolism”) AND (“real-time urban metabolism”)). The following literature review provides a detailed comprehension of digital technologies that favor the circularity of urban metabolism and serves as a theoretical basis for the analysis of circular cities. Specifically, the analysis of the digitalization of the circularity of urban metabolism concerns the six cities that compose the Partnership on Circular Economy (PCE) promoted by the Urban Agenda of the European Commission and includes: the Municipality of Porto [205], the Flanders region [206], the Municipality of The Hague [207], the Municipality of Prato [208], the Municipality of Oslo [209], and the Municipality of Kaunas [210] (as illustrated in Table 1).

Table 1. Summary of digital technologies on circularity of urban metabolism. Source: authors (2021).

Circular City	Location	Initiative	Urban Metabolism Dimension	Digital Technology	Source
Municipality of Porto	Portugal	Via Verde Boleias Repositorio de materiais Horta à Porta OPO' Lab	Mobility Construction Agriculture Economy	Web sharing platform Web sharing platform Web sharing platform Coworking sharing platform	[205]
Flanders region	Belgium	Cambio Dégage Peerby	Mobility Mobility Materials efficiency	Web sharing platform Web sharing platform Web sharing platform	[206]
Municipality of The Hague	The Netherlands	Made in Moerwijk KledingBank Den Haag Lekkernassuh De Groene Regents	Social entrepreneurship Social entrepreneurship Agriculture Energy	Web sharing platform Web sharing platform Web sharing platform Web sharing platform	[207]
Municipality of Prato	Italy	Automatic Vehicle Monitoring Cityworks Trucks Monitoring in urban cleaning Smart Safety Baciacavallo purification plant Smart Energy	Mobility Mobility; construction Environment Safety Water; wastewater Energy	Sensor dashboard Sensor dashboard Real-time monitoring platform Digital video surveillance cameras Real-time monitoring stations Smart grids; smart meters	[208]
Municipality of Oslo	Norway	Urban Ecological Innovation Centre	Waste; economy	Physical and web sharing platforms	[209]
Municipality of Kaunas	Lithuania	Sustainable Economic Development promotion and enhancing competitiveness Developing a clever and civil society Sustainable Territory and Infrastructure Development	Economy Governance; population and social conditions; health; education; urban planning; safety Water; Wastewater; Energy; transport; waste; mobility	Web platform; real-time monitoring stations; sensor dashboard Real-time monitoring stations; sensor dashboard	[210]

The choice to consider and analyze the digital and circular initiatives implemented by the cities that constitutes the Partnership on Circular Economy (PCE) of the Urban Agenda of the European Union represents a study limitation. Consequently, the investigated sample does not consider the circular cities located in other contexts, such as China, Australia, Germany, Japan, South Korea, and so on. Therefore, the small number of circular cities analyzed does not represent the totality of the cities involved in the digitalization of the circularity of urban metabolism. However, most cities around the world are not equipped to collect, monitor, analyze, and evaluate the performance of the circularity of urban metabolism through real-time monitoring stations, sensors, smart grids, digital cameras, GPS tracking systems, and so on. In this sense, the study considers six European circular cities characterized by high quality social, economic, environmental, and technological infrastructures.

The aforementioned circular cities were analyzed and compared with each other. In this sense, the analysis was based on a qualitative approach, considering the various urban reports and master plans developed by municipal, national, and international policymakers. Specifically, this choice was made based on the difficulty of identifying detailed quantitative data on social, economic, and environmental flows catalyzed by the digital technologies of the circular cities under consideration. Therefore, to elaborate a coherent and robust analysis, the cities were examined through the 'Circular Resource Efficiency Management Framework' implemented by the European Commission [85] (as illustrated in Figure 2). In fact, since the various sources adopt different terminologies and frameworks, the choice to standardize the analysis through a unified framework provided by an independent institution that aims to identify, analyze, and evaluate the circularity flows of urban metabolism goes in the direction of creating a homogeneous and consistent study.

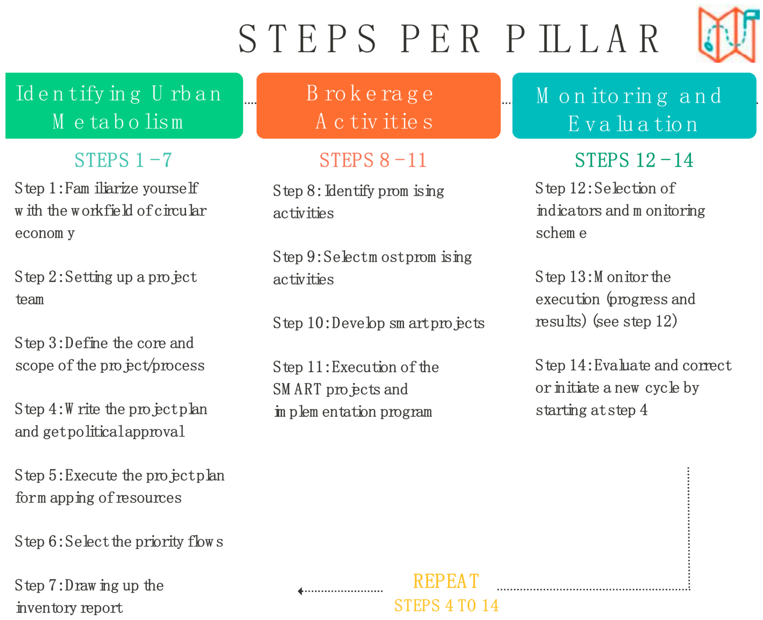

Figure 2. Circular Resource Efficiency Management Framework. Source: European Commission [85].

The 'Circular Resource Efficiency Management Framework' offers a systemic and holistic roadmap to be implemented in the management of social, economic, and environmental resources in a circular and digital manner. In detail, it consists of three phases:

1. *Identification of urban metabolism* aims to map the economic, social, environmental, and technological resources that operate within the city context. In this sense, this information provides a knowledge heritage essential to improve the efficiency of resources [211].
2. *Brokerage activities* allow the identification, involvement, and empowerment of the stakeholders in each urban process. Specifically, this phase aims to assign and connect stakeholders involved to their respective flows of social, economic, environmental, and technological resources.
3. *Monitoring and evaluation* activities permit the monitoring of progress of the implemented activities and evaluation of the effectiveness of urban policies adopted. To do this, policymakers, stakeholders, urban policymakers, urban managers, and planners must have detailed, systemic, and multidimensional urban data to confirm or redefine the developed urban strategy.

Specifically, the following analysis was based on a detailed investigation of the essential points of the urban reports and master plans examined to integrate them into the various "steps" of the identification of urban metabolism, brokerage activities, and monitoring and evaluation phases of the Circular Resource Efficiency Management Framework. Therefore, the rigorous compliance with the "steps" provides a comprehensive overview of the economic, social, environmental, and technological differences in the modus operandi to urban circularity. Furthermore, the lack of in-depth studies in the literature on the role of digital technologies in city-scale metabolism validates this exploratory analysis; focusing on the experiences of pioneer cities could provide recommendations and reflections for other cities.

4. Results

4.1. Identifying Urban Metabolism

In terms of theoretical and managerial sources, most of the digitalization strategies of the circularity of urban metabolism come from urban reports and master plans elaborated by municipalities and municipal-owned utilities. For example, regarding the first step of the 'Circular Resource Efficiency Management Framework' (as illustrated in Figure 2), the familiarization of the Municipality of Prato with digital technologies of urban metabolism takes place with the implementation of the 'protocol for the development of smart city projects' [208] and the 'Prato Circular City project', which promote the image of Prato as a city able to exploit digital technologies; e.g., real-time monitoring stations, sensors, and mobile platforms to optimize urban processes. Similarly, the Municipality of Porto approaches the circularity of urban metabolism through the launch of the ScaleUp Porto's Manifesto, which includes several web platform-initiatives to promote sharing practices inherent in mobility, urban spaces, and food [205]. Otherwise, the Municipality of The Hague elaborated the 'Grondstoffenakkord' (Resource Agreement) with other Dutch cities to develop the 'Circular Netherlands in 2050′ program. According to the 'strategic development plan of the Municipality of Kaunas' [210], Lithuanian policymakers aim to transform Kaunas into a "sustainable and civic-minded city'. Recently, the government of Flanders defined the digitalization of the circularity of urban metabolism as the priority of the 'Vision 2050, a long-term strategy for Flanders', emphasizing the decisive role of OVAM (public waste agency of Flanders) in the transition towards urban circularity [206]. In this sense, regarding step 2, the urban reports and master plans of circularity of cities taken into consideration show the fundamental contribution of municipal and national departments and utilities (see Table S1 in Supplementary Materials). For example, the Municipality of Prato involves a wide range of utilities such as ASM Ambiente Servizi Mobilità (waste management), CAP Società Cooperative (public transport), Consiag Servizi S.r.l (IT services), Estraclima S.r.l (thermo-hydraulic systems), and so on, to plan, monitor, and evaluate circularity performances of urban metabolism [208]. Otherwise, the Kaunas City Municipality Administration (KCMA), through the various internal divisions (e.g., energy, environment, mobility, social housing, etc.), is responsible for most of the circularity initiatives [210]. The Municipality of Oslo integrates both agencies such as the water and wastewater services agency, the real estate and urban renewal agency, the fire and rescue services agency, etc., and 'municipal undertakings' for educational buildings, cultural and sports facilities, and so on [209]. The Flanders region is promoter of the multidisciplinary partnership 'Flanders Circular' [206] with the municipalities of Ghent, Leuven, and Antwerp. The Municipality of The Hague shows a plethora of stakeholders, which includes: (a) national institutions, such as the economic and climate affairs, the infrastructure and water management, the social and employment projects ministries; (b) research centers, such as the Leiden and Delft universities, and (c) organizations, such as Maex, Platform31, shareNL, and Lekkernassuh [207]. Finally, the Municipality of Porto includes the municipal-owned utility Lipor (waste management) and cooperatives such as Fruta Feia, ADREPES, and RE-Food to promote biodiversity conservation and community engagement [205].

Therefore, with regard to the core and scopes of the circularity projects of urban metabolism (step 3), the analyzed circular cities share the idea of transforming their urban contexts into dynamic and digital ecosystems, utilizing different urban notions that recall the importance of systemic and cross-departmental thinking as 'smart living lab' (Municipality of Porto), 'aggregator' (Municipality of Porto), 'center' (Municipality Kaunas), and 'urban ecological innovation' (Municipality of Oslo).

However, the analysis urban metabolism flows (step 6) highlights a heterogeneity of priorities between the circular cities investigated deriving from different social, economic, environmental, and technological infrastructures. Specifically, the Municipality of Prato uses digital technologies, e.g., real-time monitoring stations for the energy and water consumption, sensors for the traceability of public transport vehicles, and ICTs and social media platforms for the circularity of data and information between administrative departments and citizens [208]. The Municipality of Kaunas focuses mainly on (a) economic development, in particular, competitiveness and internationalization of local businesses; (b) social inclusion, to create a 'clever and civic society', and (c) sustainable development of territory and infrastructure [210]. Otherwise, the circularity strategy of the Municipality of Porto is based on web platforms concerning ride sharing (Via Verde Boleias), reselling goods (Repositorio de materias), community garden (Horta a Porta), and coworking spaces (OPO' Lab) [205]. The Municipality of Oslo prioritized flows that concern waste, elaborating strategies to encourage sustainable production and consumption such as sharing and recycling of goods and materials [209]. Similarly, the Flanders region developed three 'green deals', which embrace circularity in the building materials sector, public procurement, and mobility [206]. The Municipality of The Hague favors social entrepreneurship initiatives in the field of circular economy aimed at reducing poverty and social exclusion (e.g., Made in Moerwijk, KledingBank Den Haag, Lekkernassuh, and De Groene Regents) [207].

4.2. Brokerage Activities

The identification, selection, and development of urban metabolism circularity projects (steps 8–10) of cities investigated show a wide range of digital technologies to improve the efficiency of urban processes. Specifically, real-time monitoring stations and tracking sensors platforms are the most used solution by municipalities within the mobility, water, and energy flows of urban metabolism. On the other hand, policymakers employ online platforms on institutional websites to share data and information between municipal departments and provide remotely administrative documentation to citizens. Furthermore, smartphone apps are used as tools to engage citizens to improve engagement and participation. As regards mobility dimension, the Municipality of Prato uses a sensor dashboard (Automatic Vehicle Monitoring) to acquire data about waiting and travel times of public transport vehicles to monitor the efficiency and effectiveness of flows [208]. Similarly, the sensor system implemented by ASM Servizi S.r.l (Municipality of Prato) permits control in real-time the route of trucks involved in urban cleaning and the state of bins. The Cityworks real-time platform implemented by ASM Servizi S.r.l (Municipality of Prato) monitors the progress of construction sites to create vehicle flow scenario models. Otherwise, the Municipality of Porto, through the support of Brisa (private transport operator), implemented Via Verde Boleias, a ride-sharing platform for smartphones and fixed technological devices [205]. Similarly, public transport utility De Lijn (Flanders region) holds two-thirds of the shares of the Cambio car-sharing platform. In detail, Cambio allows intermodal mobility, promoting the use of bicycle and public transport and a more efficient use of public space [206]. At the same time, Dégage is a private car sharing initiative that has a fleet of 240 cars and a bike sharing network throughout the Flanders region aims to spread the principles of circular mobility through sharing practices, to minimize use of cars, raw materials, and public space [206]. Peerby is a social platform with around 1 million shared products and services and 30,500 users in Flanders region. Based on a survey elaborated by Peerby, users participate in the initiative not only to share goods and services, but because this sharing increases social cohesion and trust among the inhabitants [206]. Digital video surveillance cameras are used by municipalities of Prato [208] and Kaunas [212] to capture real-time data and information to reduce traffic congestion and intervene in the event of accidents, infringements, and crimes. Specifically, the Municipality of Kaunas installed over 240 surveillance cameras in sensitive urban zones such as bridges, parks, traffic lights, underpasses, public transport stops, etc., coordinated by the Kaunas Traffic Control Center [212]. Similarly, the Municipality of Prato, through a georeferencing platform equipped with GIS technology and 3D visualization permits the municipal police to acquire and share information in real time. In terms of waste management, Repositório de Materiais is an online platform carried out by APRUPP (Portuguese Association for Urban Rehabilitation and Heritage Protection) and Municipality of Porto, which aim to spread reusing building materials practices [205]. In detail, it intends identify and centralize transactions between who own the building materials and those who—in a zero-waste approach—are willing to buy them. Similarly, the Flanders region included the 'circular construction sector' among the urban metabolism actions financed by the 'Circular Flanders' committee [206]. At the same time, the municipalities of Prato and Porto and the Flanders region also redefined the procedures of public procurement integrating circularity standards. On the other hand, the Municipality of Oslo installed several 'urban ecological innovation platforms' dedicated to the exchange/purchase of clothes, equipment, building and plastic materials, electronic tools, food, etc., and aim to improve awareness of circular economy practices [209]. Real-time monitoring stations are used also in Baciacavallo purification plant (Municipality of Prato) to track and monitor the water and wastewater quality to detect the production and distribution performances. Moreover, digital sensors allow the municipal utility Estra S.p.A (Municipality of Prato) to manage a complex network of smart grids to improve energy efficiency and interact through smart meters with users in the event of faults and outages [208]. Otherwise, De Groene Regents is a network of local residents in the Municipality of The Hague who developed an organization for the sharing of 2000 solar panels installed on the roofs of public buildings that covers the needs of 200 families [207]. Furthermore, the Municipality of The Hague financially supported the installation costs of solar panels. Within the social dimension of urban metabolism, the municipalities of Prato and Kaunas developed several e-governance initiatives to allow a transparent and secure circularity of data and information between stakeholders. Differently, the Municipality of Porto has projected the OPO' Lab coworking laboratory dedicated to the implementation of digital technologies for urban planning, architecture, and engineering [205]. However, OPO' Lab operates not just a sharing coworking space that favors interactions between entrepreneurs, researchers, policymakers, associations, and companies, but actively contributes to the dissemination of circularity principles. In this regard, the Municipality of Oslo involved schools, kindergartens, libraries, associations, and businesses in cultural events at the urban ecological innovation centers located in the 15 local districts [209]. The Municipality of The Hague is particularly involved in the social cohesion, poverty, and immigration themes. In this sense, Made in Moerwijk, KledingBank Den Hague, and Lekkernassuh initiatives identified the 'parallel economy' as a useful practice to reduce marginalization of the unemployed, immigrants, and socially excluded people. In practice, goods and services with a high social and environmental value are produced, contributing to the integration of the part of population excluded from the most competitive and technological labor market [207]. At the same time, Plarform31 addresses the issues of poverty, energy transition, health and well-being, climate, labor market, social housing, etc.; shareNL digital platform connects local authorities, associations, companies to develop circular economy initiatives, and the MAEX fund finances urban circularity projects.

4.3. Monitoring and Evaluation

In each circular city analyzed, digital technologies have a positive impact on the circularity of the urban metabolism, creating social, economic, and environmental value in the flow management strategies. Among the digital technologies identified, real-time monitoring stations and tracking sensors are the most used in the data collection on metabolic flows. In this regard, through monitoring and tracking technologies, the Baciacavallo plant (Municipality of Prato) can collect and analyze the quality and quantity of water and wastewater flows, improving the efficiency of the production and distribution service [213]. Similarly, the tracking sensors located in public transport vehicles and in the electricity grids allow Municipality of Prato to monitor energy consumption levels and develop urban metabolism strategies in line with the specificities of the city context [208]. Digital platforms for fixed and mobile devices such as smartphones, tablets, etc., that incentivize shared mobility practices (e.g., bike sharing and car sharing) allow the Municipality of Porto (Via Verde Boleias) and the Flanders region (Green Deal Shared Mobility) to improve the quality of vehicular flows [88]. Specifically, Via Verde Boleias permits reduced costs (parking and fuel) and carbon emissions (up 75% per user) and maximizes the use of existing vehicles, improving the culture of sharing [205]. From an environmental perspective, the Cambio and Dégage mobility sharing platforms allow a more efficient and sustainable use of public spaces by reducing car parks [206]. On average, through the platform implemented by Dégage, each car is shared and used by 10 people, convincing about 1000 people not to buy a car. From an economic perspective, therefore, each owner who shares his car on the platform saves around 1400 euros per year, while those who do not own a car save around 600 euros [206]. The following initiative also had the ability to expand the number of users using transport, increasing participation and social cohesion. Through the digital surveillance cameras localized in certain critical points, knowledge and understanding of real-time data of vehicular flows in the municipalities of Kaunas and Prato improved [214]. Furthermore, in the Municipality of Prato, the urban regeneration of the Macrolotto Zero district through social housing, public parks, and smart electricity networks revitalized existing infrastructures, improving the flow of resources [208]. In this regard, the Groene Regents energy platform initiatives implemented in the Municipality of The Hague allowed approximately 607,578 kWh/year of additional renewable energy produced by the solar panel network [207]. The integration of public procurement with urban circularity standards implemented in the Municipality of Oslo and in the Flanders region optimized the flows of construction materials and the tracing capacity. The physical (urban ecological innovation center) and virtual (shareNL and Platform31) sharing platforms allowed the municipalities of Oslo and The Hague to improve the exchange and reuse of resources. For example, the Peerby platform has around 800–1000 shared goods and services monthly and 30,500 users in the Flanders region [206]. Therefore, the Peerby sharing platform allows savings in money and consumption of energy, water, fuel, and raw materials. Furthermore, the sharing activities also strengthen the sociality, safety, and economy of the neighborhoods, mainly involving highly educated people in urban circularity practices [206]. Likewise, the Made in Moerwijk platform allows reuse practices of plastic and construction waste, tires, etc. through social projects that create jobs for socially excluded citizens and provides them with greater environmental awareness [207]. Annually, Kledingbank Den Haag supplies 3000–4000 items of clothing to around 1400 people [207]. As it is a nonprofit organization, most of the income comes from private donations and public subsidies from the Municipality of The Hague. Therefore, thanks to the applied price policy, most the clothing is sold at a symbolic price of 1 euro, allowing wide access to that part of the population with low income, unemployed, and vulnerable people [207]. In the municipalities of Prato and Kaunas, Information and Communication technologies (ICTs) allow a circularity of data between departments and provide administrative documentation through telematics methods. Furthermore, apps for smartphones and tablets permit a continuous and dynamic interaction with citizens and stakeholders, offering increasingly personalized and categorized urban services.

5. Discussion and Conclusions

The digitalization of the circularity of urban metabolism integrates the traditional aspects of urban metabolism with the need to computerize urban processes to better address the social, environmental, economic, and technological challenges of urbanization and datafication of urban contexts [215]. Therefore, the digital technologies identified as real-time monitoring stations for water, wastewater, and energy consumption, tracking sensors for vehicular flows (public transport, cars, trucks, etc.), digital surveillance cameras for guaranteeing safety and security within urban circularity, and physical and virtual platform for the sharing/reuse/regeneration of goods and services allow policymakers to optimize and improve urban metabolism. Furthermore, digital technologies permitted municipalities to innovate the circularity of urban metabolism by providing greater understanding, awareness, and knowledge of monitored data and information. In this sense, the implementation of digital technologies is highlighted by the circular cities investigated as an enabling and preeminent factor for the smart and sustainable circularity of urban metabolism. Hence, the ability to collect, monitor and analyze large volumes of environmental, economic, and social data is critical to achieving urban structural change. However, policymakers who have not adopted digital technologies to improve the circularity of urban metabolism flows must recognize that their installation, application, development, maintenance, and redefinition requires incremental investments in urban governance, technical, and economic infrastructures. The study proposes a twofold contribution to the issue of digital technologies for urban metabolism. Firstly, it contributes to the theoretical literature through a detailed overview of digital technologies capable of promoting the circularity of urban metabolism, such as sensors, big data analytics, cloud computing, AI, AR, GPS tracking systems, real-time monitoring stations, video surveillance cameras, and so on. In this sense, Section 2 provides an exhaustive review of the dimensions of urban metabolism in which circularity exploits digital technologies as environment, energy, transport, economy, education, telecommunications, health, safety, governance, urban planning, waste, etc. Secondly, the study involves the 'Circular Resource Efficiency Management Framework' developed by the European Commission [85] to identify, analyze, and evaluate the digital initiatives of the circularity of the urban metabolism of the six cities (Kaunas, Flanders region, Porto, Prato, The Hague and Oslo) that characterize the Partnership on Circular Economy (PCE) promoted by the Urban Agenda of the European Union. For example, through the real-time monitoring stations located in the Baciacavallo plant, the Municipality of Prato can control the quality of the water production and distribution service. Similarly, the tracking sensors allow the municipalities of Kaunas and Prato to organize the vehicle fleet and routes of the public transport service. The virtual sharing platforms shareNL and Platform31 operating in the Municipality of The Hague and physical (urban ecological innovation center) located in the 15 districts of the Municipality of Oslo provide tools for sharing goods and services, reducing the flow of waste. Furthermore, the platforms Made in Moerwijk, Kledingbank Den Haag, and Lekkernassuh implemented in the Municipality of The Hague aim to include vulnerable people in the labor market by providing them with the principles of urban circularity. As for mobility, car and bicycle sharing practices developed in the municipality of Porto and in the Flanders region allow for a reduction of emissions and a better vehicular circularity. Furthermore, the investigation of the circular cities highlights the need to develop an ecosystem of departments, agencies, ministries, municipal divisions, and state and municipal owned utilities to correctly attribute the competences and objectives of each urban metabolic flow.

The study of the digitalization of the circularity of urban metabolism elaborated in this paper analyses only the cities that compose the Partnership on Circular Economy (PCE). Therefore, we are aware that this choice of case-specific selection limits the scope and generality of the analysis. However, through the practical application of the European Commission's Circular Resource Efficiency Management Framework and a literature review of digital technologies for urban metabolism, we improved the validity of the analysis, allowing generalization of the conclusions. However, the lack of quantitative data on the social, economic, and environmental flows of the circularity of the cities taken into consideration requires us to base our analysis on a qualitative methodological approach, analyzing urban reports and master plans elaborated by municipal, national, and international authorities. For this reason, it is necessary to conduct further quantitative research to further test the results of the following qualitative study to provide more details on the digitalization of the circularity of urban metabolism.

Thus, the wide range of digital technologies identified and analyzed in this theoretical study clarifies the crucial role of urban technology that improves not only metabolic flows, but also transparency, accountability, and citizen participation in urban governance. In this regard, the proposed analysis is extremely beneficial for policymakers, urban managers, and planners who aim to monitor, analyze, and evaluate the potential of the economic, social, and environmental improvements provided by urban circularity.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13116043/s1, Table S1: Circularity city stakeholder matrix. Source: Authors (2021).

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