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SMART URBAN METABOLISM:

Understanding the Digitalization of the Circularity of Urban Metabolism

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Abstract

Smart Urban Metabolism is a hybrid approach – where technological, economic, social and environmental perspectives are simultaneously considered – to feed and improve the circularity of flows within urban contexts. In a global era characterised by intense and pervasive urbanization and datafication, the digital technologies-driven approach is becoming decisive among cities around the world engaged in the transition towards a smart and sustainable urban metabolism. In this regard, tools such as real-time monitoring stations, GPS tracking systems, sensors, radars, drones, cloud computing, artificial intelligence, augmented reality, smart grids, big data analytics, Internet of Things, and so on, have been recognized as enabling factors for improving the quality and efficiency of urban metabolism circularity. Therefore, these fixed and mobile digital devices make Smart Urban Metabolism a strategic framework for policymakers, urban planners and managers in order to collect, monitor, elaborate and analyse data and information regarding circularity performance within the economic, environmental, social and technological spheres of cities. The following Thesis investigated the contribution of the digitalisation of the circularity of urban metabolism in the improvement of decision-making processes of natural and artificial urban resources. Specifically, three research objectives were identified: (1) what digital technologies are capable of improving circularity within the various dimensions of urban metabolism? (2) It is necessary to plan and develop urban technological infrastructures such as sensors, monitoring stations and tracking systems? and (3) What are the social, economic, environmental and technological challenges that emerge from the digitalisation of the circularity of urban metabolism? In order to achieve these research objectives, the study was based on an extensive and detailed literature review on urban digital technologies and on a multiple analysis of case studies of cities considered to at the forefront worldwide of urban metabolism circularity driven by technology. The proposed Smart Urban Metabolism, enabled by the emerging context of circular cities, provides a perspective of social, economic and environmental performance with greater spatial-temporal resolution, characterised by data and feedback processed continuously and in real-time. One of the most interesting insights that emerge from Smart Urban Metabolism is that this new perspective overcomes some of the limitations identified in the traditional concepts of urban metabolism and urban smartness. The results confirm that there are under-treated social, economic, environmental and technological aspects that can be discovered and analysed through the digitalisation of the circularity of urban processes and operations. Therefore, taking these aspects into consideration in the planning, monitoring and evaluation phases of circularity can lead to the identification of appropriate strategies and practices for the development of smart and sustainable urban metabolism.

Keywords

Smart Urban Metabolism; digital technologies; smart and sustainable urban development; urban circularity; digitalisation; sustainability

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Preface

The research produced in this thesis is the result of the investigation activities carried out during the Ph.D. Program in Economics, Management and Statistics at the University of Messina (Italy). In this sense, the basis of this thesis was started, discussed and elaborated with my Supervisor Prof. Giuseppe Ioppolo, who in his Paper "Can cities become smart without being sustainable? A systematic review of the literature" has sentenced that to be truly smart, cities must be sustainable in the first place.

The notion of Smart Urban Metabolism proposed and analysed in this thesis takes place when the concepts of circular economy, urban smartness and digitalization have forcefully entered the theoretical and managerial debate on the management of natural and artificial resources of our cities. In this regard, I submitted a presentation entitled "Cities as Circularity Ecosystems: Smartness Indicators and Industrial Ecology Methods for Measuring Transition Towards Smart Circular Economy" at the XXIX Italian Congress of Commodity Sciences and I realized that the digitalization of the circularity of urban metabolism deserved a particular deepening and a multidimensional and holistic focus.

Starting from the challenging task of continuous and real-time planning, monitoring and evaluation of the social, economic and environmental flows of urban metabolism, my co-authors and I explored how this could be done through the support of digital technologies. Gradually, through the mixed methodological approach consisting of literature review and case study analysis, the theoretical and managerial aspects of Smart Urban Metabolism began to take shape and substance.

The result is the integration of the five papers described below that constitute the platform that led to the development of Smart Urban Metabolism as a concept that encompasses the circularity of urban metabolism enabled by digital technologies.

Paper I

Title: D'Amico, G., Taddeo, R., Shi, L., Yigitcanlar, T., Ioppolo, G. (2020a). Ecological indicators of smart urban metabolism: A review of the literature on international standards. *Ecological Indicators*. 118. 106808.

This article introduces the social, economic, environmental and technological challenges of the growing urbanization and datafication of cities by proposing the concept of Smart Urban Metabolism as a perspective to overcome the limitations embedded in the traditional notions of urban metabolism and urban smartness. In sum, Smart Urban Metabolism holistically integrates the aspects of urban metabolism (circularity) and urban smartness (continuous and real-time planning, monitoring and evaluation) in order to improve the quality of life.

Paper II

Title: D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., Ioppolo, G. (2021a). Digital Technologies for Urban Metabolism Efficiency: Lessons from Urban Agenda Partnership on Circular Economy. *Sustainability*. 13. 6043.

This article provides a wide range of digital technologies such as real-time monitoring stations for water and energy consumption, digital cameras for controlling vehicle flows, web platforms for sharing goods and services, tracking sensors for public transport, and so on, capable of optimizing the efficiency of the circularity of urban metabolic flows in the dimensions of mobility, energy, environment, waste, telecommunications, safety, etc. the digital technologies identified and analysed provide policymakers, urban planners and managers with useful tools to collect, monitor, analyses and evaluate the social, economic, environmental and technological performances. At the same time, this study increases understanding and awareness of digital technologies in this paradigm shift.

Paper III

Title: D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., Ioppolo, G. (2022). Digitalisation driven urban metabolism circularity: a review and analysis of circular city initiatives. *Land Use Policy*. 112. 105819.

This article, through a systematic review of the literature and an analysis of case studies, investigates and evaluates the urban metabolism circularity initiatives adopted by the circular cities of Porto (Portugal), Prato (Italy), Oslo (Norway), Kaunas (Lithuania), Flanders region (Belgium) and The Hague (The Netherlands) which constitute the European Urban Agenda Partnership on Circular Economy (PCE). The analysis reveals a wide range of strategies and practices that optimise the circularity of social, economic and environmental urban metabolic flows.

Paper IV

Title: D'Amico, G., Szopik-Depczyńska, K., Dembińska, I., Ioppolo, G. (2021b). Smart and sustainable logistics of Port cities: A framework fro comprehending enabling factors, domains and goals. *Sustainable Cities and Society*. 69. 102801.

This article investigates the most recurring themes regarding smart and sustainable logistics initiatives within port cities in order to develop a multidimensional framework capable of holistically integrating the prevailing enabling factors (Ecosystem, Internal Organization, Data and Security, Policy and Regulation, Finance and Funding, and Digital and Technology), domains (Mobility, Environment, Economy, Telecommunications, Safety and Security, Government, and Community) and goals (Sustainable Development and Digitalisation) that characterise the development of the circularity within smart and sustainable logistics. Furthermore, the different port cities analysed considered pioneering such as Rotterdam, Hamburg, Singapore, Los Angeles, Amsterdam, etc. in partnerships with technology companies such as Cisco, IBM, Huawei and SAP show that the smart and sustainable logistics initiatives have the potential to improve the efficiency of economic, environmental, social and technological flows and increase engagement and awareness of stakeholders such as couriers, shipping company, citizens, port authorities, municipalities, security officers, gate and terminal personnel, and so on.

Paper V

Title: D'Amico, G., L'Abbate, P., Liao, W., Yigitcanlar, T., Ioppolo, G. (2020b). Understanding Sensor Cities: Insights from Technology Giant Company Driven Smart Urbanism Practices. *Sensors.* 20. 4391.

This article generates insights from the sensor city best practices by placing some of renowned projects, implemented by Huawei, Cisco, Google, Ericsson, Microsoft, Deutsche Telekom, Telefonica, and Tim, under the microscope. The investigation findings reveals that the sensor city approach: (a) has the potential to increase the smartness and sustainability level of cities; (b) manages to engage citizens and companies in the process of planning, monitoring and analysing urban processes; (c) raises awareness on the local environmental, social and economic issues, and (d) provides a novel city blueprint for urban administrators, managers and planners. Nonetheless, the use of advanced digital technologies poses a multitude of challenges related to (a) quality of the data used; (b) level of protection of traditional and cybernetic urban security; (c) necessary integration between the various urban infrastructure, and; (d) ability to transform feedback from stakeholders into innovative urban policies.

1. Introduction

Currently, much of the world's population is urbanized, generating more than 85% of global GDP (Ellen MacArthur Foundation, 2019; UN, 2019). At the same time, cities are attributed at least 75% of the exploitation of natural resources, 75% of greenhouse gas emissions and 50% of global waste production (United Nations Environment Programme, 2017; Climate-KIC and C40 Cities, 2018).

As a consequence, this urbanization has produced criticalities related to biodiversity (González-García et al., 2022), economy (Liu et al., 2021a), education (Jin et al., 2020), renewable energy sources (Trencher et al., 2016), climate change (Ferreira et al., 2021), urban governance (König, 2021), medical care (Carmichael et al., 2019), housing (Debrunner et al., 2020), social cohesion (Vanhuyse et al., 2021), leisure (Liu et al., 2021b), safety, security and cybersecurity (Asghar et al., 2019), waste management (Guerrero et al., 2013), telecommunications (Huang et al., 2021a), transport and mobility (Acheampong et al., 2021), agriculture and food (Kingsley et al., 2021), urban planning (Mwathunga et al., 2018), water and wastewater management (Herslund et al., 2019), and so on. Therefore, the aforementioned critical issues listed above placed cities at the cornerstone for reversing the trend and promoting urban metabolism in a smart and sustainable manner (Lyons et al., 2018; Musango et al., 2020; Domínguez et al., 2022).

Hence, based on the insights of Walker et al. (2014) and Cohen et al. (2021) on the contribution of digital technologies in optimizing the circularity of social, economic, environmental and technological flows of urban metabolism and in improving the quality of life, Paper I (D'Amico et al., 2020a) proposes the concept of "smart urban metabolism", which aims to specify and holistically summarise this vision.

This new model of urban metabolism 5.0, through the support of technological platforms (Barns, 2018; Caprotti et al., 2020) and dashboards (Kourtit et al., 2018; Young et al., 2020), integrates Internet of Things (IoT) (Zahmatkesh et al., 2020), Artificial Intelligence (AI) (Broekman et al., 2021), 3D printers (Demir et al., 2021), tracking sensors (Gulia et al., 2020), Augmented Reality (AR) (Zhu et al., 2021), GPS localization systems (Rout et al., 2021), drones (Jin et al., 2021), real-time monitoring stations (Kaivonen et al., 2020), smart grids (Thornbush et al., 2021), Big Data analysis techniques (Bibri et al., 2017), autonomous vehicles (Acheampong et al., 2019), 5G connections (Huseien et al., 2022), robots (Silvestri et al., 2019), Blockchain (Li et al., 2022), cloud computing (Ujjwal et al., 2019), actuators (Nie et al., 2021), digital twins (Deng et al., 2021), cameras (Kujawski et al., 2021), and other fixed and mobile information and communication technologies.

In practice, their integration with the natural and artificial infrastructures that characterise the urban fabric such as roads, lamps, traffic lights, energy production and waste treatment plants, water distribution systems, surveillance cameras, buildings, public transport stops, vehicles, ports, airports, bridges, highways, rivers, lakes, public lighting systems, warehouses, subway lines, docks, drawbridges, streams, waterfalls, lakes, oil platforms, poles, antennas, and so on, allow cities to collect, monitor, analyse, and share among the various stakeholders, improving urban products and services, their circularity, and their ability to increase the quality life.

Given the growing importance of digital technologies in the urban metabolism circularity, technology giant companies (e.g., Huawei, Ericsson, Microsoft, Oracle, Alibaba, Deutsche Telekom, Samsung, Siemens, and Google) are involved in the planning and development of innovative urban projects in the cities of Toronto, Valencia, Dallas, Singapore, Kansas City, Hamburg, Shenzhen, Adelaide, Dublin, and so on. At the same time, the technology-driven circularity initiatives of urban metabolism have placed the cities of Singapore, Zurich, Oslo, Geneva, Copenhagen, Auckland, Melbourne, Taipei, Helsinki, Bilbao, and Düsseldorf occupy the top of the ranks elaborated by IMD World Competitiveness Center's Smart City Observatory on the sustainability and smartness of urban services (IMD, 2019).

At the European level, the Urban Agenda of the European Commission has established the Partnership on Circular Economy (PCE) involving the cities of Prato (Italy), Oslo (Norway), The Hague (The Netherlands), Kaunas (Lithuania), Porto (Portugal) and the Flanders region (Belgium), in order to share and promote initiatives of urban circularity driven by technology (Jentoft, 2017). To do this, the Partnership on Circular Economy (PCE) has included a wide range of 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.

Therefore, the examples mentioned above consider cities as technological hubs capable of attracting investments and talents from all over the world (Akhavan, 2017). To do this, in terms of decision-making process, local authorities, administrative departments, agencies, interdepartmental committees, cabinets, divisions, municipal, regional and state owned utilities, universities, research centres, companies, trade unions, NGOs, start-ups, and so on is required a multidimensional and holistic approach to urban metabolism (Mondschein et al., 2021; Siokas et al., 2021).

However, most cities around the world don't operate as the High-Tech companies mentioned above. Specifically, they tend to be disorganized; for example, departments do not cooperate with each other and often do not work together on solutions. In this regard, Cugurullo (2018) explains that cities promoted as best practices are often fragmented and disconnected, characterised by several incompatible components. Furthermore, cities excessively tied to digital technologies have often been criticized for being too techno-centric, organized on the basis of the priorities of the technology companies involved and for underestimating the social and environmental aspects of urban metabolism (Yigitcanlar et al., 2019a). In this regard, Demaria and Schindler (2015) demonstrate that the reconfiguration of urban metabolism can cause social conflicts, further widening the divergences and inequalities between people. At the same time, the idea of urban metabolism introduced by Wolman (1965) represents an obsolete and simplistic perspective in order to consider the complexities and needs of a city in continuous and rapid technological change.

In this perspective, the innovative concept of "smart urban metabolism" has been proposed as a response to the limitations of urban metabolism and urban smartness approaches, specifying that both aspects should be combined in an integrated and holistic manner. In this regard, international intergovernmental organizations such as the United Nations and international standardization organizations such as International Organization for Standardization (ISO), International Telecommunications Union (ITU) and European Telecommunications Standards Institute (ETSI) provide best practices and indicators that embrace a wide range of dimensions (e.g., energy, health, telecommunication, transport, wastewater, water, etc.), in order to support the transition towards smart urban metabolism.

Indeed, the theoretical and managerial literature on urban metabolism provides a plethora of notions that emphasise the role of digitalisation of the urban metabolism, such as the digital city (Fumagalli et al., 2021), intelligent city (Ye, 2020), ubiquitous city (Rad et al., 2018), sensitive city (Dada et al., 2021), knowledge city (Musterd and Gritsai, 2009), smart city (Yigitcanlar et al., 2021), techno-centric city (Willis et al., 2017), creative city (Landry, 2008), sustainable city (Sodiq et al., 2019), circular city (Paiho et al., 2020), informational city (Rutherford, 2020), green city (Gu et al., 2021), low-carbon city (Huang et al., 2021b), eco-city (Lin, 2018), smart sustainable city (Dindarian, 2022), and artificially intelligent city (Yigitcanlar et al., 2020).

Although the holistic human-computer-nature combination within a single and coherent multidimensional framework has become a focal point in the strategies and practices of policymakers, urban planners and managers in terms of prioritizing the allocation of resources and scenario forecasting (Rohn et al., 2014), the digitalisation of the circularity of urban metabolism through real-time monitoring stations, tracking sensors, cameras, radars, and so on, outlines a multitude of challenges and criticalities related to the social, economic, environmental and technological spheres (Mao et al., 2020; Upadhyay et al., 2021). For example, the enormous costs of planning, maintenance and development of digital technologies which exclude most underdeveloped or developing cities (Cristino et al., 2021), the balance of governance between the public and private stakeholders involved (Suzuki, 2015), and the degree of quality, security and integration of a heterogeneous range of data and information (Huber et al., 2021) are some of the challenges that characterise the digitalisation of the circularity of urban metabolism.

Therefore, this is context from which the following Doctoral Thesis emerged. Following this phase of introduction and conceptualization of circularity within smart urban metabolism (Section 1), Section 2 outlines the methodological framework adopted, describing the approach used in each procedural phase. Section 3 develops a literature review on (a) digital technologies that foster and fuel the circularity of urban metabolism and (b) international standards needed to measure such technology-assisted urban circularity. Section 4 provides the testing and description of the results phase of the comparative analysis of the circular cities that constitute the Partnership on Circular Economy (PCE) of the EU Urban Agenda. As part of the ever-increasing integration between Industrial Ecology and urban symbiosis, Section 5 introduces the practical applications of the circularity of the technology-driven urban metabolism within the logistics of port cities. Section 6 proposes a future perspective of urban circularity by introducing the notion of Sensor City into the theoretical and managerial debate. Finally, Section 7 provide several considerations on the social, economic, environmental and technological enabling factors and barriers that characterise the digitalisation of the circularity of urban metabolism and Section 8 includes the final conclusions.

1.1 Aim

First, the idea was conceived of defining in detail the smart urban metabolism within Urban Symbiosis and Industrial Ecology, analysing the various dimensions such as economy, energy, education, telecommunications, transport, water, and so on, that qualify this concept. After further qualitative and quantitative analysis, it became evident that the concept of urban metabolism was inadequate to achieve smartness and sustainability and that it needed to be revised to support the transition towards urban circularity driven by digitalisation.

Therefore, the study proposed in this Doctoral Thesis arises from the social, economic, environmental and technological challenges that emerge from the intensive and pervasive development of the circularity of flows that characterise the technology-driven urban metabolism. In this sense, urban metabolism provides a multidisciplinary perspective of circularity, as it integrates a wide range of disciplines such as urban planning, geography, strategic management, statistics, architecture, policy science, environmental management, sustainability management, technology and innovation management, data science, engineering, biology, physics, and so on, in order to identify the boundaries of the urban system, inputs and outputs.

However, the theoretical and managerial literature on the circularity of urban metabolism has been mainly based on statistical data characterised by poor spatial and temporal quality, enormously limiting the ability to prioritise and recognise the most critical areas or in which the city is performing well. This raises several practical insights, such as: (a) what digital technologies are capable of improving circularity within the various dimensions of urban metabolism? (b) It is necessary to plan and develop urban technological infrastructures such as sensors, monitoring stations and tracking systems? (c) What are the social, economic, environmental and technological challenges that emerge from the digitalisation of the circularity of urban metabolism?

Thus, the aim of this Doctoral Thesis is to identify and explore the potential of the circularity of urban metabolism driven by digitalisation in the improvement of decision-making processes of natural and non-natural resources.

1.2 Audience

The following Doctoral Thesis is mainly aimed at three types of audience. The first refers to sustainability experts, scientists and professionals such as industrial ecologists and commodity science economists who advocate circular economy, life cycle thinking and holistic approach in urban development. In this regard, urban metabolism is recognized as one of the most relevant models for describing and analysing flows of natural and non-natural resources within cities and this Thesis offers an innovative perspective of this model. The second target group are specialists and scientists focused on smart cities, in particular on the role of Information and Communication Technologies (ICTs) in the transition to sustainable development. In this regard, there are two contrasting views in the literature: on the one hand, supporters who define smart cities as the panacea for sustainable urban development, and on the other hand, the critics who consider smart cities as a ‘product’ elaborated by high-tech giants aimed exclusively at the efficiency of urban processes and operations and not at the full and complete sustainability of our cities. In line with the results of Yigiticanlar et al. (2018), this Thesis demonstrates how the development towards smart urban metabolism can only be achieved through a holistic integration between people, technology and nature. The third target community refers to policymakers, urban planners, administrators, managers of municipal, regional and state utilities, and so on, committed to planning, monitoring and redefining the strategies and practices of circularity of the urban metabolism assisted by technology. However, most local authorities around the world are not equipped to detect, collect, monitor, analyse and evaluate the social, economic, environmental and technological performance through digital platforms an dashboards, which makes it difficult to measure and interpret the progress of public policies.

Therefore, the Thesis aims to integrate the conceptual basis of digital technologies that favour the circularity of urban metabolism with an analysis of a wide range of cities taken as case studies, in order to develop a framework able to improve comprehension and awareness and to provide new insights to the theoretical and managerial debate.

1.3 Scope

The papers included in this Doctoral Thesis are focused on a limited sample of cities with high quality social, economic, environmental and technological infrastructures, considered paradigmatic cases of the circularity of urban metabolism driven by digitalisation. Consequently, the small number of cities taken into consideration does not represent the totality of cities globally. However, most cities in the world are not equipped to collect, monitor, analyse and evaluate the performance of urban metabolism circularity through real-time monitoring stations, sensors, smart grids, digital cameras, GPS tracking systems, and so on. Therefore, the field of application is focused on the social, economic, environmental and technological flows of urban metabolism that operate within advanced urban contexts, with particular attention to the contribution of digital technologies to their circularity.

2. Methodology

This Thesis aims to enrich the theoretical and managerial debate on the strategies and practices of Industrial Ecology, in particular those concerning urban metabolism and urban symbiosis.

In this sense, the adopted mixed methodological approach aims to provide the theoretical/conceptual and practical/managerial bases necessary to better address the technology-driven circularity of urban metabolism. In practice, the approaches used in the literature review and in the analysis of multiple vase studies feed and renew each other in an integrated manner. Consequently, it improves the comprehension and awareness of this issue by policymakers, planners, economists, scientists, students, administrators, citizens, organizations and entrepreneurs.

Hence, the methodological framework that characterise the following Thesis consists of five procedural phases: (1) Conceptualization; (2) Literature Review; (3) Testing and Description of Results; (4) Practical Applications to Circularity: Green Logistics for Greener Cities, and; (5) Future Perspective of Urban Metabolism Circularity: Sensor City.

Each phase is assigned a reference paper published in scientific journals that deal with the development of the circularity of urban metabolism enabled by digital technologies. Specifically, within each phase a series of results and techniques relating to the research questions are identified, analysed and interpreted. In summary, the methodological approach followed is represented in Table 1.

Table 1. Methodological approach adopted in this Thesis

	Section	Title	Journal	Authors
1	Introduction and Conceptualization	Ecological indicators of smart urban metabolism: A review of the literature on international standards	Ecological Indicators	D'Amico, G., Taddeo, R., Shi, L., Yigitcanlar, T., Ioppolo, G.
2	Literature Review	Digital Technologies for Urban Metabolism Efficiency: Lessons from Urban Agenda Partnership on Circular Economy	Sustainability	D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., Ioppolo, G.
		Ecological indicators of smart urban metabolism: A review of the literature on international standards	Ecological Indicators	D'Amico, G., Taddeo, R., Shi, L., Yigitcanlar, T., Ioppolo, G.
3	Testing and Description of Results	Digitalisation driven urban metabolism circularity: a review and analysis of circular city initiatives	Land Use Policy	D'Amico, G., Arbolino, R., Shi, L., Yigitcanlar, T., Ioppolo, G.
4	Practical Applications to Circularity	Smart and sustainable logistics of Port cities: A framework for comprehending enabling factors, domains and goals	Sustainable Cities and Society	D'Amico, G., Szopik-Depczyńska, K., Dembińska, I., Ioppolo, G.
5	Future Perspective of Urban Metabolism Circularity	Understanding Sensor Cities: Insights from Technology Giant Company Driven Smart Urbanism Practices	Sensors	D'Amico, G., L'Abbate, P., Liao, W., Yigitcanlar, T., Ioppolo, G.

Conceptualization

The conceptualization phase explained in Section 1 “Introduction” refers to Paper I “Ecological indicators of smart urban metabolism: a review of the literature on international standards” published in Ecological Indicators journal.

The following article coined and proposed the term of “smart urban metabolism” in order to overcome the limitations of the traditional perspective of urban metabolism, strongly oriented to environmental aspects and urban smartness, mainly focused on technological factors (Yigitcanlar et al., 2019b). In summary, smart urban metabolism emphasizes the need that both perspectives should be combined in an integrated and holistic manner. In this regard, smart urban metabolism is characterised by a wide range of digital technologies such as real-time monitoring stations, tracking sensors, drones, radars, digital cameras, artificial intelligence, augmented reality, 3D printers, smart meters, smart public lighting, autonomous vehicles, and so on, which aim to identify, collect, monitor, analyse, evaluate and redefine the social, economic, environmental and technological flows that circulate within urban contexts.

Therefore, the study recognizes the inadequacy and obsolescence of the traditional approach of urban metabolism developed by Wolman (1965) and proposes a smart and sustainable perspective in order to face the current and future challenges deriving from urbanization and datafication of urban contexts.

Literature Review

The literature review phase begins with Paper II “Digital Technologies for Urban Metabolism Efficiency: Lessons from Urban Agenda Partnership on Circular Economy” published in Sustainability journal.

As regards the objective and the research question, the article aims to identify and analyse the digital technologies that favour the circularity of the urban metabolism. Through ScienceDirect, Google Scholar and institutional websites, the study integrates journal articles, books, conference proceedings and grey literature such as urban reports and master plans provided by local authorities and municipal, regional and national utilities. 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”) AND (“circular urban metabolism”) AND (“circular and digital urban metabolism”)).

In terms of results, the Paper II described in section 3.1 “Digital Technologies for Urban Metabolism Circularity” identifies the dimensions of the urban metabolism on which digital technologies act: (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 and, at the same time, it serve as a theoretical and conceptual basis for policymakers, urban managers, planners, citizens, companies, utilities, and universities who intend to plan, develop or redefine their urban circularity strategies and practices.

In parallel, section 3.2 "International standards for smart urban metabolism circularity" of the thesis which refers to Paper I "Ecological Indicators of smart urban metabolism: a review of the literature on international standards" published in Ecological Indicators offers the above mentioned stakeholders an investigation of the indicators necessary to measure the circularity of urban metabolism through technology.

As regards the research question, the study aims to show the composition and divergence in the evaluation approaches of urban circularity adopted by international standardization organizations, in particular if their attention is more focused on urban smartness or urban metabolism aspects. In terms of inclusion criteria, international standards were analysed that satisfy the criteria of: (a) acceptability; (b) methodological rigor; (c) consistency; (d) usefulness for comparative purposes; (e) innovativeness, and; (f) long-term perspective. At the same time, the exclusion criteria were identified which include urban reports, research centres and university studies, scientific articles, national standards and official documents that only deal with urban metabolism or urban smartness. In terms of research databases, international standardization organizations official websites and reports are chosen to implement the comparative analysis. Furthermore, the following keywords were used to elaborate the literature: 'city/smart city standards', 'city/smart city indicators', 'smart sustainable city indicators', 'urban metabolism indicators', 'sustainable development indicators', 'standardization for smart city', and 'urban indicators'.

This review produced a set of eight international standards and a wide range of indicators that more or less holistically address circularity within urban smartness and urban metabolism, in line with the purpose of the research. Specifically, the international standards represented in the study are: ISO 37123 – Sustainable cities and communities – Indicators for resilient cities (ISO, 2019a); ISO 37122 – Sustainable cities and communities – Indicators for smart cities (ISO, 2019b); ISO 37120 – Sustainable cities and communities – Indicators for city services and quality of life (ISO, 2018); UNECE-ITU – Smart Sustainable Cities Indicators (UNECE-ITU, 2015); ETSI TS 103 463 – Key Performance Indicators for Sustainable Digital Multiservice Cities (ETSI, 2017); ITU-T Y. 4901 – Key performance indicators related to the use of information and communication technology in smart sustainable cities (ITU, 2016a); ITU-T Y.4902 – Key performance indicators related to the sustainability impacts of information and communication technology in smart sustainable cities (ITU, 2016b) and; ITU-T Y.4903 – Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals (ITU, 2016c).

Abovementioned eight major international standards, thus, were analysed and compared. In this sense, the comparative analysis is developed in several phases. Firstly, each standard was examined in its focus (urban metabolism or urban smartness). When analysing and classifying urban circularity indicators, it is often difficult to distinguish between urban metabolism and urban smartness indicators based exclusively on the name. In this regard, a detailed analysis of each of the 534 indicators was required for a coherent comparison of the standards since the individual standards examined adopt non-uniform terminology. Specifically, the following analysis is based on the calculation of the score, assigning one point per indicator for each dimension considered. For example, the indicator "percentage of total amount of plastic waste recycled in the city" has a focus mainly on urban metabolism, while the indicator "percentage of public transport lines equipped with a publicly accessible real-time system" has a smartness focus.

Secondly, a detailed analysis is conducted, highlighting the percentage distribution of the social, economic and environmental components of each standard taken into consideration. Following the same score method, for example, the indicator "survival rate of new businesses per 100.000 population" is part of the economic dimension, "electrical and thermal energy (GJ) produced from wastewater per capita per year" involves the environment dimension, while "annual number of online visits to the municipal open data portal per 100.000 population" is a typical indicator of the social dimension. Furthermore, Table X shows a further analysis of the balance between urban metabolism and urban smartness focuses of each indicator and the following Table X the weight (%) of each urban area on the standard taken into consideration.

Testing and Description of Results

After establishing the theoretical and conceptual bases in sections 3.1 "Digital Technologies for Urban Metabolism Circularity" and 3.2 "International standards for smart urban metabolism circularity", it is necessary to evaluate the technology-assisted urban circularity initiatives. The testing and description of results phase is included in Paper III entitled "Digitalisation driven urban metabolism circularity: A review and analysis of circular city initiatives" published in Land Use Policy journal.

The research provides a multiple analysis of case studies including six self-defined "circular" cities: Porto (European Union, 2020a), the Flanders region (European Union, 2020b), The Hague (European Union, 2020c), Prato (Municipality of Prato, 2020), Oslo (Hirsch, 2017) and Kaunas (KCMA, 2015), which constitute the Partnership on Circular Economy (PCE) of the EU Urban Agenda. In practice, the study aims to identify, investigate and evaluate the digitalisation initiatives of the circularity of urban metabolism adopted by the aforementioned cities (Table 2).

Table 2. Circular city initiatives identified and investigated.

Initiative	Technology	Urban Metabolism flow	City	Source
Via Verde Boleias	Web sharing portal	Mobility	Porto	European Union, 2020a
Reporitorio de materiais	Web sharing portal	Construction		
Horta à Porta	Web sharing portal	Food		
OPO' Lab	Web sharing portal	Labour		
Cambio	Web sharing portal	Mobility	Flanders region	European Union, 2020b
Dégage	Web sharing portal	Mobility		
Peerby	Web sharing portal	Housing; Mobility; Recreation		
Made in Moerwijk	Web sharing portal	Social business	The Hague	European Union,

KledingBank Den Haag	Web sharing portal	Social business		2020c
Lekkernassuh	Web sharing portal	Food		
De Groene Regents	Web sharing portal	Energy		
Automatic Vehicle Monitoring	Sensors	Mobility	Prato	Municipality of Prato, 2020
Cityworks	Sensors	Construction; Mobility		
Urban cleaning vehicles monitoring	Sensors; Real-time Monitoring Stations	Waste		
Smart Safety	Digital video vigilance cameras	Safety; Security		
Baciacavallo treatment centre	Sensors; Real-time Monitoring Stations	Water; Wastewater		
Smart Energy	Smart grids and meters	Energy		
Urban Ecological innovation Centre	Web sharing portal; Physical platform	Economy; Waste; Social cohesion	Oslo	Hirsch, 2017
"Developing a clever and civil society"	Web portal; Real-time Monitoring Stations; Sensors	Governance; Social cohesion; Education; Safety	Kaunas	KCMA, 2015
Sustainable infrastructural and territorial development	Real-time Monitoring Stations; Sensors	Transport; Mobility, Economy; Water; Energy		

However, the choice to analyse a small sample of six European circular cities that constitute the EU Partnership on Circular Economy (PCE) may undoubtedly entails limitations to research. In this sense, the study does not represent the totality of cities globally engaged in the circular and digital transition of urban metabolism. Furthermore, a wide range of cities around the world are not equipped with the necessary technological infrastructures to detect, track and evaluate the social, economic and environmental flows of urban metabolism in real time.

The analysis of digitalisation initiative of the circularity of urban metabolism also suffers from a difficulty in finding detailed quantitative data on social, economic, environmental and technological impacts. The lack of transparency, sharing and publicity of qualitative and quantitative data undoubtedly represents a criticality in a multiple analysis of case studies. This criticality is due to the resistance of stakeholders (e.g., municipalities, municipal, regional and national utilities, companies, organizations, etc.) to share part of their information assets and the lack of a participatory and holistic long-term perspective. Furthermore, the urban circularity initiatives documented in the report and master plans use non-uniform schemes and terminologies, giving rise to the need to standardise the results through a coherent and integrated framework.

In this regard, the EU Urban Agenda defines the "Circular Resource Efficiency Management Framework" implemented by the European Commission (2020) as a systemic and holistic scheme.

In systemic terms, the framework provides: (a) a step-by-step plan to guide cities through the resource management development process; (a) a model for making well-informed decisions in order to specifically adapt the plan to the ambitions and possibilities of the city, and; (c) information on the management of the circularity of resources through technology. In holistic terms, however, the framework highlights interdisciplinary aspects in relation to urban metabolism, such as: (a) the city as an ecosystem; (b) social, economic, environmental and technological flows within the city; (c) interactions between the stakeholders involved in decision-making processes, and; (d) attempts to redefine the city through innovative and forward-looking socio-economic visions.

For these reasons, we have decided to use the European Commission's "Circular Resource Efficiency Management Framework" in the testing phase of the social, economic, environmental and technological impacts of the circularity of urban metabolism driven by digital technologies within the circular cities of the Partnership on Circular Economy (PCE). Specifically, the framework is characterised by the phases of:

1. *Identification*, which aims to identify urban metabolic flows. In this phase, the data and information collected on the social, economic, environmental and technological aspects of urban metabolism allow the planning of circular policies and strategies;
2. *Brokerage activities*, which attribute operational responsibility for metabolic flows to the respective stakeholders involved. Therefore, after the phase of mapping the flows, the stakeholder engagement phase in urban processes and operations takes place and, finally;
3. *Monitoring and evaluation* aim to establish the effectiveness of the initiatives to digitalise the circularity of the urban processes and operations adopted. In particular, the following activities provide policymakers with a wide range of detailed data in order to confirm or refine the initiatives implemented.

Practical Applications to Circularity: Greener Logistics for Greener Cities

The practical applications to circularity phase that refers to Paper IV entitled "Smart and sustainable logistics of Port cities: A framework for comprehending enabling factors, domains and goals published in Sustainable Cities and Society journal aims to provide a multidisciplinary perspective on the circularity of urban metabolism.

The study is based on the definition of "port city" provided by Van den Berghe et al. (2018), who defines it as a self-organized system, characterised by a 'relational geometry' through which interact a wide range of: (a) actors, such as municipalities, port authorities, shipping companies, couriers, logistic service companies, financial institutions, terminal workers, trade unions, non-profit organizations, container operators, research centres, universities, transport companies, technology companies, manufacturing companies, start-ups, and so on; and (b) flows of economic, environmental, social and technological resources.

Consequently, port cities are at the centre of the theoretical and managerial debate on the role of green logistics in the environmental, social, economic and technological challenges of the transition towards a smart and sustainable urban metabolism. Furthermore, the focus on smart and sustainable logistics in port cities is not limited to identifying and analysing the social, economic, environmental and technological flows of urban metabolism within cities, but also includes aspects of circularity typical of industrial symbiosis.

The study proposes an in-depth investigation of the most recurring themes concerning circularity within smart and sustainable logistics in port cities, in order to create a multidimensional framework capable of holistically integrating the prevailing enabling factors, domains and goals.

In terms of sources, ScienceDirect and Google Scholar were chosen as databases to develop the theoretical and managerial section. In particular, the search includes peer-reviewed journal articles, grey literature such as port authorities reports, logistic plans, non academic research, conference proceedings and any other sources in line with the development of circularity within smart logistic in port cities. In order to implement the analysis, a keyword search of ("port city" OR "port cities") AND ("smart city port" OR "smart cities ports") AND ("smart port" OR "smart ports") AND ("maritime logistics") AND ("port logistics") AND ("smart logistics") AND ("intelligent port" OR "intelligent ports") AND ("automated port" OR "automated ports") AND ("robotic port" OR "robotic ports") AND ("sustainable port" OR "sustainable ports") AND ("sustainable logistics") AND ("smart and sustainable logistics") AND ("smart and sustainable port" OR "smart and sustainable ports")).

In order to improve the robustness and quality of the study, the 195 initially selected sources were examined through a series of inclusion and exclusion criteria. Specifically, the inclusion criteria embrace: (a) adequacy and coherence with the research question; (b) scientific robustness; (c) methodological rigor; and (d) adaptability with the long-term and innovative vision of the study. The screening produced an exhaustive and comprehensive overview (n = 139) that includes the most recurring themes regarding the planning, implementation, development and analysis of circularity within the smart and sustainable logistics in port cities. In addition, the research provides a limited sample of port cities that include Rotterdam, Amsterdam, Los Angeles, Antwerp, Montreal, Hamburg, Hanian, Valencia, Stockholm, and Singapore considered leading players in smart and sustainable logistics worldwide, equipped with high quality social, economic, environmental and technological infrastructures.

The small number of port cities taken into consideration represents a limitation of the study as it does not represent the totality of the cities involved in port logistics. However, most port cities around the world are not equipped to collect, monitor, analyse and evaluate logistics circularity performance through sensors, real-time monitoring stations, drones, radars, smart grids, artificial intelligence, GPS tracking systems, and so on.

On the basis of the topic of each identified and analysed source, macro-areas have been created that specify the enabling factors, domains and goals of the circularity within logistics of port cities. The investigation produced enabling factors that include ecosystem, internal organization, data and security, policy and regulation, technology, finance and funding, and digital and technology. The domains embrace safety and security, mobility, environment, economy, telecommunications, government and community. Finally, the goals of circularity within smart and sustainable logistics of port cities have been identified in sustainable development and digitalisation.

Thus, the grouping around the enabling factors, domains and goals has developed a multidimensional and holistic framework able to explain the main issues that characterise the circularity of urban metabolism within logistics of port cities.

Future Perspective of Urban Circularity: Sensor City

The phase of elaboration of future perspective of urban circularity is based on the insights included in Paper V "Understanding Sensor Cities: Insights from Technology Giant Company Driven Smart Urbanism Practices" and published in the Sensors journal.

The following paper – through a qualitative approach – analyses several sensor cities considered successful examples of disruptive urban actors, capable of integrating sensor strategies with the economic, social, and environmental aspects of urban metabolism. The result is a framework for policymakers that collect the forward-looking ICT urban initiatives developed with the technical support of high-tech giants such as Cisco, Google, Alibaba, Huawei, Deutsche Telekom, Tim, Ericsson, Microsoft, Nokia, IBM, Siemens, Oracle, Samsung, Tencent, Apple, and Telefonica.

The study includes peer-reviewed journal articles, book chapters, and conference proceedings, grey literature such as government documents, and industry technical reports. In terms of databases, ScienceDirect, Google Scholar and cities' websites were utilized to achieve the analysis. Furthermore, the keywords searched include: (("sensor city" OR "sensor cities") AND ("ubiquitous city" OR "ubiquitous cities") AND ("digital city" OR "digital cities") AND ("real-time city" OR "real-time cities") AND ("sentient city" OR ("sentient cities") AND ("intelligent city" OR "intelligent cities") AND ("data-driven city" OR "data-driven cities") AND ("smart city" OR "smart cities") AND ("sustainable city" OR "sustainable cities") AND ("sustainable development") AND ("smart urban applications") AND ("urban IoT") AND ("urban sustainability") AND ("urban development") AND ("big data applications") AND ("urban sensors") AND ("knowledge city" OR "knowledge cities") AND ("disruptive urban development")).

As a result, the review provides a clear and comprehensive definition of the concept of sensor city, introducing urban dimensions (e.g., governance, economy, environment, mobility, people, and living) and technological solutions (e.g., IoT, sensors, AI, ICTs, big data analytics) necessary for its implementation. The case study analysis approach provides a detailed framework useful for developing a theoretical approach to sensor cities, underlining the holistic relationships between urban metabolism, circularity and technology companies.

Nonetheless, it is important to consider that sensor cities taken into consideration in the case studies analysis use non-uniform terminology and lack detailed quantitative data on sensor infrastructures. In this sense, a greater understanding and awareness of urban sensing is needed to develop forward-looking projects in line with future urban challenges,

This research is focused on 20 sensor cities, with a high quality in social, economic, environmental and technological infrastructures. Consequently, the sample analysed does not represent the different types of cities globally. Most cities around the world are not equipped to collect, monitor, analyse and evaluate urban performance through innovative platforms and dashboards.

In sum, the Paper V provides: (a) a clear definition of sensor city; (b) a sensor city framework; (c) a detailed analysis of several sensor cities, and; (d) various different sensing policy and actions that currently policymakers have in place.

3. Literature Review

Huovila et al. (2019) and Abu-Rayash et al. (2021) highlight an opportunity for industrial ecology and urban metabolism to support the transition to circularity assisted by digital technologies, through both a theoretical review of digital technologies and a toolbox of urban indicators, allowing policymakers to receive useful feedback in order to assess the strengths and weaknesses of an urban context.

While the development of urban metabolism is a strongly context-driven phenomenon (e.g., local culture, governance model, citizen awareness, level of technological progress, industrial structure, etc.), the urbanization issues we face today are in largely similar all over the world (Rizzo et al., 2020). Thus, attempts to standardise through international standards for comparison, sets of indicators for analysis, best practice example to benchmark, and success and failure stories to learn from, are crucial in addressing the current urbanization and datafication rates.

Therefore, the challenge for policymakers is to define in detail urban metabolism and the digital technologies that support it, selecting what and how to measure, how often, and how to consider social, economic, environmental and technological aspects of the indicators (Sharifi, 2019,2020). It is also the concept that the following Thesis aims to develop further, providing in the next section the theoretical background essential for its understanding.

3.1 Digital Technologies for Urban Metabolism Circularity

According to Currie and Musango (2017), urban metabolism represents a complexity of socio-technical and socio-ecological processes through which flows of raw materials, emissions, by-products, energy, waste, people, information, data, and so on, characterise 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 (Cui, 2018; Cui et al., 2019; Zhang, 2019). Furthermore, advances in urban metabolism perspectives are proposed (Dijst et al., 2018; Li et al., 2018), different frameworks at the city level were implemented (Beloin-Saint-Pierre et al., 2017), several case studies in various region of the world examined (Musango et al., 2017; Céspedes Restrepo et al., 2018) and, finally, demonstrated the relationship between the efficiency of urban metabolism and the sustainability of the city (Kissinger et al., 2019).

Nevertheless, the definition proposed by Currie and Musango (2017) requires the integration of digital technologies capable of facilitating the circularity of the social-ecological-technical processes. In this regard, Allwinkle et al. (2011) and Barns et al. (2016) observe how Information and Communication Technologies (ICTs) occupy a central position in the urban metabolism circularity, underlining the determining role of technology in achieving urban sustainability.

Hence, in the light of the growing and pervasive datafication, the definition proposed by Currie and Musango (2017) necessitates the integration of advanced digital technologies able to improve the phases of identification, collection, traceability, monitoring, analysis, evaluation and redefinition of the circularity of the social, economic and environmental processes and operations.

In this sense, Allwinkle et al. (2011) and Barns et al. (2016) observe how Information and Communication Technologies (ICTs) significantly contribute to the efficiency of the urban metabolism decision-making processes. As explained by Ratti et al. (2011), municipal, regional and state utilities, departments, committees, citizens, entrepreneurs, NGOs, etc. – through the use of mobile and fixed digital devices – act as sensors for collecting, monitoring and evaluating data and information in real-time and disseminated throughout the territory, representing proactive agents of urban circularity.

Therefore, today, policymakers, urban planners and managers recognise the importance of digital urban infrastructures in various dimensions of urban metabolism, 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 (Strielkowski et al., 2019), but also on surveillance and early warning systems such as digital cameras (Kurilkin et al., 2015) and acoustic sensors (Mydlarz et al., 2017) capable of providing alarms and messages via apps and social media platforms in the event of earthquakes, floods, and cyclones (Yates et al., 2011). In this regard, Yigitcanlar et al. (2020) describe Artificial Intelligence (AI) as a tool to safeguard our cities from the consequences of climate change, loss of biodiversity, natural disasters, pandemics, and unsustainable development.

Smart grid systems transformed the energy dimension of urban metabolism, facilitating the demand management to respond quickly during outages, shifting peak loads and failures (Mbungu et al., 2020). 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 minimise the electricity costs (Pawar et al., 2019). Practically, real-time price models (RTP) allow consumers, distributors, and producers to monitor the costs of energy consumption in real-time (Sehar et al., 2017). Jafari et al. (2019) propose 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, Klein et al. (2017) 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 circularity 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 (Chow et al., 2018), and data sharing between urban stakeholders through cloud computing platforms (O'Donovan et al., 2015). Furthermore, tracking sensors placed on public and private buildings allow local administrators to identify possible losses or failures (Tetteh et al., 2020). To this end, the installation of smart meters in buildings (Abbas et al., 2020) and the development of apps for smartphones or fixed platforms

(Challa et al., 2021) 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 able to analyse and classify waste in smart bins through code scanners (Zhang et al., 2019a) and tracking systems shared between municipal utilities, citizens, and policymakers via cloud computing platforms to optimise resources and time (Ahad et al., 2020). In this sense, the R principles that characterise circular economy (Ghisellini et al., 2016; Reike et al., 2018), ranging from 3 R (Reduce-Reuse-Recycle) to 10 R (Refuse- Rethink-Reduce-Reuse-Repair-Refurbish-Remanufacture-Repurpose-Recycle-Recover) (Kirchherr et al., 2017) applied to electronic waste (e-waste) represent a challenge for policymakers due to their difficult management and potential environmental impacts (Chen et al., 2021).

The same digital development is being observed in the health-care dimension (Shen et al., 2020). For instance, the implementation of ICTs changed the traditional relationships between patients and medical facilities, moving towards integrated e-health systems (Hajli et al., 2018). Furthermore, smartphones, social media platforms, and wearable devices provide enormous amounts of data useful for planning health programs remotely and sharing feedback and experiences to monitor health conditions in a more personalized manner and reduce long-term health costs (Mital et al., 2017; Sodhro et al., 2018). Farahani et al. (2018) indicate that the use of cloud computing platforms capable of optimizing the vehicular flow of ambulance, emergency vehicles, and mobile clinics can minimise the number of visits to healthcare facilities.

Safety and security management and control through satellite monitoring (Huang et al., 2017), CCTV surveillance (Agustina et al., 2011), and the use of global positioning system (GPS) (Feng et al., 2019) 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 (Borrion et al., 2019; Laufs et al., 2020).

Regarding the education, the COVID-19 pandemic highlighted a series of issues related to the inadequacy of the digital urban infrastructure (Watts, 2020). For example, many cities failed to provide online education due to lack of adequate broadband connections or web traffic overload (Whitelaw et al., 2020). 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 (Beaunoyer et al., 2020).

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 (Adam, 2019). For example, several tourist cities diversified their offer by providing virtual tours and 3D experiences through the support of augmented reality and artificial intelligence (Eichelberger et al., 2020), capable of attracting tourists from all over the world.

Internet of Things (IoT) structurally changed the economic dimension of urban metabolism (Carayannis et al., 2018; Sodhro et al., 2019). Specifically, the employment and unemployment rate are experiencing a change in the type and quality of jobs (Esser et al., 2020). For example, many companies use automated recruitment processes assigning other tasks to human resources departments (Kim, 2021). Therefore, many of the products and services offered by human workers are now revolutionized or replaced by technology (Ingemarsdotter et al., 2020), radically transforming the industrial and manufacturing sectors towards models of industrial hubs (Kitheka et al., 2021), industrial clusters (Noori et al., 2020), incubation centres (da Silva Andrade et al., 2016), and science parks (Benny Ng et al., 2020).

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 (Cugurullo et al., 2020; Cepeliauskaite et al., 2021). In addition, public transport equipped with electronic payment systems (Maldonado Silveira Alonso Munhoz et al., 2020), urban areas mapped in real time by interactive graphics (Orro et al., 2020), radar systems to detect critical events (Škultéty et al., 2021), and multimodal mobility (e.g., car sharing, bike sharing, carpooling, ride sharing, etc.) aim at optimizing vehicular circularity within urban contexts (Alomari et al., 2021). The next challenge for policymakers 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 (Santana et al., 2021).

Furthermore, the role of Information and Communication Technologies enabled urban governance to collect, integrate, analyse, and interpret data on a plethora of circularity dimensions (Poncian, 2020). In this sense, data-based urban management allows better governance as policymakers, urban managers and planners can make informed decisions and formulate appropriate policies (Artyushina, 2020). 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 urban circularity evolve, adapt, and respond to various conditions (De Carlo et al., 2020). To integrate Big Data, AI, and machine learning, new approaches such as Blockchain technology can improve the circularity of the urban metabolism. Voto (2017) argue that Blockchain can significantly contribute to the circular economy in cities by enabling distributed, secure, and digitalised urban governance, supporting systemic and holistic cooperation between machines, 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 (Kitchin et al., 2016; Barns, 2020), allowing citizens to acquire greater knowledge and awareness of urban processes, and therefore, to provide opinions and feedback (Bhushan et al., 2020).

3.2 International standards for smart urban metabolism circularity

3.2.1 Overview

Today, urban policymakers, managers and planners are offered a wide range of indicator frameworks and quantitative tools capable of assessing urban metabolism or urban smartness (Huovila et al., 2019). Nonetheless, choosing the right indicators to use for developing, monitoring and evaluating smart urban metabolism is a challenge. This brings the importance of standardized frameworks of urban indicators. Presently, International Organization for Standardization (ISO), International Telecommunication Union (ITU) and European Telecommunications Standards Institute (ETSI) produce worldwide international standardization studies whereas European Committee for Standardization (CEN) and European Committee for Electro-technical Standardization (CENELEC) work closely with the European Commission to ensure that standards are coherent with the EU legislation.

ISO 37120 describes urban indicators as quantitative, qualitative or descriptive measures that provide information, such as trends and change on a complex system. In this sense, city indicators represent a tool to evaluate the strength and weaknesses of a city (ISO, 2018). By analysing the performance indicators of a city, it is easier to set priorities and recognise which areas are most critical or which areas the city is performing well. Consequently, rankings are used as a tool to measure the competitiveness of a city system, communicate its marketing strategy externally and increase transparency towards citizens. Paper I lists and analyses the eight international standards currently relevant for the evaluation of smart urban metabolism.

The ISO 37101 standard helps cities to become smarter and focuses everything a city must integrate to become smarter (ISO, 2016). ISO 37120 defines and develops a set of core, supporting and profile indicators to measure the performance of city services and quality of life (ISO, 2018). At the same time, the World Council on City Data is implementing a comprehensive platform that permits to explore, monitor and compare cities across the ISO 37120. Furthermore, ISO 37122 provides a detailed scheme of indicators and methodologies able to support policymakers to implement smart city policies (ISO, 2019b). In parallel, the ISO 37123 on resilient cities can be used as a tool to monitor progress towards a resilient city (ISO, 2019a).

The leading providers of voluntary European Standards, CEN and CENELEC, develop high-quality standards for products and services that satisfy certain quality, safety and environmental requirements. In addition, they cooperate closely with the ISO and IEC standard organizations in order to pursue the goal of 'one standard, one test, accepted everywhere'.

The ETSI "Key Performance Indicators for Sustainable Digital Multiservice Cities" framework identifies 73 city indicators that focus on monitoring the evolution of an urban system towards a smart city model (ETSI, 2017).

The ITU-T Group on Smart Cities and Communities contributes through recommendations to increase the knowledge in the context of smart urban metabolism. In this regard, each of these recommendations describes indicators from different perspectives. ITU 4901 analyses the application of ICTs in smart environment (ITU, 2016a), ITU 4902 on their sustainability impacts (ITU, 2016b) and ITU 4903 to assess the achievement of Sustainable Development Goals (SDGs) of the UN 2030 Agenda (ITU, 2016c). Moreover, the UNECE-ITU "Smart Sustainable indicators" framework developed by the United Nations in cooperation with the International Telecommunication Union and other stakeholders evaluates the urban smartness and the metabolism of urban contexts in order to comply with the Sustainable Development Goals (UNECE-ITU, 2015). Specifically, the SDG 11 "Make cities and human settlements inclusive, safe, resilient and sustainable" of the UN 2030 Agenda for Sustainable Development constitutes a worldwide-approved scheme for the assessment of anthropogenic pressure throughout the world (UN, 2015).

3.2.2 Analysis

Despite the large number of reports on smart cities, scientific articles and urban reports developed by consulting companies, research centres, technology companies, and car manufactures, only the most important international standards focused on urban metabolism and smart solutions of urban context were examined. In terms of literature sources, most of the indicators' standards (n = 7; 87.5%) come from two international organizations: International Organization for Standardization (ISO) and International Telecommunication Union (ITU).

In detail, Fig. 1 shows the balance (%) of indicators related to urban smartness and urban metabolism for each international standard considered in the analysis. The results are highly polarized: most of the standards investigated focus more on urban metabolism (n = 6: 75%), while a minority part (n = 2; 25%) focuses on urban smartness. Specifically, the outcomes highlight the importance of ISO 37123, ISO 37120, ITU-T Y.4902 and ETSI TS 103 463 as appropriate measurement schemes for the resilience and quality of services and quality of life. On the other hand, ITU-T Y.4901 focus more on urban smartness (with a score of 92%). The remaining ISO 3722 and UNECE-ITU standards represent the most balanced schemes in the analysis. Therefore, this first part of the analysis represented in Fig. 1 demonstrates several difficulties in integrating and balancing the urban smartness and urban metabolism aspects in an integrated scheme.

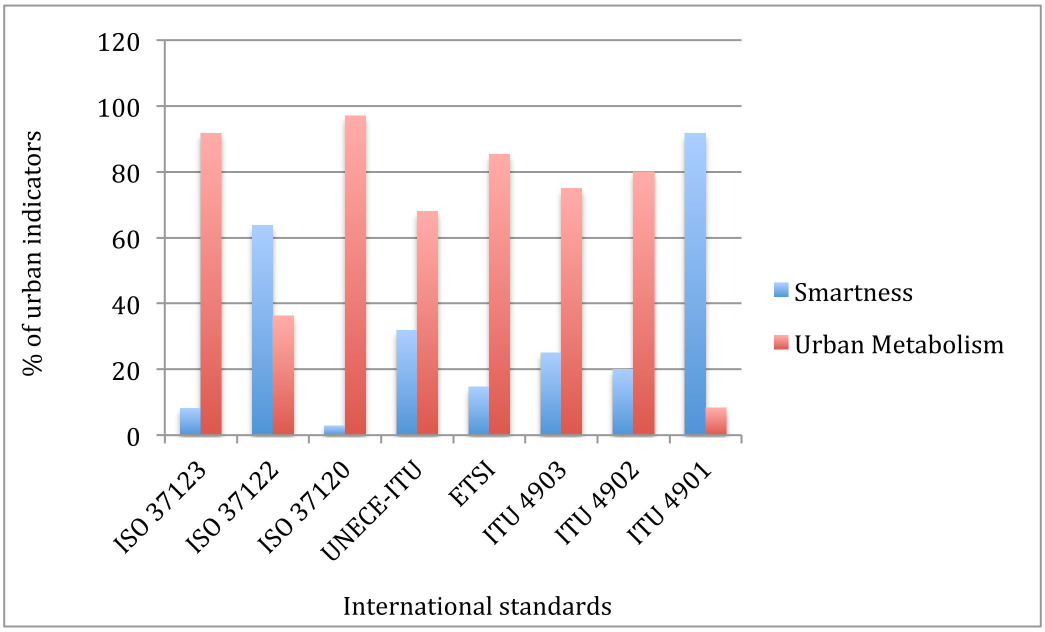

Fig. 1 Urban smartness and urban metabolism perspective

In line with the Triple Bottom Line approach to sustainability defined by the Brundtland report (Brundtland, 1987), the smart metabolism of an urban system is closely related to the balance of its social, economic and environmental dimensions. In this sense, the innovative perspective of this investigation is the integration of the urban smartness component in each dimension of the international standards analysed. Specifically, Table 3 shows the number of indicators that characterize each standard and the frequency (%) of the three dimensions (social, environment, economic).

Table 3. Review and triple bottom line analysis of smart urban metabolism indicator standards

Standard	**Focus**		**Number of indicators**
ISO/DIS 37123 - Sustainable development indicators for resilient cities (ISO, 2019b)	Economic:	24.66%	73
	Social:	50.68%	
	Environment:	24.66%	
ISO 37122:2019 - Sustainable development indicators for smart cities (ISO, 2019a)	Economic:	28.75%	80
	Social:	32.50%	
	Environment:	38.75%	
ISO 37120:2018 - Sustainable development indicators for city services and quality of life (ISO, 2018)	Economic:	20.19%	104
	Social:	40.38%	
	Environment:	39.42%	
UNECE - ITU - Sustainable indicators for Smart Cities	Economic:	36.11%	72
	Social:	37.50%	

(UNECE-ITU, 2015)	Environment:	26.39%	
ETSI TS 103 463 - Indicators for Smart sustainable cities (ETSI, 2017)	Economic:	38.16%	76
	Social:	30.26%	
	Environment:	31.58%	
ITU-T Y.4903/L.1603 - Indicators for smart cities to assess the achievement of SDGs (ITU, 2016c)	Economic:	25%	52
	Social:	38.46%	
	Environment:	36.54%	
ITU-T Y.4902/L.1602 - ICT sustainability impacts indicators in Smart Cities (ITU, 2016b)	Economic:	43.33%	30
	Social:	23.33%	
	Environment:	33.33%	
ITU-T Y.4901/L.1601 - ICT indicators for Smart Cities (ITU, 2016a)	Economic:	43.75%	48
	Social:	27.08%	
	Environment:	29.17%	

In detail, the economic and social dimensions are the most represented in terms of number of indicators, recording respectively a maximum of 43.75% in ITU-T Y.4901 and a minimum of 20.19% in ISO 37120 and a maximum of 50.68 in ISO 37123 and a minimum of 23.33 in ITU 4902 (Table 3). On the other hand, the environmental dimension does not prevail in any investigated standard, indicating a maximum of 39.42% in ISO 37120 and a minimum of 24.66% in ISO 37123. Four out of eight standards (ISO 37123, ITU-T Y.4903, UNECE-ITU, ISO 37120) focus more on the social dimension, with a percentage ranging from 37.50% (UNECE-ITU) to 50.68% (ISO 37123). The result reported by ITU-T Y.4903, suitable for measuring urban performance in terms of SDGs, focuses more on the social (38.46%) and environmental (36.54%) dimensions of urban metabolism. In addition, ITU-T Y.4901 standard dedicates 43.75% of its ICT indicators to measure the economic dimension necessary for a transition towards smart urban metabolism model. Otherwise, ETSI TS 103 463 provides the most balanced distribution of the three dimensions: economic (38.15%), social (30.26%) and environment (31.58%) (Fig. 2).

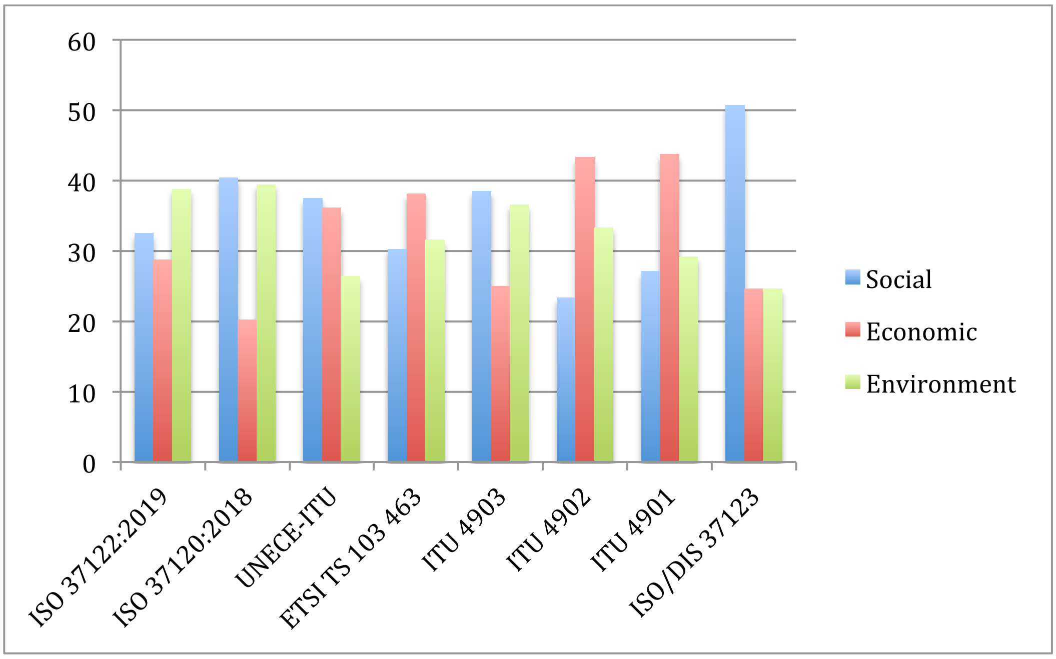

Fig. 2 Indicator standards through a Triple Bottom Line analysis

The analysis of the distribution of the indicators (see Table 3) shows an evident result concerning the economic dimension: ITU-T Y.4902 stands out with 23.33%, followed by ETSI TS 103 463 with 21.05%. In addition, Fig. 3 shows the results of this investigation.

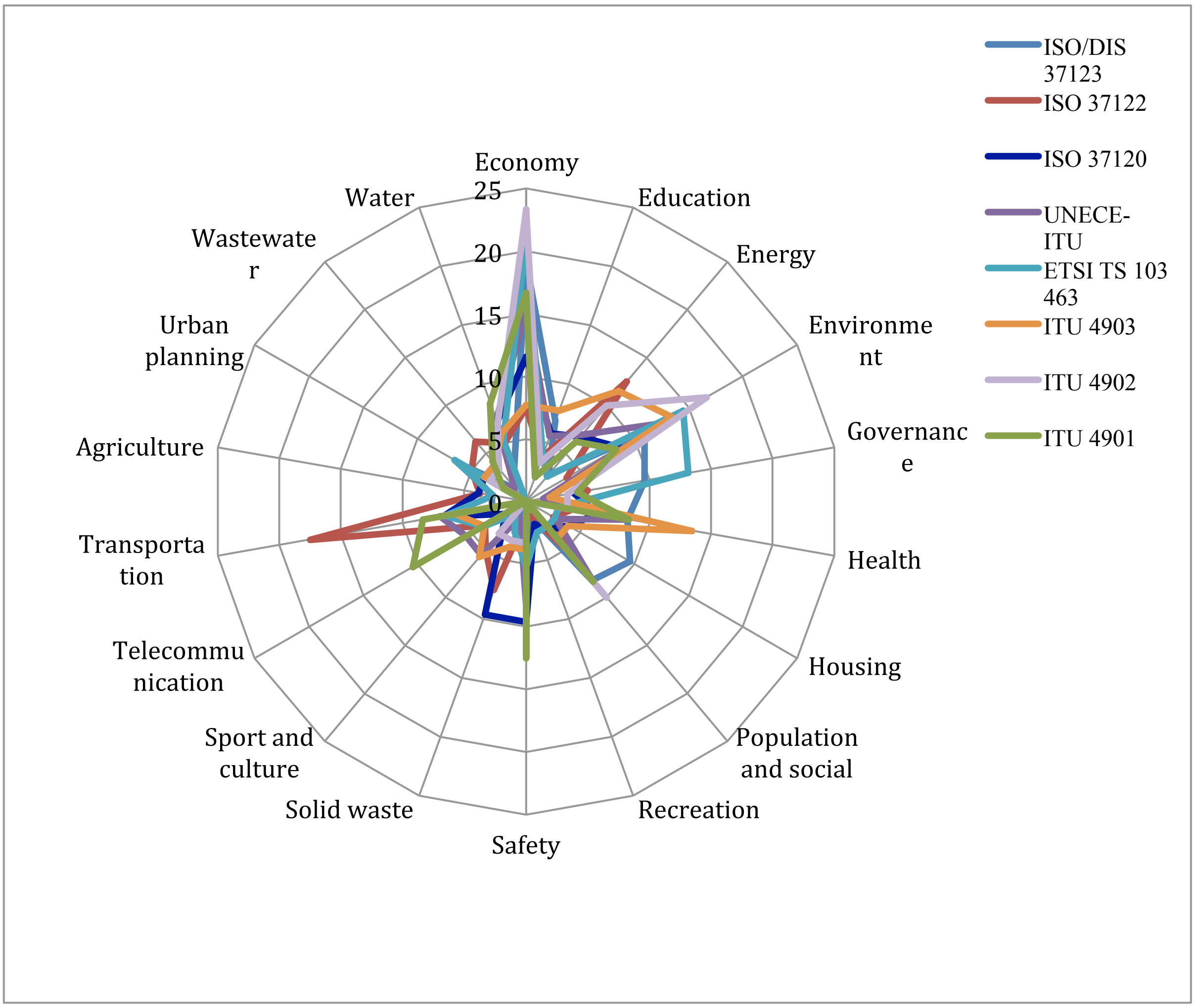

Fig. 3 Indicator standards composition (%) through a radar chart

Alongside the classic economic indicators that characterize urban metabolism (e.g. employment and unemployment rate, GDP growth rate, industrial sector development), the economic indicators shared among all the investigated standards regarding smart urban metabolism emphasize the importance of technology companies and high skilled workers within the urban system (e.g. percentage of employees in ICT sector, number of innovation hubs in the city per 100.000 inhabitants, number of patents per 100.000 inhabitants). ISO 37122 records the highest percentage of transport indicators (17.50%); it provides a wide range of transport solutions in order to control road traffic (e.g. public transport, autonomous vehicles, industrial vehicles) via sensors and real-time monitoring stations (e.g. percentage of city streets covered by real-time online traffic monitoring system, percentage of public trans- port equipped with e-payments systems, percentage of smart traffic lights, percentage of city area mapped by real-time interactive street maps, percentage of autonomous vehicles). ITU-T Y.4901 focuses 10.42% of the indicators on telecommunications, in particular on the implementation of ICT infrastructures and how citizens use these solutions (e.g. percentage of city area covered by fast broadband, number of fixed and mobile internet connections per 100.000 inhabitants, Wi-Fi coverage in public spaces). ITU-T

Y.4901 records the highest percentage (8.33%) in the ICT water management system and the second in the wastewater treatment (4.17%).

Specifically, the water and wastewater indicators provide information regarding the quality monitoring system and the efficiency of the supply service (e.g. number of real-time water quality monitoring stations per 100.000 inhabitants, percentage of buildings equipped with smart water meters, percentage of treated wastewater reused, percentage of wastewater pipeline monitored by a real-time data-tracking sensor system). As regards the environment, ITU-T Y.4902 allocates the highest percentage (16.67% of its indicators) mainly to air quality, in particular to the control of the CO2 and GHG emissions through real-time monitoring stations. ISO 37122 has the highest percentage of indicators referring to the energy dimension (12.50%). In general, they tend to focus on the percentage of electrical and thermal energy produced by renewable energies and waste treatment and on monitoring of energy consumption through smart technologies (e.g. percentage of city gas system management stations equipped with ICT monitoring system, total electricity consumption per capita, total energy consumption of public buildings per year).

Safety indicators analysed cover not only traditional aspects (e.g., number of traffic accidents, crime rate, number of deaths at work, percentage of city area controlled by digital surveillance) but also those of technological security (e.g., the city's cyber security level and data protection). The indicators that refer to social conditions highlight the percentage of city population who lives below the national and international poverty line. To this end, standards use the Gini coefficient as an effective instrument to measure the income or wealth distribution among city's inhabitants. In addition, the percentage of people engaged in social assistance programs, and the percentage of municipal budget allocated for people with special needs are the most common indicators.

Education indicators provide useful information about the proportion of citizens with a tertiary education level, the percentage of school enrolment, the percentage of inhabitants with digital literacy and the productivity of the educational resources. In the health context, the ITU-T Y.4903 standard integrates the largest number of indicators (13.46%) concerning: life expectancy, number of doctors and nursing per 100.000 inhabitants, percentage of city's inhabitants with an online unified health file and the percentage of pharmacies and hospitals using ICT solutions. Sport, culture and recreation are the dimensions that characterize smart urban metabolism with the lowest percentages in most of the international standards analysed, with a maximum of 5.77% in ITU-T Y.4903 and a minimum of 0% in ITU-T Y.4901.

Governance plays a fundamental function in terms of defining the best combination of all the actions previously considered. In this regard, the administrative departments integration, the availability of government open data and the annual budget allocated for smart city solutions are the suitable indicators to measure the efficiency, effectiveness and proactivity of a public administration. In addition, ETSI TS 103 463 standard provides indicators such as the percentage of public services offered online, the number of public officials convicted of corruption and/or bribery per 100.000 inhabitants useful for assessing the quality of the public sector. One of the most important social aspects identified in this study is the civic participation in community decision-making, which permits to create citizen engagement, participation and aware- ness of the urban issues. For example, several indicators consider the percentage of voter participation in the last elections, the percentage of women employed in urban management personnel and the number of social projects and citizen involved in the social life of the city.

The results of the distribution of the indicators show that the ETSI TS 103 463 standards provides the best balance between the urban dimensions taken into consideration, highlighting a minimum of 1.92% and a maximum of 11.54% (Table 4).

Table 4. Indicator standards composition (%)

	ISO/DIS 37123	**ISO 37122**	**ISO 37120**	**UNECE-ITU**	**ETSI TS 103 463**	**ITU 4903**	**ITU 4902**	**ITU 4901**
Economy	19.18%	7.5 %	11.54%	15.28%	21.05%	7.69%	23.33%	16.67%
Education	6.85%	3.75%	5.77%	5.55%	3.95%	7.69%	3.33%	2.08%
Energy	2.74%	12.5%	6.73%	6.94%	2.63%	11.54%	10%	6.25%
Environment	10.96%	3.75%	8.65%	12.50%	14.47%	13.46%	16.67%	8.33%
Governance	9.59%	5%	3.85%	1.39%	13.16%	1.92%	3.33%	4.17%
Health	8.22%	3.75%	5.77%	8.33%	2.63%	13.46%	3.33%	8.33%
Housing	9.59%	2.5%	3.85%	2.78%	2.63%	3.85%	0	0
Population and social conditions	8.22%	5%	2.88%	8.33%	2.63%	3.85%	10%	8.33%
Recreation	1.37%	1.25%	1.92%	0	2.63%	0	0	0
Safety	4.11%	1.25%	9.61%	8.33%	5.26%	3.85%	3.33%	12.50%
Solid waste	1.37%	7.5 %	9.61%	1.39%	2.63%	3.85%	3.33%	0
Sport and culture	0	5%	2.88%	5.55%	1.31%	5.77%	3.33%	0
Telecommunication	2.74%	3.75%	1.92%	5.55%	3.95%	3.85%	0	10.42%
Transportation	2.74%	17.5%	6.73%	6.94%	6.58%	5.77%	6.67%	8.33%
Agriculture	2.74%	3.75%	3.85%	0	2.63%	0	0	0
Urban planning	5.48%	5%	3.85%	2.78%	6.58%	3.85%	3.33%	2.08%
Wastewater	1.37%	6.25%	3.85%	1.39%	0	3.85%	3.33%	4.17%
Water	2.74%	5%	6.73%	6.94%	5.26%	5.77%	6.67%	8.33%

Furthermore, a further analysis represented in Table 5 shows in detail the focus of each urban dimension investigated. Specifically, the comparative study of the balance between urban smartness and urban metabolism provides numerous information to highlight the divergences between the international standards taken into consideration. The urban smartness focus is predominant in the 'economy' dimension in five out of eight international standards: ISO 37120 (33.33%), UNECE-ITU (26.09%), ITU-T Y.4903 (15.38%), ITU-T Y.4902 (50%) and ITU-T Y.4901 (18.18%). On the contrary, the 'environment' dimension is totally focused on urban metabolism:

ISO 37123 (11.94%), ISO 37122 (3.54%), ISO 37120 (8.91%), UNECE-ITU (18.37%), ETSI TS 103 463 (20.31%), ITU-T Y.4903 (17.95%), ITU-T Y.4902 (25%) and ITU-T Y.4901 (100%). Similarly, indicators that include water and energy management focus on urban metabolism. Finally, the indicators of the ‘telecommunications’ sector confirm their focus on urban smartness, while the transport is focused slightly on urban metabolism.

The results of this detailed analysis confirm the difficulty of integrating the urban smartness and urban metabolism focuses into a single multidimensional indicators framework. The distribution of the indicators between the two focuses is highly polarized, obstructing a holistic view of urban dimensions.

Table 5. Urban smartness and urban metabolism composition in international standards (%)

	ISO 37123		ISO 37122		ISO 37120		UNECE-ITU		ETSI		ITU 4903		ITU 4902		ITU 4901	
Dimension	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism	Urban Smartness	Urban Metabolism
Economy	0,00	20,90	9,80	3,45	33,33	10,89	26,09	10,20	0,00	23,44	15,38	5,13	50,00	12,50	18,18	0,00
Education	0,00	7,46	3,92	3,45	0,00	5,94	8,70	4,08	9,09	3,13	7,69	7,69	16,67	0,00	2,27	0,00
Energy	0,00	2,99	5,88	24,14	0,00	6,93	8,70	6,12	0,00	4,69	7,69	12,82	0,00	12,50	6,82	0,00
Environment	0,00	11,94	3,92	3,45	0,00	8,91	4,35	18,37	0,00	20,31	0,00	17,95	0,00	25,00	2,27	100,00
Governance	16,67	8,96	5,88	3,45	0,00	3,96	0,00	4,08	54,55	9,38	0,00	2,56	16,67	0,00	13,64	0,00
Health	16,67	7,46	3,92	3,45	0,00	5,94	13,04	10,20	0,00	3,13	15,38	7,69	0,00	4,17	9,09	0,00
Housing	0,00	10,45	3,92	0,00	0,00	3,96	0,00	4,08	0,00	1,56	0,00	5,13	0,00	0,00	0,00	0,00
Population	0,00	8,96	3,92	6,90	0,00	2,97	0,00	6,12	0,00	1,56	0,00	5,13	0,00	12,50	2,27	0,00
Recreation	0,00	1,49	7,84	3,45	0,00	4,95	4,35	6,12	0,00	1,56	15,38	2,56	0,00	4,17	0,00	0,00
Safety	16,67	2,99	1,96	0,00	0,00	9,90	4,35	10,20	18,18	3,13	7,69	5,13	0,00	4,17	11,36	0,00
Solid Waste	0,00	1,49	5,88	10,34	0,00	9,90	0,00	2,04	0,00	3,13	0,00	5,13	0,00	4,17	0,00	0,00
Telecommunication	33,33	0,00	5,88	0,00	66,67	0,00	17,39	0,00	18,18	1,56	15,38	0,00	16,67	0,00	9,09	0,00
Transportation	0,00	2,99	23,53	6,90	0,00	6,93	4,35	6,12	0,00	7,81	7,69	5,13	0,00	8,33	9,09	0,00
Agriculture	0,00	2,99	1,96	6,90	0,00	3,96	0,00	0,00	0,00	1,56	0,00	0,00	0,00	0,00	0,00	0,00
Urban Planning	16,67	4,48	1,96	10,34	0,00	3,96	0,00	4,08	0,00	7,81	0,00	2,56	0,00	0,00	2,27	0,00
Wastewater	0,00	1,49	1,96	13,79	0,00	3,96	0,00	2,04	0,00	0,00	0,00	7,69	0,00	4,17	4,55	0,00
Water	0,00	2,99	7,84	0,00	0,00	6,93	8,70	6,12	0,00	6,25	7,69	7,69	0,00	8,33	9,09	0,00

4. Testing and Description of the Results

The phase of testing and description of the results through the "Circular Resource Efficiency Management Framework" (European Commission, 2020) included in Paper III (D'Amico et al., 2022) aims to identify and analyse the social, economic and environmental impacts of the previously described digital technologies.

For this purpose, the circular cities of Porto (Portugal), Prato (Italy), Oslo (Norway), Kaunas (Lithuania), The Hague (The Netherlands) and the region of Flanders (Belgium) which constitute the Partnership on Circular Economy (PCE) of the EU Urban Agenda were considered.

Therefore, the results obtained were grouped into the three phases that characterise the "Circular Resource Efficiency Management Framework" (Fig. 4): (1) Identification of urban metabolism; (2) Brokerage activities, and; (3) Monitoring and evaluation.

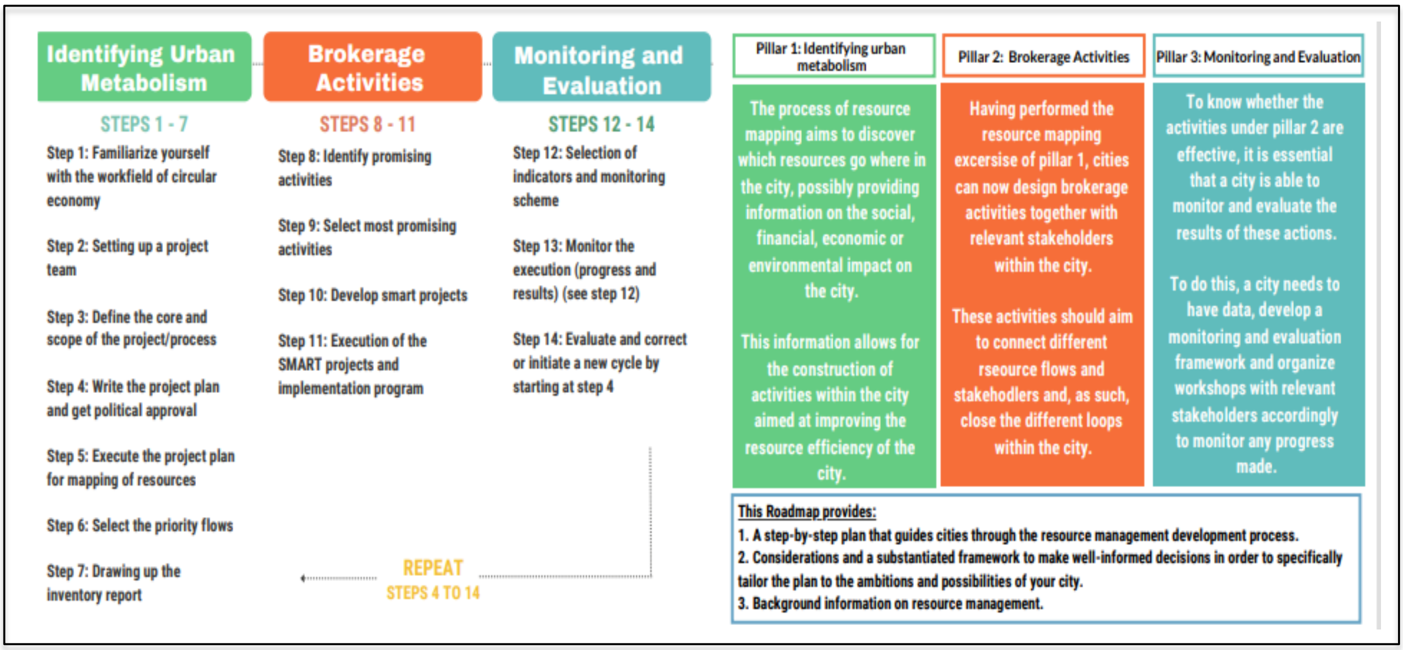

Fig. 4 Circular Resource Efficiency Management Framework. Source: (European Commission, 2020)

4.1 Identification of urban metabolism

As regards the sources, most the strategies and policies concerning the digitalisation of the circularity of urban metabolism derive from urban reports, master plans and bulletins elaborated by municipalities and municipal, regional and national owned utilities. For example, regarding the first step of the framework, 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 project' (www.pratosmartcity.it) and the 'Prato Circular City project' (www.pratocircularcity.it). Likewise, the Municipality of Porto has launched the ScaleUp Porto's Manifesto (www.scaleupporto.pt), which the various initiatives of urban circularity are adopted through digital platforms (European Union, 2020a). Differently, the Municipality of The Hague has signed an agreement (Grondstoffenakkord) with other Dutch municipalities in order to implement the 'Circular Netherlands in 2050' program (www.circulairestad.nl/en/). Policymakers of the Municipality of Kaunas – through the 'strategic development plan' (KCMA, 2015) – aim for greater sustainability and 'civic sense' within the city. In recent years, the governance of the Flanders region has established that the digitalisation of urban metabolism represents the goal of the 'Vision 2050' strategy, assigning a leading role to the waste management utility company (OVAM) (European Union, 2020b).

With regard to step 2 (project team), the initiatives to digitise urban metabolism circularity emphasise the essential contribution of utility companies, administrative departments, inter-ministerial committees, and government agencies. The Municipality of Prato, for example, embraces a multitude of utilities such as Società Publiacqua (water management), Edilizia Pubblica Pratese S.p.A (contruction), Interporto della Toscana Centrale S.p.A (logistics), Programma Ambiente S.r.l (environment), etc. (Municipality of Prato, 2020). Similarly, the Kaunas city administration includes numerous administrative departments relating to energy, mobility, social housing, security, and so on (KCMA, 2015). The city of Oslo involves government organizations that have responsibility for water and wastewater management, urban regeneration, and environmental and cultural services (Hirsch, 2017). As part of the 'Flanders Circular' program, the Flanders region has established a multitude of partnership with the cities of Ghent, Leuven and Antwerp (European Union, 2020b). The project team of the city of The Hague includes administrative departments of the economic and environmental sector, ministries, universities (i.e. Leiden and Delft) and social organizations (e.g., Maex, Platform31, shareNL and Lekkernassuh) (European Union, 2020c). The city of Porto has delegated the urban metabolism circularity initiatives to the municipal waste management utility (Lipor) and to various social cooperatives that deal with biodiversity such as Fruta Feia, ADREPES and RE-Food (European Union, 2020a).

With regard to the core and scopes of the circularity projects (step 3), the analysed 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' (city of Prato), 'aggregator' (city of Porto), 'centre' (city of Kaunas), and 'urban ecological innovation' (city of Oslo).

In step 6, the analysis of urban metabolic flows provides a heterogeneity of priorities. In detail, the city of Prato has installed several fixed and mobile sensors for tracking and monitoring water and energy flows, and the routes of buses and urban cleaning vehicles and developed applications for smartphones in order to bring the bureaucracy, citizens and stakeholders closer together (Municipality of Prato, 2020). The city of Kaunas focuses on: (a) competitiveness and internalisation of the local industrial sector; (b) social cohesion; and (c) territorial and infrastructural sustainability (KCMA, 2015). Digital technologies of the city of Porto is anchored to the development of web sharing platforms such as Via Verde Boleias (ride sharing), Repositorio de materiais (resale of goods), Horta a Porta (shared garden) and OPO' Lab (co-working spaces) (European Union, 2020a). The city of Oslo has prioritised waste management, developing a wide range of initiatives to promote recycling and reusing of products and services (Hirsch, 2017). As part of the 'green deal' program, the Flanders region embraces three sectors that characterise urban circularity such as public procurement, mobility and construction (European Union, 2020b). Finally, the city of The Hague prioritises the social dimension of the digitalisation, implementing social entrepreneurship initiatives in the field of the circular economy (e.g., Made in Moerwijk, KledingBank DenHaag, Lekkernassuh, De Groene Regents, etc.) in order to strengthen the social inclusion (European Union, 2020c).

4.2 Brokerage activities

The mapping of digital technologies (steps 8-9-10) of the circular cities analysed offers a broad spectrum of operations and procedures capable of improving the quality of urban metabolic flows. In general, real-time tracking sensors of water and energy flows and GPS monitoring devices to control vehicular flows are the most widely used digital technologies. On the other hand, policymakers leverage applications for fixed and mobile digital devices and institutional websites to interactively communicate with citizens, administrative departments and stakeholders, providing and sharing documentation in real time. At the same time, apps for smartphones and tablets represent platforms to increase the involvement and participation of citizens in decision-making processes.

As regards the digitalisation of the circularity of vehicular flows, the city of Prato has adopted the 'Automatic Vehicle Monitoring', a sensor network capable of collecting data and information on the arrival and departure times of buses (Municipality of Prato, 2020). At the same time, the sensor platform used by Programma Ambiente S.r.l (city of Prato) allows to continuously and interactively monitor the routes of the vehicles involved in the separate waste collection service. In parallel, the City-works platform in the city of Prato checks the advancements of road works in order to plan and model vehicular traffic. Through the technology provided by Brisa (mobility operator), the city of Porto has developed Via Verde Boleias, a car pooling application for smartphones, tablets and PCs (European Union, 2020a). In the Flanders region, Cambio (intermodal mobility company) is owned for two-thirds by the public transport company.

Specifically, Cambio promotes the economic, social and environmental benefits of bike sharing and public buses, favouring a rational and optimized management of urban spaces (European Union, 2020b). Similarly, Dégage aims to disseminate sustainable mobility practices through bike and car sharing initiatives, drastically reducing cars in circulation and freeing up public spaces for other uses (European Union, 2020b). Inhabitants in the Flanders region can also take advantage of Peerby, a web platform with over 1 million shared goods and services. This initiative, which has about 30,500 users, aims to increase not only the circularity of products but also social cohesion among the inhabitants (European Union, 2020b). Under the supervision of the Kaunas Traffic Control Centre, several digital vigilance cameras were placed in areas deemed sensitive such as underpasses, public transport stops, traffic lights, etc. (Kaunas, 2011). Real-time vigilance devices are also utilised by the city of Prato in order to collect data and information and ensure safety and timeless during critical events (Municipality of Prato, 2020). Specifically, the georeferenced localization system integrated with 3D technology allows the security department of the city of Prato to analyse and share images, statistics and graphics in real time.

Regarding waste management, the city of Porto have developed a web platform (Repositorio de Materiais) that centralise transactions between those who offer building materials and those who request them, encouraging initiatives of circularity in the construction sector (European Union, 2020a). Likewise, among the initiatives on urban metabolism planned by the 'Circular Flanders' committee there is also the 'circular construction sector' (European Union, 2020b). In addition, the circularity standard in the procedures for awarding public contracts has been included in the cities of Prato and Porto and the Flanders region. Otherwise, the city of Oslo has installed in its 15 districts numerous 'urban ecological innovation' centres in order to reuse, repurchase and share goods and services such as plastics, building materials, clothes, food, and so on, increasing the awareness and comprehension of circularity practices (Hirsch, 2017). In the city of Prato, the Baciacavallo water and wastewater treatment centre was equipped with tracking sensors to monitor the quality of the production and distribution systems. At the same time, the city of Prato, through the public service company Estra S.p.A, has installed a vast network of smart meters for efficient energy management and continuous interaction with users in the event of breakdowns and disservices (Municipality of Prato, 2020). Contrarily, the city of The Hague financed the starting investment of the solar panel circuit (De Groene Regents), located above the public and private buildings (European Union, 2020c). The city of Porto has created the OPO' Lab dedicated not only as co-working space for urban planners, architects and engineers involved in the implementation of digital technologies for circularity, but also as a location to spread the values of the circular economy between entrepreneurs, researchers, policymakers, and associations (European Union, 2020a). Similarly, in the urban ecological innovation centres, the city of Oslo engaged non-profit organizations, universities and research institutes from the 15 districts (Hirsch, 2017). Through the parallel economy, circular digital initiatives such as Made In Moerwijk (Vlaanderen-circulair, 2020), KledingBank The Hague (European Union, 2020c) and Lekkernassuh (Leiden University, 2021) developed in the city of The Hague focus mainly on social issues as marginalisation unemployment, immigration and poverty (European Union, 2020c). Similarly, Platform31 embraces the themes of social housing, poverty, energy, etc. (Platform31, 2017), share NL connects associations, companies, and local authorities in the planning of circular economy projects (van de Glind, 2015), and the MAEX fund finances circular economy initiatives (www.maex.nl).

4.3 Monitoring and evaluation

In all the strategies and policies of the circular cities investigated, the circularity initiatives of urban metabolism driven by digital technologies have generated positive social, economic, environmental and technological impacts. For example, by equipping the Baciacavallo water and wastewater treatment centre with monitoring stations capable of monitoring flows in real time, the policymakers of the city of Prato have improved the quality of production and distribution activities (Borsacchi et al., 2018). At the same time, public transport and urban cleaning vehicles equipped with GPS tracking sensors offer continuous and dynamic control of the routes carried out, allowing the city of Prato to better organise fleets in order to provide customised public services (Municipality of Prato, 2020).

The initiatives of the city of Porto (Via Verde Boleias) and Flanders (Green Deal Shared Mobility) through web sharing portals for smartphones encourage sustainable circularity practices, strengthening the use of shared bicycles and cars (de Ferreira et al., 2019). In detail, Via Verde Boleias allows users to reduce fuel and car park costs and emissions by up to 75%. In this way, the city of Porto optimises the volume of vehicles in circulation and spreads the culture of circularity among the inhabitants (European Union, 2020a). In the Flanders region, the Cambio and Dégage web platforms optimise land use by reducing parking areas (European Union, 2020b). Specifically, Dégage allows users to save on the purchase of a car and on ancillary costs (e.g., insurance, car tax, etc.), saving around 1,400 euros per year. At the same time, non-car users save around 600 euros through shared journeys and routes (European Union, 2020b).

The digital surveillance cameras installed in different urban areas of the cities of Prato and Kaunas allow a detailed and comprehensive knowledge of vehicular flows (Feiferytė - Skirienė et al., 2020). Urban rehabilitation activities in the field of public green, smart grids and public housing units have revitalised the Prato Macrolotto Zero district (Municipality of Prato, 2020). The solar panel network managed by the Groene Regents platform in the city of The Hague produced nearly 607,578 kWh/year of solar energy (European Union, 2020c). The integration of the circularity standard in public procurement and the implementation of physical platforms in Oslo and virtual in Flanders has significantly improved the sharing and recycling of goods and services. In this sense, the Peerby portal in the Flanders region made available a wide range of products (about 1,000 monthly), involving almost 31,000 subscribers (European Union, 2020b). In sum, Peerby’s circularity initiatives allow not only to save money, energy, water, fuel, and so on, but also to strengthen sociality and safety between neighbourhoods. In this sense, the social projects elaborated by the Made in Moerwijk platform have created jobs in the field of reuse of plastics, construction waste, tires, etc., integrating low-school residents into society and providing them with the principles of environmental sustainability (European Union, 2020c). Thanks to the 'solidarity' pricing policy, KledingBank Den Haag annually provides nearly 4,000 items of clothing for the vulnerable population (European Union, 2020c). In the cities of Prato and Kaunas, the digitalisation of circularity has changed the way in which administrative documentation is accessed. Specifically, applications for smartphones, tablets and PCs allow personalised and categorised interaction with stakeholders.

5. Practical Applications to Circularity: Green Logistics for Greener Cities

The current growth of port commercial traffic worldwide (Cong et al., 2020; Shi et al., 2020) and the growing relevance of digital technologies such as IoT, cloud computing, sensors, Big Data, ICTs, AI, AR, etc. (Molavi et al., 2020), for the collection, monitoring, processing and analysis of the circularity of economic, social and environmental flows have placed port cities at the centre of the theoretical and managerial debate on environmental, social, economic and technological challenges of the transition towards a smart and sustainable logistic model (Muñuzuri et al., 2020).

According to Van den Berghe et al. (2018), the term *port city* used in this Thesis refers to a self-organized system, characterized by a 'relational geometry' through which interact a wide range of: (a) actors, such as municipalities, port authorities, shipping companies, couriers, logistic service companies, financial institutions, terminal workers, trade unions, non-profit organizations, container operators, research centres, universities, transport companies, technology companies, manufacturing companies, start-ups, and so on; and (b) economic, environmental, social and technological resources.

These aspects are discussed in the 'World Ports Climate Action Program', where policymakers from major port cities globally came together to make their contribution to achieving the goal of the Paris agreement on climate change mitigation (Fenton, 2017). In this regard, port authorities, managers, local administrators, urban planners and stakeholders aim at a paradigm change of the port-city social, environmental, economic and technological relations through a smart and sustainable redefinition of logistic processes (Durán et al., 2019).

The European Council (2008) had already defined the port as a critical infrastructure for the development of the social, economic, environmental and technological aspects of cities, but which required an innovative strategic approach capable of integrating digital technologies and urban circularity initiatives in order to improve the efficiency of maritime operations and the quality of life. In sum, the transition towards a smart and sustainable logistics within port cities aims to manage in a digital and circular manner the ever-increasing quantity of tons of imports and exports and the consequent congestion, in order to reduce vulnerability and anthropogenic pressure on urban contexts (Alzahrani et al., 2020).

According to the "Smart Ports Market by Technology report" published by Markets and Markets (2019), the smart port market will reach USD 5,3 billions, with a growth of 25.0% compared to 2019. Specifically, the study investigates investments in Internet of Things (IoT), Blockchain, Automation and Artificial Intelligence (AI) technologies in the smart and sustainable ports located in America, Europe, Asia, Middle East and Africa. Specifically, Asia represents the largest market in terms of investments and the smart automation sector the one with the largest share of strategic interest.

This growing relevance of digital technologies such as IoT, cloud computing, sensors, Big Data, ICTs, AI, AR, etc., for the collection, monitoring, processing and analysis of the circularity of economic, social and environmental flows of logistics within port cities (Jun et al., 2018; Jović et al., 2020), has led several technological giants such as Cisco, IBM, Huawei, SAP, Nokia and Deutsche

Telekom to be called upon by port authorities to co-implement smart and sustainable logistics initiatives (Chen et al., 2019; Molavi et al., 2019).

Among the cities currently engaged in the smart and sustainable logistic transition, we undoubtedly include the port city of Hamburg (Notteboom, 2016). Through the 'Smart Port Logistics' project, the Hamburg port authorities have developed a platform that includes sensors, IoT technologies and a Cisco Wi-Fi Real-Time Location System (RTLS) capable of collecting, exchanging and evaluating data and information provided by ships, trucks and trains. Similarly, the port city of Rotterdam is implementing an Internet of Things (IoT) dashboard with IBM, Cisco, Tele2 and Axians that can integrate dynamic data such as weather, currents, visibility and wind (Witte et al., 2018). In the United States, the logistical infrastructures of Middle Harbor Long Beach and Trapac Terminal, costing respectively 1.49 billion dollars (Portnews, 2018) and 630 million dollars (Los Angeles Times, 2018), are equipped with highly automation processes and sensors able to robotically move cranes in order to transfer containers from ships to zero-emission vehicles. China, which hosts the port cities with the largest freight volumes in the world, has inaugurated the Qingdao Qianwan Container Terminal in the port of Qingdao, the first fully automated container terminal that, through digital technologies, it can improve efficiency by 30% and reduce labour cost by 85% (Jiang et al., 2018).

Although there are various conceptions of the definition of smart and sustainable logistics, there is unanimous consensus on its role in improving the efficiency and digitalisation of port logistics processes and operations through digital technologies (Shafiq et al., 2020). In this sense, smart and sustainable logistics represents an ecosystem of automation, high productivity and ecological infrastructure (Moros-Daza et al., 2020).

EL Sakty (2016) explains that smart and sustainable logistics in port cities refers to the operational, energy and environmental spheres, indicating energy consumption as a valid criterion for evaluating the efficiency of smart and sustainable logistics. At the same time, Botti et al. (2017) explain that digital technologies in the context of smart and sustainable logistics in port cities increase the competitiveness of the supply chain, improving the flow of containers, vehicles, trucks, personnel, etc. through information systems based on real-time data.

Therefore, smart and sustainable logistics initiatives allow inter-changeability between offshore and onshore modes, as well as accessibility to data and information relating to economic, social and environmental flows, in order to increase collaboration and awareness between the stakeholders involved in port cities (Shinohara et al., 2018; Kavirathna et al., 2019).

From a social perspective, smart and sustainable logistics must be implemented by prioritizing the well-being of citizens and the quality of life of port city (Mat et al., 2016; Pham et al., 2019). While digital technologies make it easy to obtain economic, environmental and social data, the technical skills (human, economic and technological capital) and the know-how that allow the research and development of smart and sustainable logistics initiatives are difficult to find in underdeveloped or developing urban/industrial contexts (Giurco et al., 2011). Therefore, human-based logistics is able to fuel and support co-creation processes, attracting talents, entrepreneurs, researchers and start-ups from around the world (Esser et al., 2020).

However, port cities that use real-time monitoring stations for water and energy consumption, GPS tracking system located in trucks, ships and industrial vehicles, cameras placed in cranes, poles, antennas and buildings, sensors distributed in docks and water pipes, and so on, require significant investments and financing for their acquisition, assembly and maintenance, representing a barrier to smaller port cities or located in less developed regions (Musso et al., 2006). Furthermore, policymakers, port managers and planners need to integrate digital technologies that are: (a) heterogeneous, capable of providing numerous types of quantitative and qualitative data; (b) dynamic and adaptive, able to adapt to changing industrial and urban scenarios; (c) unforeseeable, capable of providing conflicting results by analysing the same data, as they use different protocols and standards, and; (d) nurtured by different energy sources, such as solar, thermal, gas, etc.

From an environmental point of view, for example, digital technologies permit to minimise or avoid the negative impacts on citizens caused by noise and atmospheric pollution or by the spill of dangerous substances into the water (Sun et al., 2017). In this regard, the regulations and conventions on safety and security as the International Convention for the Prevention of Pollution from Ships (Marpol, 1973) elaborated by the International Maritime Organization (IMO) and the ITU international standards on the interoperability of the smart port with the smart city (ITU, 2020) provide a wide range of actions to be implemented to mitigate anthropogenic pressure.

Although theoretically the enabling factors, domains and goals that characterise the smart and sustainable logistics of port cities can be defined as universal and homogeneous, urban and industrial contexts tend to be heterogeneous and specific (Tseng et al., 2019). For example, the port cities hosting logistic infrastructures have different social, economic, environmental and technological characteristics and are administered by bureaucratic systems with priorities that are difficult to integrate into a single port logistic project (Han, 2018; Parola et al., 2018). In general, the success of a smart and sustainable logistics strategy depends on the social, economic, environmental and technological characteristics and on the internal organization and ethical factors of the stakeholders involved in the port cities (Tan et al., 2018).

Therefore, on the basis of the practices and strategies of urban circularity within port logistics adopted worldwide, the most recurring enabling factors, domains and goals of smart and sustainable logistics have been taken into consideration, catalogued and grouped. The result is the multidimensional framework of smart and sustainable logistics in port cities illustrated in Fig. 5.

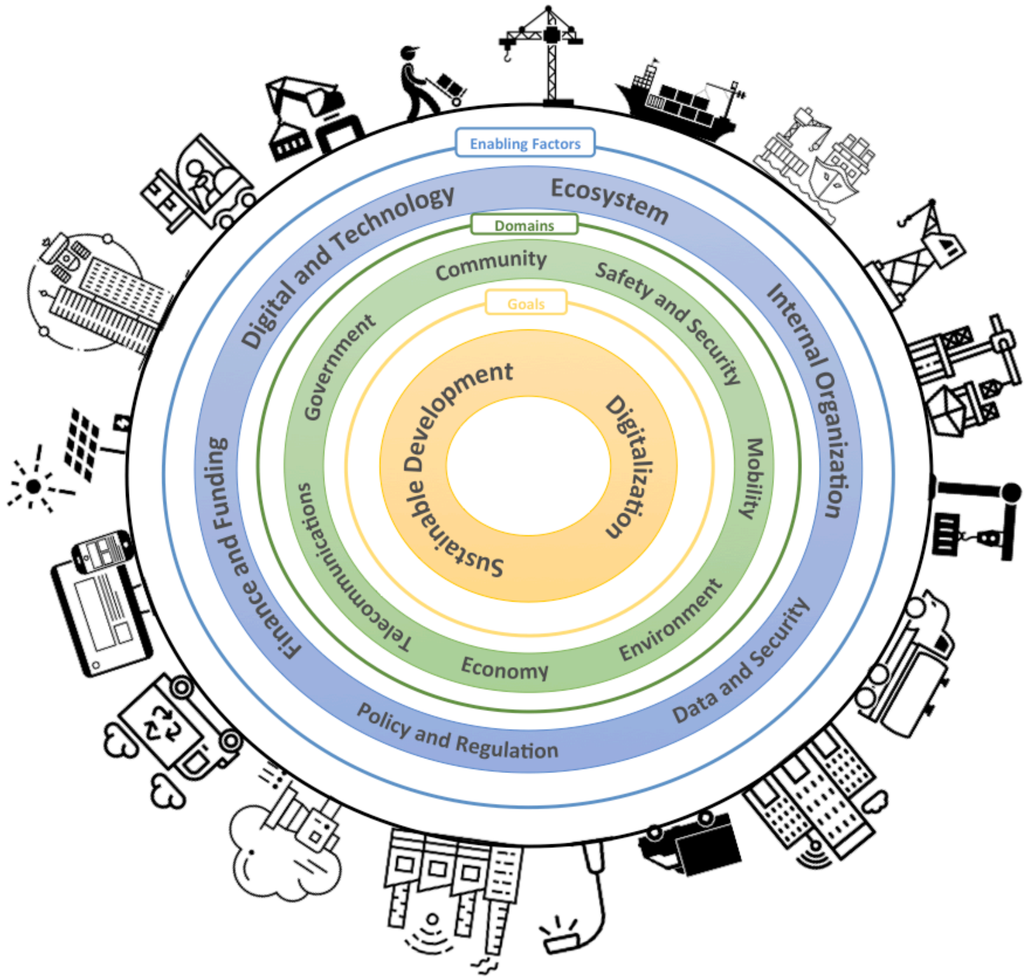

Fig. 5 Smart and Sustainable Logistics in Port Cities Framework

5.1 Enabling Factors

5.1.1 Ecosystem

Nowadays, many port cities involved in smart and sustainable logistics transition around the world are implementing bottom-up approaches involving municipalities, municipal or state owned utilities, agencies, technology companies, start-ups, universities and research centres, and so on, in order to co-create smart and sustainable logistics solutions in line with the needs of port authorities, couriers, shipping companies, terminal workers, logistic service companies, and public institutions (Anbleyth-Evans et al., 2020; Sdoukopoulos et al., 2020). Therefore, ecosystem port models are becoming increasingly important as shared planning and design methods (García-Onetti et al., 2018). In general, ecosystem port models are shared physical and virtual spaces where port managers, planners, administrators, entrepreneurs, students, citizens, start uppers, non-profit organizations, etc. can conceive, design, develop, test and redefine forward-looking project in the field of logistics and port management. Specifically, they allow to demonstrate the efficiency and effectiveness of the smart and sustainable logistics initiatives and their acceptance between the various stakeholders involved and to elaborate the necessary changes before being adopted by port cities (Twrdy et al., 2020). For example, start-ups specializing in robotics, automation and artificial intelligence have provided a crucial contribution to the development of the Port of Montreal innovation ecosystem. To do this, the Montreal Port Authority has involved the Concordia University in the implementation of the "District3 Center" hub, which encompasses a wide rage of port logistics projects (Witte et al., 2018). Likewise, the Port of Rotterdam has supported numerous start-ups initiatives in the field of smart and sustainable logistics such as PortXL and Port Innovation Lab in order to create systemic relationships with port companies as Vopak and Boskalis (Witte et al., 2018). The port of Rotterdam is engaged annually in the elaboration of the world port hackathon, where several hackers and port experts are engaged in designing, implementing and testing innovative smart and sustainable logistics initiatives.

5.1.2 Internal Organization

In order to holistically manage the relationships between the stakeholders involved in logistics (e.g., couriers, shippers, shipping companies, port authorities, road and rail transport companies, technology companies, financial institutions, logistics services companies, etc.) an internal organization capable of prioritizing and empowering the actor involved in the planning, design, development, monitoring, implementation, analysis, evaluation and redefinition of smart and sustainable logistics initiatives is necessary (dos Santos et al., 2019). Although the departments and divisions of port authorities, municipalities, utilities and private companies hold the technical and knowledge resources, the presence of barriers to sharing data and information and the lack of digital technologies such as platforms and dashboards that allow participatory and inclusive governance undermine the effectiveness of smart and sustainable logistics initiatives implemented (Gjerding et al., 2018). In this regard, many port cities have established councils that include representatives of the various stakeholders involved (e.g., warehouse staff, environmental associations, terminal personnel, trade unions, municipal administrators, managers, etc.) in order to represent the different sensitivities of smart and sustainable logistics initiatives in decision-making processes (Schrobback et al., 2020). For example, the port of Hamburg is equipped with the "Hamburg Vessel coordination Center (HVCC)" (Figure 6) that includes container terminal operators e.g. Hamburger Hafen and Logistik AG (HHLA) and EUROGATE Container Terminal Hamburg GmbH (CTH) which, through the sharing of data and information, they effectively manage the logistic flows (HVCC, 2020).

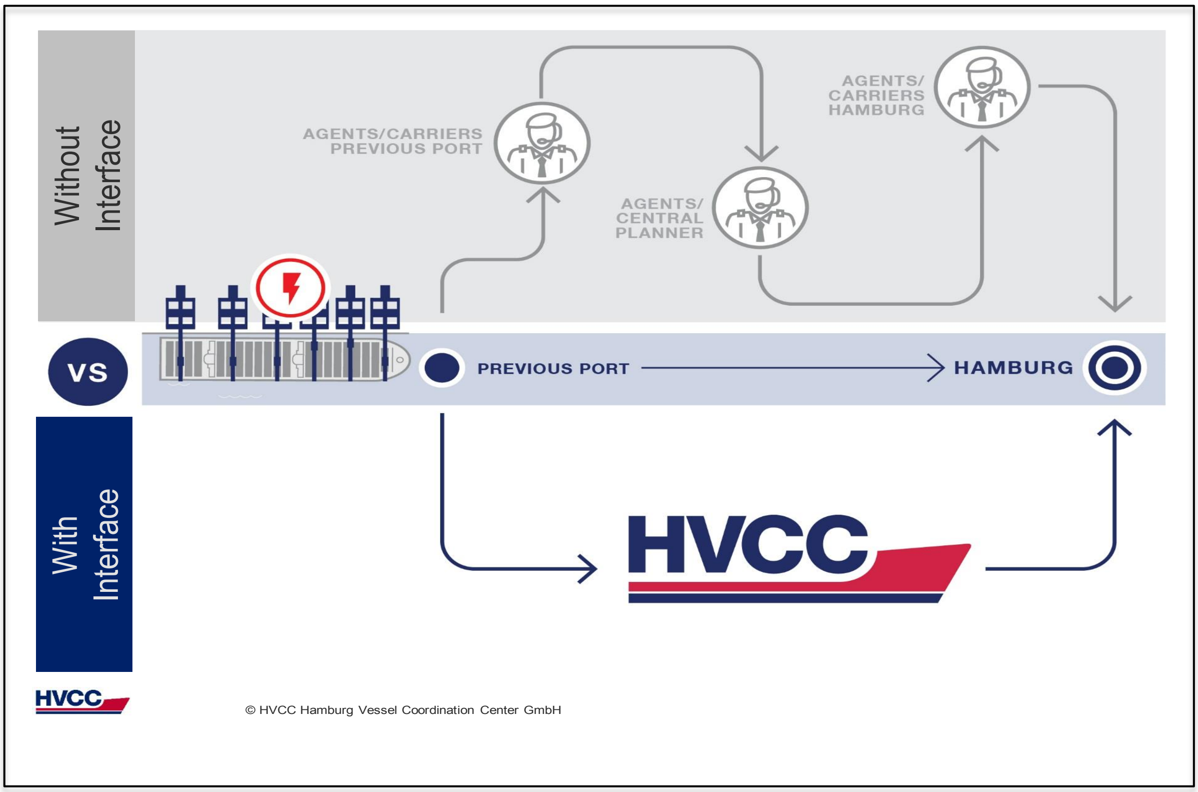

Fig. 6 Hamburg Vessel Coordination Center GmbH Framework. Source: Hirt, 2019

Therefore, port cities involved in the smart and sustainable logistic transition must equip themselves with an internal organization systems that go beyond the traditional and obsolete silos-based approach that limits the effectiveness of systemic and multidimensional initiatives (De Martino et al., 2020; Taljaard et al., 2021).

5.1.3 Data and Security

The development of dashboards and platforms has enabled port managers, planners, port authorities and administrators to collect, monitor, integrate and analyse a broad spectrum of economic, environmental, social and technological data provided by a wide range of digital technologies such as sensors, monitoring stations, tracking systems, drones, radars, cameras, antennas, actuators, and so on, in order to improve the efficiency of logistic processes and operations (Langenus et al., 2018). However, the intensive and pervasive use of fixed and mobile digital devices such as GPS tracking systems, real-time consumption and emissions monitoring stations, sensors for controlling incoming and outgoing flows, trucks and vehicles equipped with radars, smart bins for waste disposal, aircraft drones for terminal control, and so on, highlight a multitude of issues in order to ensure a high standard of quality (Le et al., 2020), traditional and cyber security (Scholliers et al., 2016; Yang et al., 2014), integration (Cheng et al., 2016) and the ability of policymakers to transform raw data into smart and sustainable logistics strategies (Jiannan et al., 2020). The risk of considering incomplete and insignificant data or not involving the necessary stakeholders can undermine the usefulness and effectiveness of data management and the overall logistics strategy (Široka et al., 2021). At the same time, according to the SMM Maritime Industry Report (MIR) (SMM, 2018), almost 80% of operators in the maritime sector state that cyber security in the phases of data collection, processing, monitoring and storage represent a priority for effective management of logistics processes. In this regard, in 2019, Ningbo port, one of the top three busiest ports in the world, with an annual cargo volume of over 1 billion tons, Huawei and China Mobile have developed a joint cyber security project in line with the latest challenges of the 5G Internet Industrial network (Huawei, 2020). Based in the recommendations provided by international standardization organizations such as GSMA (Global System for Mobile Communications), ISO (International Organization for Standardization), ITU (International Telecommunication Union), 5G-ACIA (5G Alliance for Connected Industries and Automation) and IMT2020 (International Mobile Telecommunications) (GSMA, 2020), the port of Ningbo has invested significantly in traditional and cyber security, deploying several HD cameras in the various physical infrastructures, capable of remotely signalling user access to the network of over 500 cranes, terminals and docks. Therefore, the transparency and security that allow users to interact with each other through mobile and stationary digital devices improve their trust and understanding of the methodologies in which port cities operate and increase the effectiveness of smart and sustainable logistics processes and operations (Bullock et al., 2021).

5.1.4 Policy and Regulation

Port cities adopt policies and regulations to define guidelines for the development of sustainable and smart logistics initiatives (Merkel et al., 2019), which, if adopted correctly, can represent useful frameworks to balance the power of influence between governmental authorities, technology companies, logistics companies and communities (Chen et al., 2020a). However, digital technologies have highlighted the non-flexibility of several port cities and authorities in facing the challenges of growing datafication (Caldeirinha et al., 2020). In this regard, digital technologies described above have amplified the concerns about a correct and effective management of traditional and cybernetic data security (Zarzuelo, 2021). In this regard, a wide range of international standards elaborated by independent organizations encourage port cities to adopt regulatory frameworks in line with current urban and industrial challenges (Halff et al., 2019; Van et al., 2019; Aneziris et al., 2020). For example, the scheme provided by International Maritime Organization (IMO, 2018a,b), the International Association of Ports and Harbours (IAPH, 2008), World Port Climate Initiative (WPCI, 2010), and the International Institute for Sustainable Seaports (IISS, 2013) addressing the criticalities of climate change and atmospheric pollution within port cities. The International standard ITU-T Y.4209 "Requirements for interoperation of the smart port with the smart city" (ITU, 2020) provides a wide range of economic (e.g. interests of passengers, tour and excursion operators, vehicles on-board and off-board management, etc.), social (e.g. municipal events, touristic activities, recommendations from the local and national authorities, etc.) and environmental (e.g. waste management, energy supply, meteorological forecast, etc.) requirements that port cities must consider in their relations with the surrounding urban system, in order to provide smart and sustainable services. In this regard, port authorities, departments and divisions of municipalities can encourage the correct use of digital technologies through zoning ordinances, licenses, authorization rules and permits useful to promote safer and more inclusive digital technologies (Brown et al., 2018).

5.1.5 Finance and Funding

The design, planning, implementation, development and maintenance of smart and sustainable logistics initiatives are characterized by significant costs (Balliauw, 2020), which make them prohibitive for port cities located in regions with low social, economic, environmental and technological development. In order to overcome these criticalities, several municipal, regional, national and transnational institutions provide financing with restriction on their use in order to support the investments that favour the digitalization of logistic processes and operations within port cities (Balliauw et al., 2020). Port city government authorities can establish Special Economic Zones or Zones of Opportunity that benefit from a preferential tax regime for investments in green technologies or grants for research and development activities (Yang, 2009; Cocconcelli et al., 2018; Mullins et al., 2018; Anna et al., 2019). For example, the Chinese government in defining the Hainan Free Trade Port (FTP) guidelines has focused more on tax leverage (zero tariffs and low tax rates) and legal (simplified regulations) as incentives to attract foreign investors (Wong, 2020). In detail, the zero tariff regime is implemented in two phases. In the first phase (before 2025), some categories of imports will have zero tariff treatment in order to develop the tourism, e-commerce and logistics sectors in Hainan FTP. In the second phase (from 2025), a separate tariff regime (e.g. no VAT or consumption tax) will be implemented for a wide range of imports, based on a classification elaborated by the authorities of Hainan FTP (ITR, 2020). Therefore, public funds represent an effective lever to create the social, economic and environmental foundations of innovation, which consequently can incentivize future private sector investments (Yang et al., 2020a). For example, the funding underlying the smart and sustainable development of ports of Kapellskär and Naantali in Sweden is based on the integrated use of the European Social Fund (ESF) and the European Regional Development Fund (Ports of Stockholm, 2020). Concerning the port of Kapellskär, the funding includes an automatic mooring system, capable of making dockside operations safer and more efficient. At the same time, the Swedish Environmental Protection Agency has financed the shore-based electricity supply system for ships docked at the quay, which allow them to shut down their engines and operate using electricity provided by the local electricity grid, drastically reducing the environmental impacts on the surrounding context. However, the choice of investments to be financed and included in the overall logistics strategy and those to exclude represents a challenge for policymakers, port managers, planners and urban administrators (Balliauw et al., 2019). Port and municipal authorities can develop procurement plans in the logistics and technology sector with requirements that take into account the social, economic, environmental and technological impacts on the community (Quak et al., 2019). Policymakers can also demand how companies will engage the community and mitigate the technology gap by imposing certain investments in specific topics (e.g., broadband connections, Blockchain, big data, cloud computing, sensors, etc.). At the same time, port cities can involve entrepreneurs, start-uppers, venture capitalists, technology, logistics and shipping companies, freight forwarders, couriers and other private sector in order to make smart and sustainable logistics investments (Musso et al., 2006).

5.1.6 Digital and Technology

The ability of port cities to involve stakeholders in the logistics industry depends on their willingness to access and share data and information through digital technologies (Kermanshah et al., 2020; Bjerkan et al., 2019). However, despite the rapid and pervasive expansion of technological infrastructure such as Big Data analytics, cloud computing, Blockchain, data sharing and integration platforms and dashboards, 5G connections, and so on, many logistics operators still do not have cognitive and practical accessibility adequate to the current trends of trade datafication and globalization (Vural et al., 2020). Indeed, digital technologies used in pioneering port cities have the potential to improve the efficiency in the collection, monitoring and analysis of economic, social, environmental and technological logistic flows and the connectivity between the various stakeholders (Kavakeb et al., 2015; Im et al., 2018). For example, Ericsson has developed the 'Water Monitoring Networks' project involving the port of Stockholm, the Royal Institute of Technology, Telia Company, Linköping University, Stockholm University and Stockholm Water in order to address the challenges of water management, climate change mitigation and environmental resilience (Ericsson, 2017). Specifically, the 'Water Monitoring Networks' project aims to install an IoT (Internet of Things) sensor system in the water distribution infrastructure that allows real-time monitoring of water quality in terms of temperature, pH, oxidation, and so on. Furthermore, the technical support of the Swedish Innovation Agency 'Vinnova' permits the elaboration of modelling algorithms of the dynamics of water flows, which, through IoT sensors and Big Data analysis, provide more detailed information on changes in production and distribution of the water service. However, most port cities located in less developed regions are struggling to adopt and implement smart and sustainable logistics solutions (Delphine et al., 2019). In addition, port cities should also ensure that logistics operators (e.g., monitoring and security officers, terminal staff, shippers, warehouse workers, couriers, etc.) have the necessary digital skills. To this end, collaborations and/or partnerships with technology companies, universities, and research centres represent an attempt to improve their digital literacy (Duru et al., 2020).

5.2 Domains

5.2.1 Safety and Security

The domain of safety and security within the logistics sector refers to the traditional safety (Corrigan et al., 2019; Motter et al., 2017) and cybersecurity (Alcaide et al., 2020) issues that involve port cities. As regards traditional safety, for example, through the support of Cisco Internet of Things (IoT) Edge Intelligence (Figure 7), the Port of Rotterdam has equipped about 20 patrol vessels with data management systems capable of improving predictive maintenance, in order to operate optimally and improve the response to incidents quickly (Cisco, 2020). At the same time, in the event of fire or engine failure, patrol vessels – equipped with water cannons – act is fire-fighters and tugs to rescue the ships. Therefore, through the Edge Intelligence platform, it is possible to manage in real time which patrol vessel must operate and how, in order to respond quickly to the critical event. In addition, the Port of Rotterdam uses the Cisco Edge Intelligence software to securely elaborate the data provided by patrol vessels through a multi-cloud dashboard. Once acquired and examined, the information can be used in decision-making process in order to improve logistics processes and operations. The drive-by system guarantees a secure solution for the acquisition and management of data for operators on board ships, personnel on land and people nearby ships in the event of a cyber attack. Therefore, the Port Authority of Rotterdam aims to equip the entire fleet of patrol vessels with the Edge Intelligence system to continue monitoring and analysing data in real time in order to help security and maintenance officers on interventions planning.

Fig. 7 Cisco Internet of Things Platform. Source: (Port of Rotterdam Authority, 2019)

Similarly, the partnership between the Port of Los Angeles and IBM Security has developed the Port Cyber Resilience Center (CRC) (IBM News Room, 2020). This multi-year agreement, with a value of USD 6,8 millions, aims to improve the cybersecurity of the port and to enhance the data sharing platform within the supply chain in the event of cyber threats. In this sense, IBM provides technology and skills that can help port authorities to protect information systems and improve the awareness and readiness of all stakeholders involved in logistical flows. Through the Cyber Resilience Center (CRC) (Figure 8), stakeholders have the ability to provide information on cyber threats and benefit from a broader and more structured intelligence system. In general, IBM Security provides the Port of Los Angeles with: (a) a team of IBM Security X-Force Threat Intelligence experts, capable of developing cyber threat management models; (b) an IBM Cloud Pak for security platform, which allow to analyse and integrate data and information in a more thorough and effective manner; (c) IBM Security SOAR, which permits users to code cyber threat response processes; (d) Security Intelligence and Operations Center (SIOC) to conduct real-time threat analysis, configuring defence activities according to the needs of each stakeholders.

Fig. 8 IBM Cyber Resilience Center. Source: (Port of Los Angeles, 2020)

5.2.2 Mobility

The mobility domain in port city logistics embraces, amongst others, trucks and vehicles equipped with sensors and information and communication technologies (ICTs) (Li et al., 2020; Caballini et al., 2020; Road Vehicles, 2019), bridges with automated control systems (Yang et al., 2020b; Nguyen et al., 2020) and real-time vehicle flow monitoring stations (Mondragon et al., 2012; Ibarra-Espinosa et al., 2020). As part of the Port of Valencia logistics innovation project, the Mediterranean Shipping Company (MSC) together with the Port Authority of Valencia and the Fundacion Valenciaport (FVP) aim to provide a better overview of vehicular traffic in the port (Valenciaport, 2020). Specifically, the trucks of MSC Spain have been equipped with IoT devices implemented by Traxens, in order to provide real-time monitoring of vehicle routes. By doing so, port authority has the opportunity to predict and manage any congestion of trucks at the gates. Therefore, the monitoring of pre and post transport vehicle flows offers improved fleet management and greater overall operational efficiency. The Municipality of Hamburg and Cisco have developed a smart and sustainable port-city Memorandum of Understanding (MoU) with the aim of implementing a series of innovative projects focused on transport, smart street lighting and parking involving partners such as AGT International, avodaq, InnoTec DATA, Philips, Streetline, T-Systems and Worldsensing (MoU, 2014). Since 2011, the Municipality of Hamburg and the Port Road Management Center (Figure 9) have installed over 300 sensors on roads and bridges in order to monitor and analyse traffic congestion (sia-partners, 2016). In this sense, traffic lights and street lighting have been adapted to provide real-time monitoring of temperature, humidity, air and noise pollution, and so on. Likewise, smart parking management aims to equip users with an App to directly provide information on the smartphones of vehicles and trucks drivers. These data allow policymakers to make well-informed and efficient decisions on the management of traffic flows in order to improve route management and reduce transit time and congestion in port logistics. Similarly, in order to digitally and effectively manage the flow of trucks in the port area, the Port Authority of Singapore uses the Flow-Through Gate that can process data of up to 700 trucks per hour (PSA). The system adopted allows drivers to verify their identity through a biometric fingerprint reader and, through Big Data technology, stores driver data, truck and load characteristics on a database. Likewise, the automation in bridge control system in the Port of Hamburg simplifies the management of ship flows (sia-partners, 2016). In this sense, bridges are set up to allow remote and real-time control, in order to open and close only when necessary. Location and speed identification via radar and drones enable the Port Road Management Center to improve travel time forecasts and optimize forward-looking investments in traffic flow management infrastructures. Furthermore, through RFID, the port authorities monitor in real time any movement of containers, checking the expected delivery and which port processes and infrastructures must be used for correct routes management. Therefore, data mining allows to optimize the path of the load, in order to minimize the processing times. Thanks to GPS and geo-referencing sensors, collection and shipping services can be managed automatically and flexibly in order to readjust incoming and outgoing schedules. At the same time, sensor technologies enable intelligent inspection that helps optimize physical inspectors' checks, reducing labor costs and time in customs.

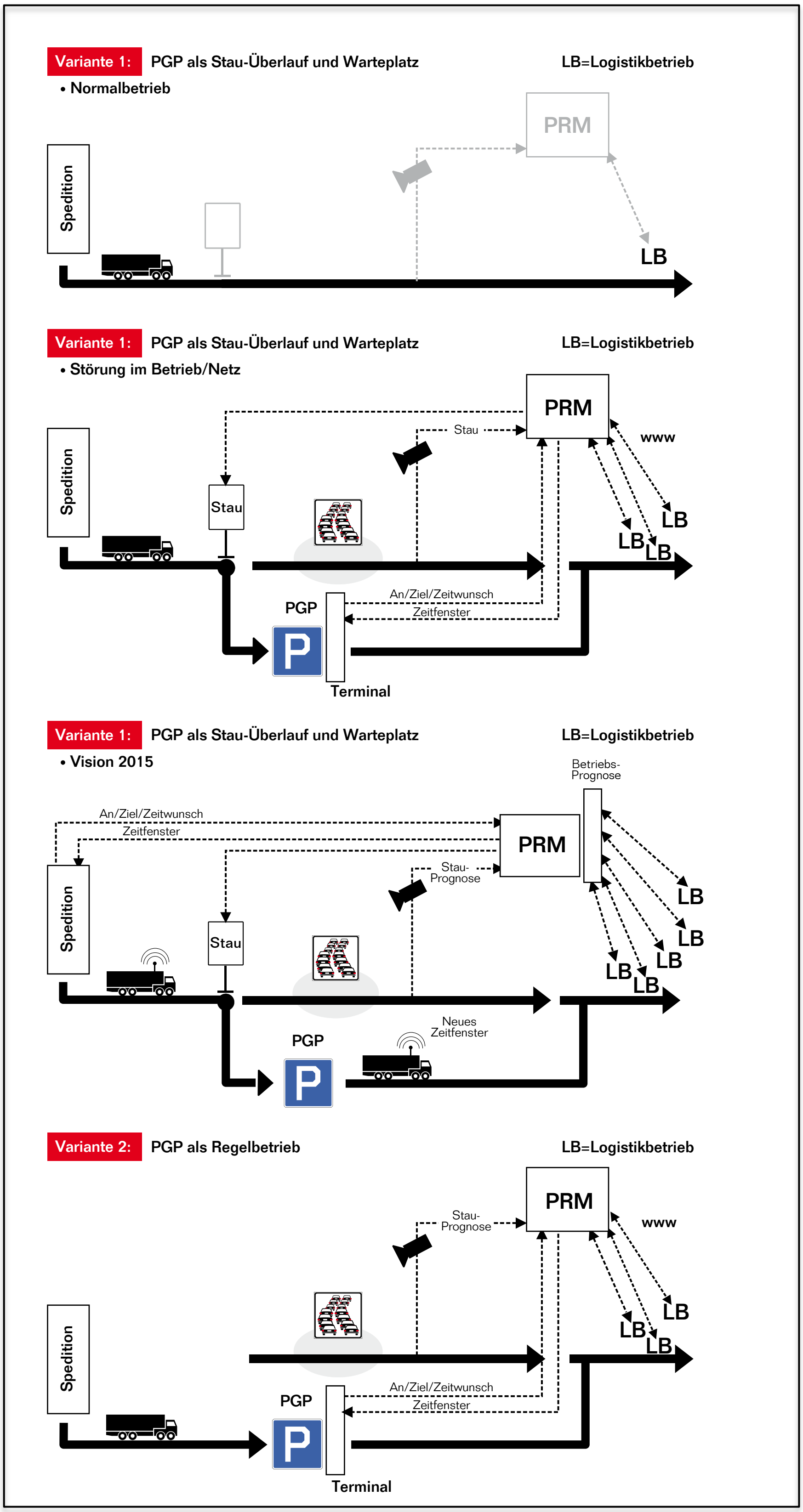

Fig. 9 Port Road Management. Source: (Hamburg Port Authority, 2010)

In the flow control strategy, the Port of Genoa uses the Zenatek Tracking System (ZTS), which is able to track, monitor and report in real time the goods arriving and departing (see, www.zenatek.com). Cisco Kinetic and IBM Watson IoT technologies equipped the Port of Rotterdam operators with the tools to predict the optimal weather conditions for a safe and controlled ship entry into port (Cisco, 2018). Specifically, the technology implemented includes: (a) a secure authentication and data management system; (b) data generator for decision-making process; (c) remote handling of sensors; (d) data management in an intuitive manner; (e) visualization of data and information via cloud computing platforms.

5.2.3 Environment

The environment domain in port cities includes for example waste management (Gobbi et al., 2019), energy efficiency (Wang et al., 2020a), renewable energy sources (Sifakis et al., 2020), water usage (Fang et al., 2021), material flows (Ioppolo et al., 2019; Tanguy et al., 2020), biodiversity preservation (Gkargkavouzi et al., 2019), land use organization (Witte et al., 2020), and atmospheric and acoustic pollution (Cafaro et al., 2018). For instance, the Port Authority of Rotterdam has implemented a wide range of digital technologies that contribute to making the port more environmentally and energetically sustainable (IBM, 2018). Specifically, the logistics infrastructures have been equipped with sensors, IoT platforms and Augmented Intelligence provided by IBM, capable of collecting, processing and providing data and information on the weather, on the availability of berths and other statistics. In this sense, the data processed on water and weather by the IBM Weather Company allows shipping companies to choose the best time with the most favourable conditions to enter the Port of Rotterdam (Fig. 10).

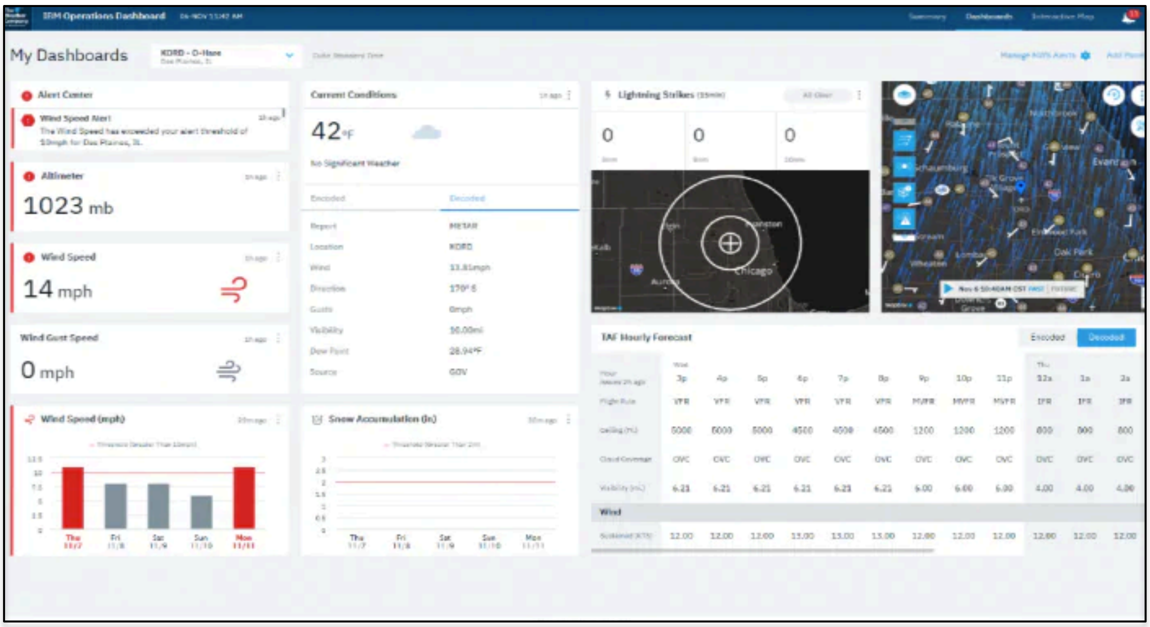

Fig. 10 IBM Weather Operations Dashboard. Source: (IBM, 2020)

The availability of data on air temperature, wind speed, humidity, the flow of tides and currents, etc. allow to elaborate forecasts on the visibility and the space of action (Široka et al., 2021). At the same time, predicting current and tidal conditions, wind direction and speed help port operators to determine the economic impact on fuel consumption and to ensure a safe entry of the ship into port (Solari et al., 2012). The system enabled by IBM Connecting Services and adopted by the Port of Rotterdam allows the development of a system of smart docks and buoys equipped with sensors that facilitate the transfer of data such as weather and water conditions (Port of Rotterdam, 2018). Similarly, the port of Antwerp in Belgium uses Virtual Reality (VR) to analyse and estimate the water level and the speed of currents inside the piers (Port of Antwerp, 2020). From an energy efficiency perspective, the port of Hamburg includes several sustainable initiatives such as smart street lighting, which, through motion detection sensors, is able to illuminate only the necessary zones, saving on energy costs (sia-partners, 2016). Furthermore, the warehouse management system equipped with detection sensors able to analyse the temperature, humidity and ventilation of containers increases the quality of the products and reduces damage to the cargo (Tejesh et al., 2018). In doing so, the smart management of energy consumption in the Port of Hamburg has led to annual savings of 12 thousands tons of CO_2, through an integrated system of smart meters capable of monitoring the average consumption rate and providing savings estimates following sustainable consumption paths.

5.2.4 Economy

The economic domain refers to the ability of port context to favour a path of sustainable and computerized growth through digital technologies (Zarzuelo et al., 2020). In this sense, the use of digital technologies has a profound effect on the economic sphere of maritime companies and logistics operators (Elzendoorn et al., 2009). For instance, the timely availability of quality industrial spare parts at an affordable prices represents a challenge for maritime companies, couriers, forwarders, warehouse personnel, and so on (Pombal et al., 2019). Therefore, smart and sustainable maintenance systems prolong the life cycles of resources and infrastructures, minimizing the eventuality of inconveniencies that negatively affect supply chain activities (Zhang et al., 2017). Specifically, they monitor and analyse the frequency of use and wear of port infrastructures in order to prevent damage, breakdowns or accidents, saving enormous repair, replacement and mitigation costs (Anusha et al., 2021). The port of Rotterdam has developed the Rotterdam Additive Manufacturing (RAMLAB) (Figure 11), a research and development facility that includes 30 partners engaged in the logistics industry (www.ramlab.com). In detail, RAMLAB represents the first laboratory in the field of maritime logistics that uses 3D printing to allow an inexpensive and timely large-scale availability of certified assembly parts (Ramlab, 2017). Furthermore, RAMLAB integrates IBM's IoT cognitive technology in order to automatically manage robotic welding arms for the creation of naval components such as propellers, at minimum production cost and maximum processing speed. Similarly, the port of Antwerp has implemented a 3D model in order to quickly identify when ships, vehicles and trucks are need maintenance (IBM, 2017).

Fig. 11 Rotterdam Additive Manufacturing (RAMLAB). Source: (Port of Rotterdam, 2016)

5.2.5 Telecommunications

The domain of telecommunications within logistics in port cities mainly refers to the development of the digital network infrastructure that allows an efficient and complex transfer of data and information between the various stakeholders involved (Sullivan et al., 2020). In this sense, the Chinese technology company Huawei intends to modernize the network infrastructure in the port of Piraeus in Greece (Piraeus Port Authority, 2018). In detail, the partnership aims to install a high-speed connection from 20Gbps up to 80Gbps, improving the use and security of several logistics services. In addition, Huawei is committed to providing consulting activities that encompass the design, installation and implementation of digital equipment, and training for network operators. Likewise, the Port of Tianjin has developed a partnership with Huawei in order to support sustainable and digital transformation (Port of Tianjin, 2020). For this purpose, Huawei provides technical support for the Information and Communication Technologies (ICTs) provided. The Port Authority of Valencia (PAV) uses the TradeLens Blockchain platform in collaboration with Maersk to improve the communication network between operators involved in the supply chain, including shipping companies, port and terminal personnel, customs authorities, etc. (Valenciaport, 2018).

5.2.6 Government

The integrated and holistic involvement of logistics operators requires a bottom-up approach in the governance of port cities (Monios, 2019; Chandra et al., 2017). Consequently, digital technologies for collecting, monitoring, integrating and analysing real-time environmental, social, economic and technological performance in logistics transform shipping companies, couriers, freight forwarders, date and terminal personnel, warehouse workers, patrol vessels, truck and vehicles, etc. in active and dynamic participants able to contribute to port management (Senyo et al., 2021). For instance, the port of Singapore uses the PORTNET framework (Figure 12) to share data and information between stakeholders in order to synchronize logistic operations (PORTNET, 2020). Hence, the Computer Integrated Terminal Operations System represents the brain of the port of Singapore able to coordinate operations and infrastructures in real-time.

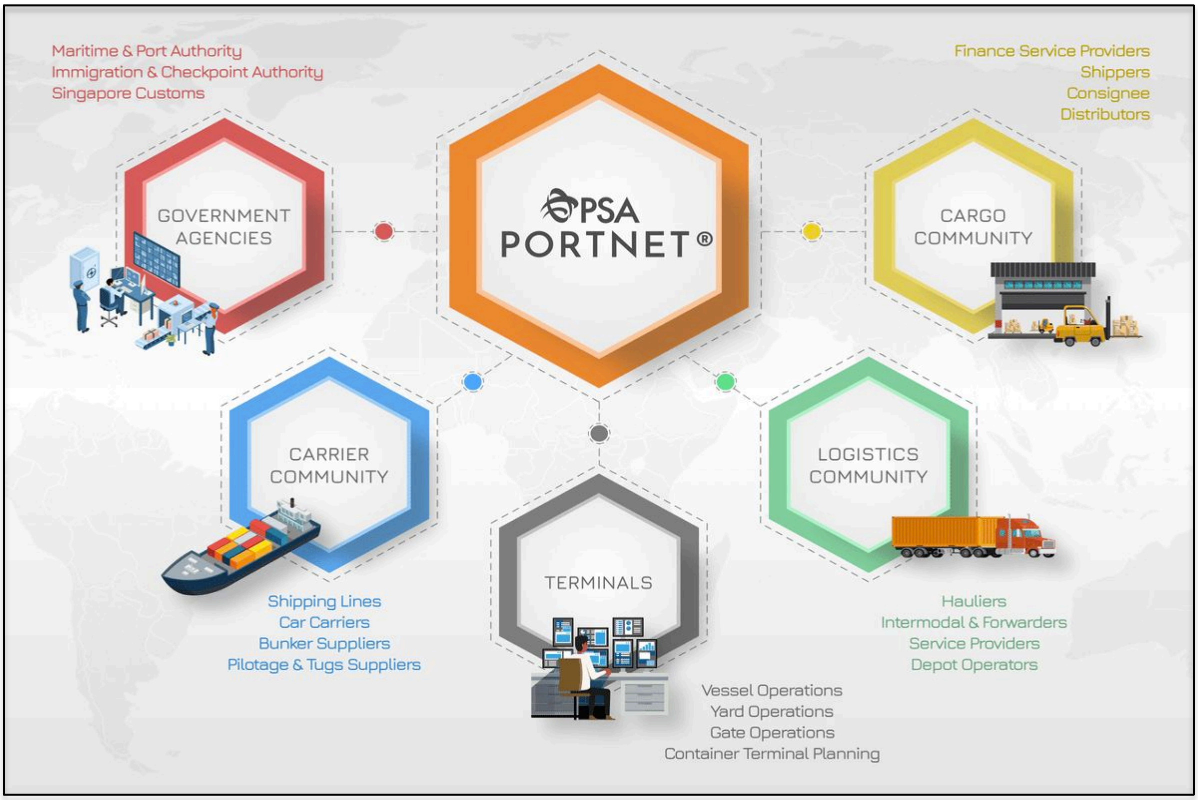

Fig. 12 Port of Singapore PORTNET framework. Source: (PORTNET, 2020)

5.2.7 Community

The community domain includes actions aimed at developing a sustainable and digitalized port context, improving operators' digital literacy and ensuring gender equality in terms of pay and office positions and a safe and healthy work environment (Brooks et al., 2016; Komugabe-Dixson et al., 2019). Ports support local, regional and national communities through job creation (Wang et al., 2019) and in freight transport (Winkler et al., 2020). Furthermore, they collaborate with municipal authorities, non-profit organizations and associations to provide training courses, environmental awareness initiatives and coordination activities for urban planning (Bjerkan et al., 2021). In 2016, the Port of Dover (UK) was awarded as Port of the Year at the national transport awards, especially for its community initiatives for the South East of England (Port of Dover, 2016). In detail, the community strategy of the Port of Dover includes: (a) partnerships with non-profit organizations; (b) allocation of funds for inhabitants with difficulties and special needs; (c) environmental education projects; (d) adoption of the "Port Marine Safe Code" for logistic operations, and; (e) the respect for the ethical principle in decision-making processes.

5.3 Goals

5.3.1 Sustainable Development

Following the triple bottom line (TPL) approach, sustainable development in port cities mainly embraces the economic, social and environmental aspects of maritime logistics (Lam et al., 2019). In this sense, the definition developed by the Brundtland Commission provides an integrated and holistic vision of the aspects linked to economic growth, social cohesion and environmental preservation (Brundtland, 1987). Subsequently, the aspects emphasized by the Brundtland Commission have been discussed, implemented and categorized within the United Nations 2030 Agenda on Sustainable Development, where the 17 goals and 169 targets are mainly addressed to local authorities, citizens, and businesses (UN, 2015). Specifically, the scheme developed by the United Nations aims to address a wide range of social, environmental and economic issues affecting the logistics of port cities such as responsible models of production and consumption, air and noise pollution, urban planning, the conservation of seas and oceans and so on. In sum, port logistics plays a crucial role in achieving the various sustainability goals and targets (Wang et al., 2020b).

First, port logistics can make a significant contribution to SDG 14, focused on the preservation of the oceans, seas and marine resources (Cormier et al., 2017; Virto, 2018). At the same time, in order to progressively reduce the anthropogenic impacts on oceans, seas and marine resources, SDG 12 on responsible production and consumption underlines the need for a paradigm shift of logistic models is required through the use of data collection, monitoring and analysis technologies (Omer et al., 2020). However, the involvement of the logistics sector goes beyond SDGs 12 and 14, such as: (a) the reduction of air and noise pollution in port areas, which undermines the health and well-being of the inhabitants specified in SDG 3; (b) ensure decent and safe working conditions, as specified in the SDG 8, for logistics operators such as warehouse workers, shippers, couriers, drivers, gate and terminal staff, etc.; (c) the development of digital technologies and logistic infrastructures capable of mitigating the impacts of vehicular and materials flows, as indicated in SDG 9; (d) the planning of urban settlements and resilient communities covered in SDG 11, and; (e) the preservation of biodiversity, described in SDG 15.

Therefore, while the SDGs that characterize the 2030 Agenda define a global and exhaustive scheme for the sustainable development in terms of port logistics, the development of digital and sustainable logistics contributes significantly to compliance with the goals and targets of the Agenda 2030 on Sustainable Development (Di Vaio et al., 2020). However, given the growing importance of the port logistics sector in achieving the goals and targets on sustainable development, the lack of scientific and practical contributions on SDGs in port logistics should be noted (Fleming et al., 2017; Sciberras et al., 2018). Some scholars have argued for this lack of attention to the difficulty on the part of the International Maritime Organization (IMO) to apply and integrate the SDGs in the maritime logistics sector, as none of the goals directly focuses on the maritime logistics sector (Sciberras et al., 2018).

Furthermore, although some of the contributions in the literature focus mainly on SDG 14 (Islam et al., 2018, Okafor-Yarwood, 2019), there is a lack of an in-depth and comprehensive study on all 17 SDGs of sustainable development applied in the port logistics sector. In this sense, a holistic and general vision of sustainable development in port city logistics is necessary to avoid simplistic and reductive approaches that compromise the usefulness of the sustainable development goals (Ntona et al., 2018, Singh et al., 2018).

5.3.2 Digitalisation

The perspective of implementing a digitized and coordinated network of fixed and mobile technological devices (e.g. sensors, monitoring stations, drones, radars, cameras, antennas, poles, traffic lights, smartphones, etc.) that facilitate the circularity of large amount of data and information has provided new opportunities for port managers, urban administrators, planners, entrepreneurs, couriers, and shipping companies to plan and develop smart and sustainable logistics processes and operations (Zarzuelo et al., 2020; Hua et al., 2020).

The development of digital technologies according to centralized and holistic approaches highlights several challenges for policy makers regarding data management in order to ensure a certain standard of quality, robustness, communicability, integration and security (López-Bermúdez et al., 2020). In this regard, port authorities, municipalities, departments, divisions and agencies of port cities collaborate with technological partners (e.g., Cisco, Huawei, IBM and Ericsson) in order to elaborate multi-year contracts for the supply and assistance of technological services (sia-partners, 2016). However, stakeholders are very reluctant to share data and information about their processes and operations with a central authority (Zheng et al., 2020). In this regard, the port cities support economic, technological and regulatory efforts in order to provide a reliable and secure data management system, capable of sharing only the data and information relevant to stakeholders through encrypted languages and guaranteed by confidentiality agreements (Meng et al., 2021).

Furthermore, the digitization of logistics processes requires not only a massive and diversified use of cutting-edge technologies, but also a paradigm shift in the structure of urban and industrial processes, which requires time, economic and technological investments and political and community availability (Urbanyi-Popiołek, 2019). Therefore, in order to collect input and feedback useful for this industrial and urban transformation, it is essential that all the parties involved believe and see the benefits of the paradigm shift. Therefore, it is crucial to identify and define in detail the main motivation and need that digital technology must satisfy. To do this, a participatory and inclusive approach is necessary in order to include all the stakeholders involved in the transformation of digital logistics such as couriers, freight forwarders, shipping companies, road and rail transport companies, customs authorities, warehouse workers, industrial companies, transport, logistic service companies, citizens, research centres, financial institutions, etc. (Monios, 2019). Furthermore, a correct application of digital technologies such as monitoring stations, sensors, tracking systems, video surveillance cameras, networks, etc. requires, for example, the adoption of standards and protocols in order to guarantee the transparency of data and information on performance between stakeholders (Caldeirinha et al., 2020).

Therefore, the digitalization of logistic processes aims to transform port cities into innovative and multifunctional ecosystems by disseminating mobile and fixed technological devices capable of collecting, monitoring, analysing and interpreting a wide range of real-time data and information in an efficient manner (Senarak, 2020).

6. Future Perspective of Urban Metabolism Circularity: Sensor City

Few (2006) in his book 'Information Dashboard Design: The Effective Visual Communication of Data' defines the dashboard as a visual, consolidated and organized display on a single screen of the most important information needed to monitor, analyse and achieve one or more urban objectives. Similarly, Kitchin (2014) explains urban dashboards as digital, physical or mixed interfaces that allow users to actively or passively interact in urban data monitoring and management in order to improve understanding of urban systems. Kitchin & McArdle (2016) and Petit & Leao (2017) describe urban dashboards as platforms that use dynamic and interactive graphic interfaces, maps, 3D models, augmented reality, bar charts, and so on, to support urban decision-making with the aim of monitoring, analysing and interpreting performance and trends of cities. Therefore, the sensor city is generally accepted as a digital platform where users are completely immersed.

Given the growing importance of sensor city solutions in the world panorama, technology giant companies (e.g., Huawei, Ericsson, Microsoft, Oracle, Alibaba, Deutsche Telekom, Samsung) are involved in numerous urban technological projects in order to provide platforms, products and services in line with the necessary paradigm of shift (Yigitcanlar et al., 2020). Thus, sensor cities aim to involve citizens and companies in the process of planning, monitoring, and analysing of urban processes and raising awareness and comprehension on environmental, social, and economic issues (Hasegawa et al., 2019; Yamagata et al., 2020). Table A1 in Appendix presents some examples of cities equipped with real-time monitoring stations and sensors that analyse and collect urban performance.

Urban contexts using IoT and/or ICT platforms require more initial efforts due to the assembly and maintenance of the infrastructure, in order to adapt it to increasingly complex urban scenarios (Sharma et al., 2020; Mocnej et al., 2021). In detail, it is a matter of integrating devices that are: (a) Heterogeneous, capable of generating different types of data; (b) Powered by different energy sources, such as battery or renewable energy; (c) Dynamic and flexible, capable of analysing constantly changing urban scenarios, and; (d) Unpredictable, in the sense that technological applications can provide conflicting results by analysing the same data, as they use different protocols and standards.

The significant costs of designing, installing, and maintaining monitor stations and sensor technologies represent a barrier to entry for smaller cities or those located in less development regions (Castell et al., 2017; Yigitcanlar et al., 2008). The success of an urban sensor strategy depends essentially on the economic, social and environmental characteristics of the urban context taken into consideration together with organizational, ethical and trans-disciplinary factors of the actors involved (Karvonen et al., 2019).

The sensor city framework is illustrated in Figure 13. In detail, the operational phases, integrated in a holistic perspective of the urban context are divided into planning, sensing, collecting, processing and analysis of urban data and results.

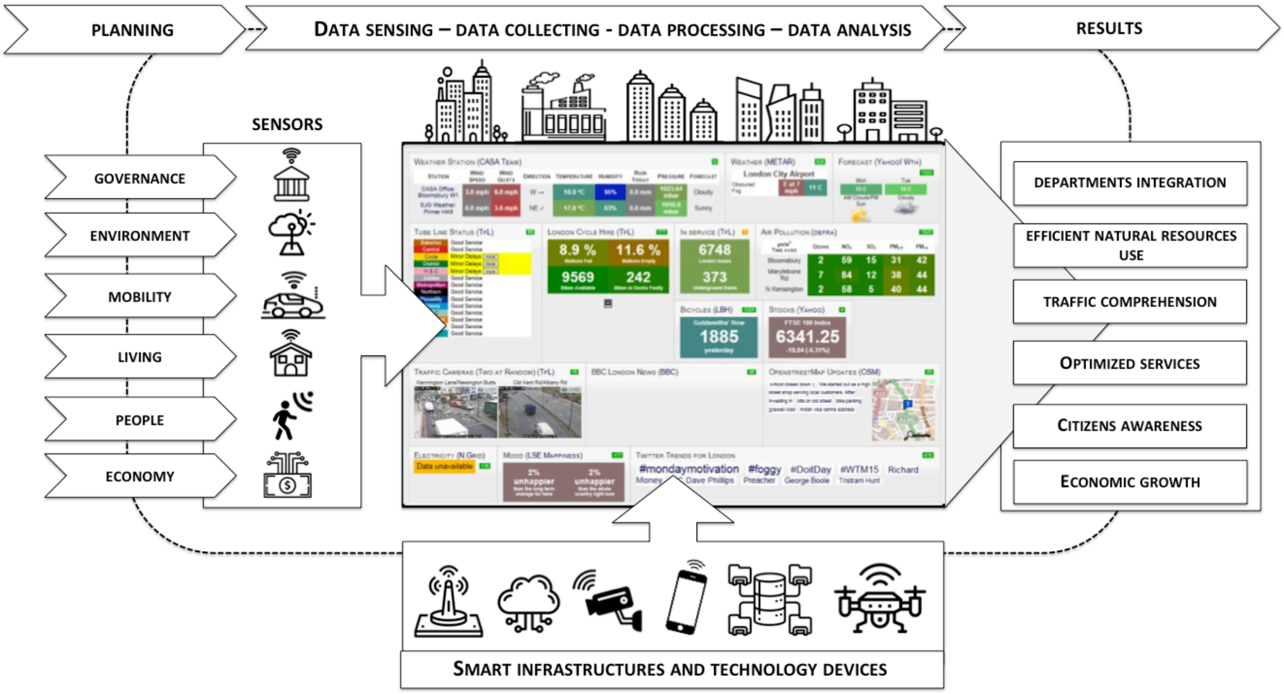

Fig. 13 Sensor city framework

In Phase 1, or *planning*, the role of ICTs is highlighted, which allow citizens to participate in the decision-making process and to enhance systemic collaboration between stakeholders involved, contributing significantly to greater comprehension, transparency and accountability (Ioppolo et al., 2016; Wijs et al., 2016; Gil et al., 2019). Hence, planning activities through smart solutions permits a holistic and integrated approach of the various urban dimensions (e.g., governance, economy, environment, mobility, living, and people), reducing costs and time of the bureaucratic collaborations between departments and improving quality and efficiency of urban services (Ruhlandt, 2018).

The Digital Single Market strategy adopted by the European Commission (2015) represents one of the fundamental pillars of the policies for creating a digital single environment. Indeed, the strategy aims to ensure a better, secure and uniform access for citizens to digital networks in order to improve technological knowledge and encourage greater social inclusion.

The *governance* dimension highlights the spread of social media (e.g., Facebook, Twitter, Instagram) and other data sharing platforms that allow increasingly integrated and structured communications between stakeholders (Johnson et al., 2020). Thus, by adopting a bottom-up approach, these feedbacks generation, sharing and management tools transform citizens, companies, local authorities, and so on, into active participants in the governance of sensor cities (Yeh, 2017; Axelsson et al., 2018; Cardullo et al., 2018).

The *environmental* dimension involves various aspects of urban context such as:

- Waste management, capable of providing real-time type and quantity of waste via cloud solutions, to optimize time and resources (Aazam et al., 2016; Ahad et al., 2020). With the development of new technology devices, electronic waste (e-waste) represents an environmental and health challenge due to its difficult disposal and potential impacts on the environment.

- Energy efficiency, which refers to all technologies able to reduce energy consumption. For example, street lighting networks equipped with sensors and public and private buildings equipped with real-time consumption monitoring system represent the forward-looking urban infrastructures needed to manage urban activities efficiently (Shahidehpour et al., 2018; Chui et al., 2018; Ghiani et al., 2018).
- Renewable energy sources, such as solar, wind, thermal and biogas, which represent a sustainable and efficient alternative to fossil fuels, capable of guaranteeing a stabilization of energy prices and a sustainable source of energy supply for urban processes (e.g., public transport, heating of public and private buildings) (Lund et al., 2014; Strielkowski et al., 2019).
- Water management, which includes solutions capable of providing real-time data on the consumption and quality of water distribution system, fundamental for the sustainability and efficiency of the urban system (Gourbesville et al., 2018).
- Material flows, those underline the exchange and transformation of resources (e.g., raw materials, by-products, waste) between various interested actors (Kennedy et al., 2007).
- Biodiversity conservation, which includes revitalization actions for abandoned urban and industrial areas and the safeguarding of green and urban spaces (Morimoto, 2010).
- Land use optimization, as support for urban agriculture and infrastructure (Kim et al., 2018).
- Air and noise pollution prevention, to reduce pollutant emissions through ICTs, sensors, and real-time monitoring stations, capable of providing high-definition videos and images to check environmental quality (Peng et al., 2017).

The *mobility* dimension includes, amongst others, smart and sustainable public transport system, availability of urban infrastructure suitable for autonomous vehicles, car sharing stations for electric vehicles and ICTs relating to traffic and road monitoring (De et al., 2019; Cugurullo et al., 2020; Acheampong et al., 2019; Arndt et al., 2013).

The aspects related to the *living* dimension include actions to improve the use of cultural and entertainment facilities (e.g., libraries, museums, schools, public parks, sport facilities) (Macke et al., 2019).

The *people* dimension includes policies aimed at promoting a 'sustainable' community, improving digital literacy, providing various assistance programs for citizens with special needs and quality healthcare system, ensuring gender equality in terms of pay and office positions and finally, safe and healthy work environments, and so on (Syed et al., 2019).

The *economic* dimension refers to the ability of the urban context to favour a path of growth through technological innovation, entrepreneurship and sustainability, attracting the most innovative companies, start-ups and talents, and capable of promoting a digitalized and collaborative development (Kumar et al., 2017).

In Phase 2, with the objective of *sensing*, *collecting*, *processing* and *analysing urban data*, the Chinese telecom company Huawei, for example, has developed 'Smart City Solution', a platform used in over 160 cities in 40 countries in Asia and Europe, capable of analysing large volume of real-time urban data and providing to policymakers a method of predictive analysis of future urban scenarios (Figure 14). Specifically, Lanzhou New Area represents the first new state-level development area in northwest China which, through the support of Huawei's network, was able to build the nation's first governmental IoT and wireless sensors network that integrates both broadband and narrowband communications, integrating 31 departments (e.g., public safety, finance, energy, transport, healthcare, education) with 45 eLTE stations. The program aims to improve the quality of life by optimizing urban resources in a smart and sustainable manner (Huawei Digital Platform, 2020).

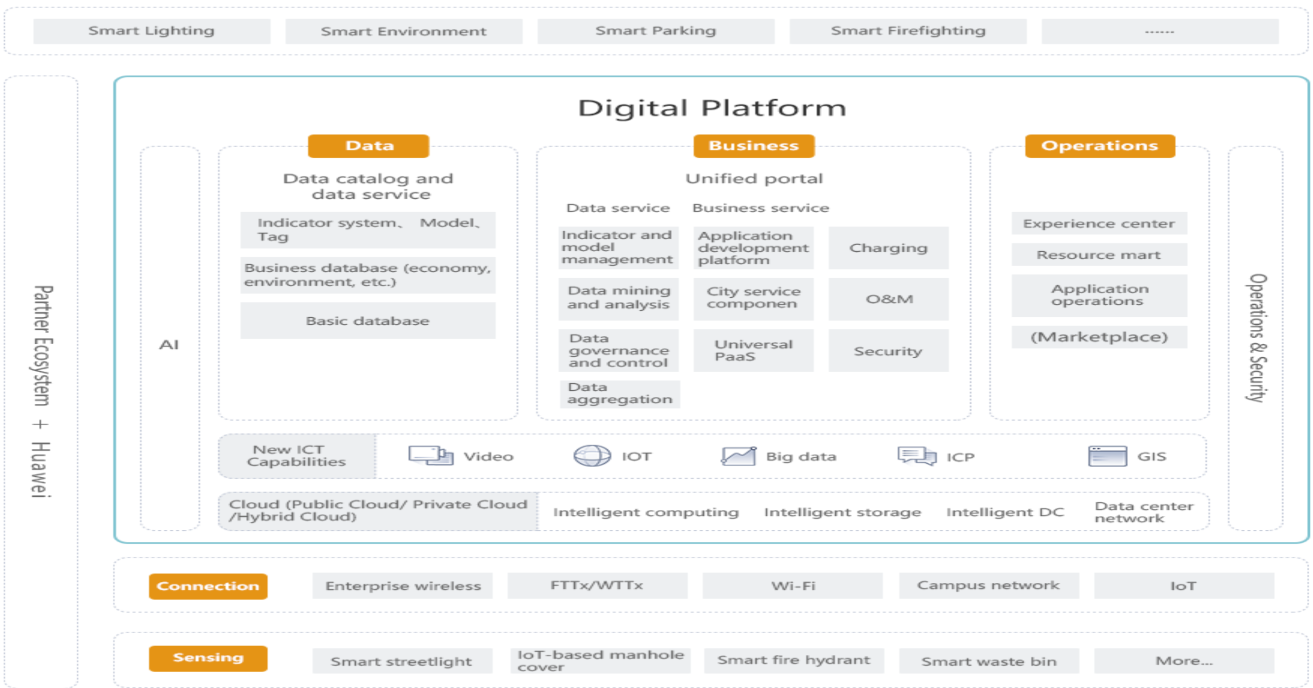

Fig. 14 Digital Platform. Source: Huawei Digital Platform (2020)

Similarly, Cisco has developed the 'Cisco Kinetic for Cities' framework, an open and easy-to-use urban data sharing platform that combines data provided by sensors, applications and other third-party devices to create a dynamic sensor city infrastructure, encouraging the exchange of innovative urban initiatives between policymakers, companies and citizens (Figure 15) (Cisco Kinetic for Cities, 2020).

Fig. 15 Source: Cisco Smart + Connected Digital Platform (2020)

At the same time, Alibaba has developed the 'City Brain' program that has also become a useful tool for city managers, providing a holistic dashboard that can improve the perception of urban data and real-time processing capacity (Zhang et al., 2019b). Figure 16 shows the real-time detection and analysis platform for city events. By integrating the data from the surveillance rooms, it is possible to coordinate traffic lights to give priority passage to response vehicles (e.g., police, fire-fighters, rescue and other vehicles) in case of emergency. Likewise, the program has been launched in several Chinese cities such as Hangzhou, Shanghai, Chongqing, Suzhou, Haikou, Beijing, Chengdu, Quzhou, and Jiaxing. Projects as CityBrain highlight the continuous interaction between local authorities and technology companies in managing urban governance. In fact, the Chinese platforms are largely owned by national technology companies (Caprotti et al., 2020).

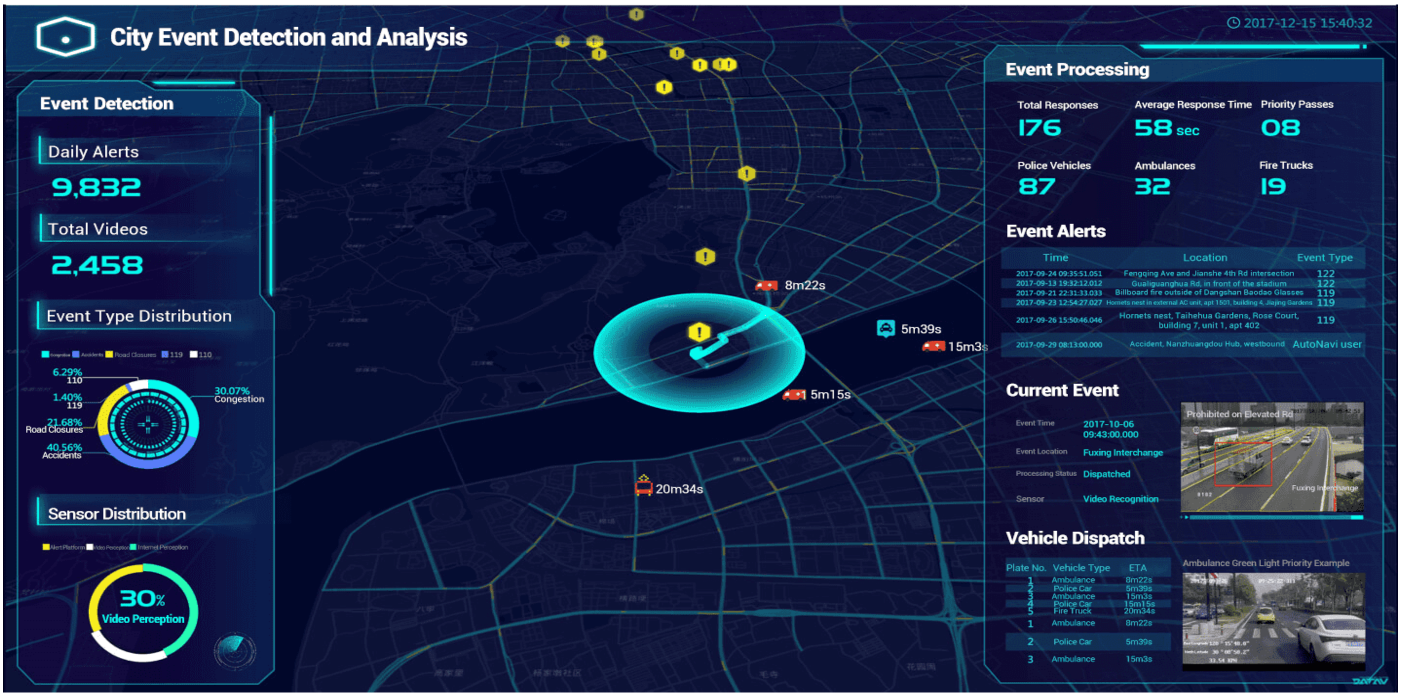

Fig. 16 Alibaba City Event detection and smart processing, derived from (Alibaba, 2020)

Barcelona has changed its sensor city approach from top-down to bottom-up, involving its citizens in participating in innovative urban projects. For example, the Smart Citizen Kit is a dashboard that collects data on the environmental such as air composition, temperature, light intensity, sound levels and humidity through sensors and ICTs (Smart Citizen Kit, 2020). The data collected in real-time are sent via Wi-Fi to an open data platform and are used to create maps that display environmental conditions, equipping public and private stakeholders with urban data in order to develop and/or improve services for citizens (Camprodon et al., 2019). Telefonica—through the Valencia Smart City Project—aims to transform the city of Valencia into an intelligent ecosystem and fully connected via 350 sensors, allowing the management of public resources through a single ICT platform and improving several urban areas such as transport, energy, efficiency and environmental services. The city of Santander has installed around 20,000 parking sensors in the streets, introducing intelligent waste containers capable of monitoring and measuring air pollution, rainfall, and traffic density. Through the integration and interpretation of the corresponding data, the Santander municipal administration optimizes waste truck routes to save staff and fuel costs, or controls the irrigation of city parks to save water (Gutiérrez Bayo, 2016).

Deutsche Telekom have implemented similar dashboard, equipping urban physical object (e.g., street lamps, bins, parking lots, traffic lights) with software, sensors and connectivity systems integrated into a shared network. In this sense, the collection, monitoring, analysis and interpretation of urban data allow the implementation of innovative service and business models (Figure 17).

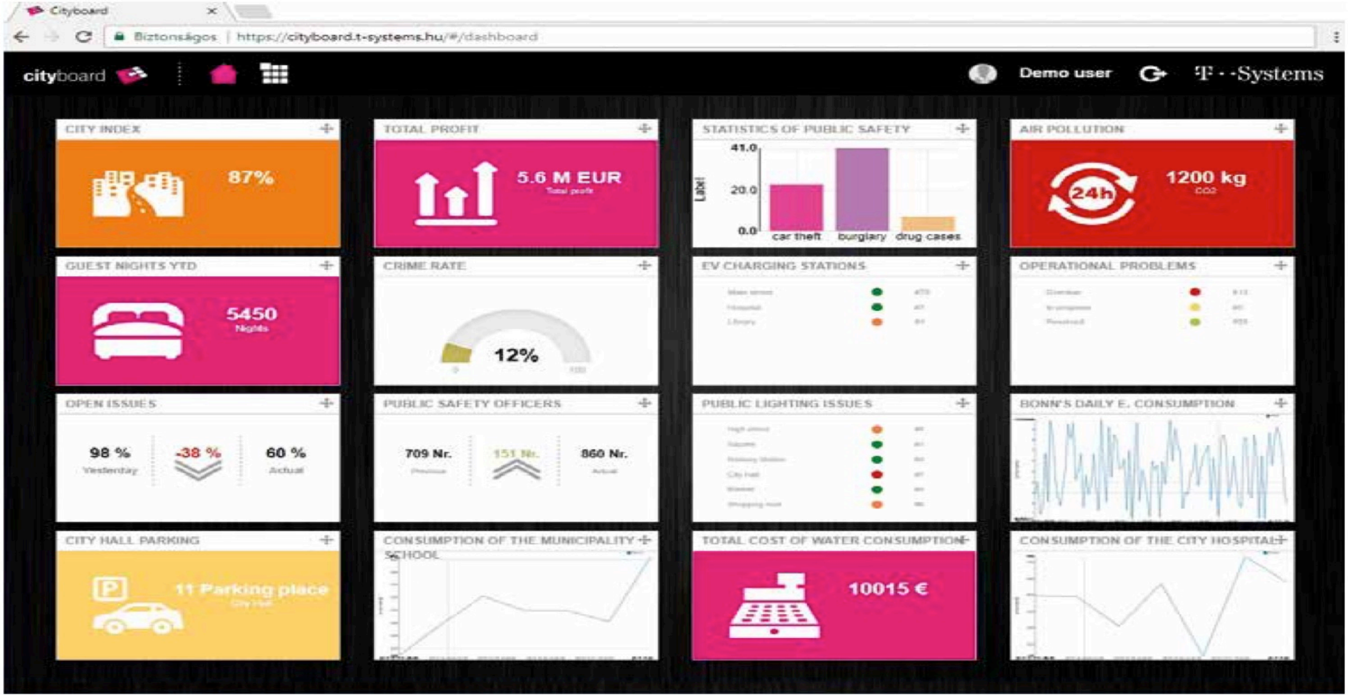

Fig. 17 Smart City Dashboard developed by Deutsche Telekom for Hungary subsidiary, derived from (www.t-system.hu)

In 2018, Deutsche Telekom and the city of Hamburg implemented around 11,000 parking spaces equipped with sensors that can provide the current availability status to users via the app (Deutsche Telekom, 2020). The local authorities of Gelsenkirchen (Germany) have decided to collaborate with Huawei and GELSEN-NET in order to implement a new open and shared urban governance system, developing an ICT infrastructure capable of integrating key data to improve the efficiency of the public services and the accuracy of the decision-making process. In particular, the 'Safe City' program uses Huawei's extensive wired and wireless broadband network and the IoT that connects industrial parks, hospitals, schools, pedestrian areas and urban centers, creating a sustainable ICT ecosystem. As part of the T-City project in Friedrichshafen (Germany), Deutsche Telekom has partnered with Alcatel-Lucent to provide hardware solutions and network devices for T-City. Specifically, Deutsche Telekom has developed over 40 pilot projects in several categories such as mobility, research, tourism, culture, health, and employment.

The LuxTurrim5G ecosystem in Espoo (Finland) aims to transform the Kera area into a sustainable and digitized urban neighbourhood, involving Nokia and several partners in order to create a multitude of urban digital services. The LuxTurrim5G platform is able to collect, store, manage and share large amounts of urban data and solutions in a safe and efficient way between local authorities, companies and citizens. Specifically, the network developed by Nokia includes, among other things, over 50 Wi-Fi devices, 75 cameras, 49 different sensors that monitor air quality, climate, temperature, road surface conditions as well as CO_2 levels, 9 radar devices, 7 information screens, a charging station for electric vehicles and a charging and landing station for drones.

Oracle through a partnership with the Indian state of Maharashtra has implemented a platform to design, develop and analyse government-to-citizen and smart-business government services across the state. Maharashtra also aims to connect all its 113 million residents via fiber, including those in the more than 300 cities of Maharashtra and its 29,000 villages. Dallas has chosen to collaborate with Ericsson to implement an advanced traffic management system through a dashboard capable of monitoring, managing, analysing and aggregating different data in real-time from traffic sensors and cameras to dynamically control the traffic lights. The goal of the city is to have an intuitive and shared analysis tool capable of integrating data from the various departments and agencies.

According to the report 'The future of street lighting', street lighting represents the main part (about 40%) of a city's overall electricity costs. In this sense, the replacement of conventional lamps with LED bulbs can reduce energy consumption by up to 80% when using a centralized management system. For example, intelligent lighting platform of Cisco and Sensity in Kansas transforms each lamppost into a sensor connected to a broadband wireless network, creating a true interconnected lighting network capable of collecting real-time data such as intelligent parking systems, electricity consumption, or air quality level. In this sense, the smart pole developed by Deutsche Telekom and Nokia represents a paradigm shift in the use of lighting poles as it goes beyond simple urban lighting and constitutes an essential component of the infrastructure of sensor cities (Figure 18).

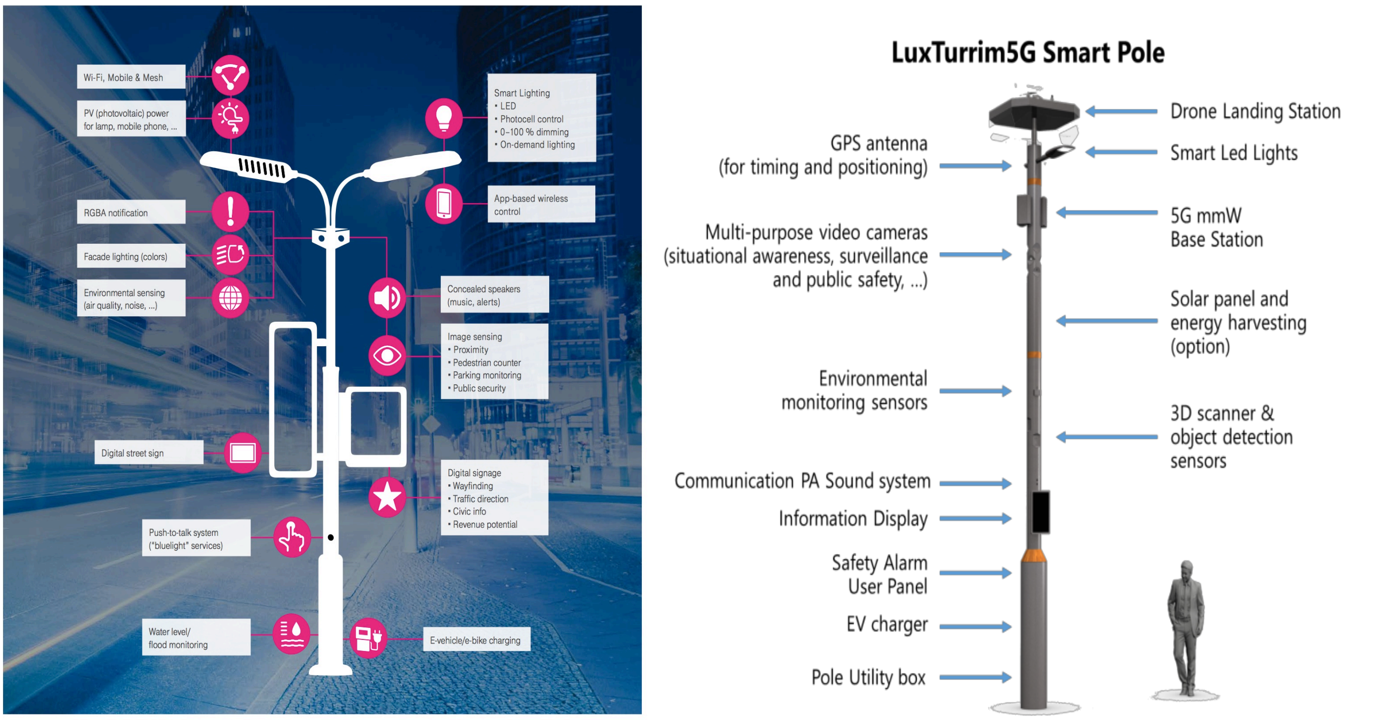

Fig. 18 Smart Street Lighting models developed by Deutsche Telekom and Nokia, derived from (Deutsche Telekom, 2020; LuxTurrim5G Smart Pole, 2020)

The Hamburg Port Authority (HPA) through Cisco systems has developed sensors that monitor the use of resources (e.g., trucks, cranes, means of transport, ships) and infrastructures (e.g., roads, parking lots, storage warehouses) in one of the busiest and most important ports in

Europe. In this sense, modernization through IoT technological innovation allows the Port Road Management Center to plan future investments in the traffic infrastructure, optimizing the flow of traffic and minimizing the externalities of the port on the inhabitants of the city.

Ericsson aims to make Stockholm the smartest city in the world by 2040. With the water Monitoring Network project, Ericsson has the ability to design and implement a real-time water quality-monitoring network using an IoT sensor system located in the Stockholm water system. In addition, big data analytics are used that can analyse the data produced by the sensors and provide more information on changes in water quality such as pH and temperature.

In many cases, small towns do not need sophisticated public transportation solutions. In this sense, the challenge is to combine the departure time of buses, subways, railways, and so on, with data from traffic jams and road works on highways, showing the best alternative connections. As a partner of the Kooperation Östliches Ruhrgebiet, Deutsche Telekom helps to connect local public transport in the German state of North Rhine-Westphalia. In this regard, Deutsche Telekom's strategy allows not only meeting the needs of passengers in terms of both transparency in information (e.g., timetables, delays) and efficiency, sharing the same platform for multiple tasks. In Croatia, Deutsche Telekom's subsidiary, Hrvatski Telekom, has developed an electric vehicle charging network of 145 charging points in 101 charging stations in 70 cities. The project also integrates an ICT infrastructure that helps users to book and pay for vehicles top-ups and receive real-time availability information.

The final phase concerning the results explaining the decisive role of sensor solutions in terms of implementation of innovative urban processes (e.g., efficient use of natural resources, cross departmental integration, real-monitoring of traffic congestion and energy consumption, smart management of infrastructures), in order to strategically improve the contribution of sensor cities to disruptive urban development. Consequently, the optimization of Quality of Experience (QoE) and Quality of Services (QoS) has become a crucial aspect in the implementation of urban services and processes (Alvarez et al., 2015). Particularly, QoE represents an evaluation of human experience when interact with technology solutions and stakeholders in a given context. Therefore, a detailed analysis of the QoE should consider several actors interacting with each other at different levels (environmental, social, economic, technological) and with different goals. To do this, it is necessary to define the main interactions between citizens, companies, local authorities, social organizations, and so on. In sum, some QoE aspects related to sensor city are listed in Table 6.

Table 6. Impact of quality of experience on sensor city, derived from (Alvarez et al., 2015)

	Economic, Social and Privacy Implications	**E-government**	**Health and Assisted Living**	**Intelligent Transportation Systems**	**Smart Grids, Energy Efficiency, and Environment**
Quality of Experience	Usability	Usability	Usability	Usability	Usefulness
	Personalization	Personalization	Availability	Usefulness	Accessibility
	Transparency	Transparency	Personalization	Effectiveness	Personalization
			Effectiveness	Accessibility	
			Accessibility	Efficiency	
			Efficiency		

In this regard, the challenge for policymakers will be the widespread use of several tools, such as devices, platforms, algorithms, and networks, to access, share and integrate the largest number and type of urban data. The big data evolution process requires significant data gathering, highly specialized personnel, and infrastructures owned by different municipalities, agencies, corporations, and private companies (Bettencourt, 2014). This attention of ICT leads urbanist mark Swilling to describe the sensor city as a form of algorithmic urbanism (Allen et al., 2016). In this sense, concepts, such as big data analysis, ICT, sensors, real-time monitoring systems, smart infrastructures, IoT, represent necessary but not sufficient solutions (Hollands, 2015; Kitchin, 2014; Yigitcanlar et al., 2019a). The reconfiguration of the urban system expresses the need to integrate the environmental, social, economic dimensions of smart technologies into an integrated, efficient, and computerized urban context (Shahrokni et al., 2015; Bifulco et al., 2016; Bibri, 2019).

7. Discussion

The digitalisation of the circularity of urban metabolism integrates the traditional aspects of urban metabolism with the need to computerise urban processes to better address the social, environmental, economic and technological challenges of the growing urbanization and datafication of urban contexts (Fratini et al., 2019). Therefore, the digital technologies identified and analysed in Section 3.1 as real-time monitoring stations, tracking sensors, digital surveillance cameras, and so on (D'Amico et al., 2021a) support the existing theoretical literature on the role of 'facilitator' of technology in the improvement of urban metabolism processes and operations (Zarzuelo et al., 2020).

In this regard, the international standards identified and investigated in Section 3.2 are in line with the literature review elaborated by Bibri (2021) on data-driven smart sustainable cities of the future, providing a detailed and comprehensive overview of urbanism initiatives based on sensors, Big Data, Internet of Things (IoT), cloud computing, blockchain, and so on. In this sense, the theoretical literature confirms the importance accorded to the concept of smart urban metabolism within cities (Shahrokni et al., 2015). At the same time, the "Circular Resource Efficiency Management Framework" used in the testing phase (Section 4) demonstrates that the planning, implementation, development and redefinition of smart urban metabolism initiatives is a complex issue that requires systemic thinking in which economic, social, environmental and technological dimensions play a decisive role. In this regard, the enabling factors, domains and goals of the circularity of urban metabolism within the logistics of port cities specified in Section 5 argue that the context in which cities operate is much more layered and intertwined that simply stating that the four dimensions (economic, social, environmental and technological) are fundamental and should be followed. Therefore, we do not argue that these criticalities have not been highlighted and addressed previously in the literature, but we argue that our Thesis holistically shows in an integrated and holistic framework the enabling factors, domains and goals that exist and provides useful contribution to improve understanding and awareness of smart and sustainable urban metabolism transition.

Firstly, most of the current theoretical literature on the smart urban metabolism emphasises the determining role of a multi-level and engaging governance (Flynn et al., 2019). Fratini et al. (2019) and Christensen (2021) explain that multilevel urban governance characterised by proactive involvement of stakeholders through co-design and decentralised monitoring initiatives is crucial for an effective and circular allocation of responsibilities between the various urban processes and operations. In this regard, the circular city of Prato embraces a multitude of utilities such as Società Publiacqua (water management), Edilizia Pubblica Pratese S.p.A (construction), Interporto della Toscana Centrale S.p.A (logistics), Programma Ambiente S.r.l (environment), etc. (Municipality of Prato, 2020). Similarly, The Hague has adopted a bottom-up approach, including ministries, universities and social organisations (European Union, 2020c). Among the enabling factors identified, the framework on the circularity of urban metabolism within port logistics (Fig. 5) underlines these aspects in Section 5.1.1 "Ecosystem" and 5.1.2 "Internal Organization", emphasizing the proactive role and organizational flexibility of a wide range of actors such as port managers, planners, administrators, entrepreneurs, citizen, couriers, shipping companies, start-ups, students, port authorities, road and rail transport companies, technology companies, financial institutions, and so on. Furthermore, the 5.2.6 “Government” and 5.2.7 “Community” domains highlight the required bottom-up approach, in order to integrate social and ethical aspects into decision-making processes (D’Amico et al., 2021b).

From an economic perspective, digital technologies disseminated in various urban infrastructures (e.g., traffic lights, vehicles for urban cleaning and public transport, meters, etc.) allow a detailed and real-time understanding of flows that improve the quality and timeless of decision-making processes (Deng et al., 2021). At the same time, GPS tracking systems, real-time monitoring sensors and smart grids significantly contribute to reducing design and maintenance costs, and avoiding price fluctuations, speculations and threats (Tchawou Tchuisseu et al., 2019). For example, the port city of Rotterdam, through the Ramlab, has achieved a revaluation of logistic assets, a maximization of resources and an extension of the life cycles of materials (Ramlab, 2017). However, the considerable costs of designing, installing, integrating, maintaining, and reprogramming advanced digital technologies undoubtedly represent an obstacle for poorly organized or less developed cities (Nambisan et al., 2021). In this regard, the search for funding for the implementation of digital technologies is crucial for the cities involved in the transition of the circularity of urban metabolism (Von Schönfeld et al., 2021). 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 diffusion of the digitalisation of the circularity of urban metabolism in Europe (Agovino et al., 2019; Cárdenas Alonso et al., 2017; Lopes et al., 2021). At the same time, policymakers tend to establish long-term partnerships and technical collaborations with universities, research centres, start-ups, non-profit organizations, technology companies, and so on, in order to exploit their skills and knowledge, providing them with tax relief and incentives (Gamache et al., 2020). In this regard, Section 5.1.5 “Finance and Funding” emphasizes the role of tax leverage as an incentive to trigger a virtuous process of logistical development. On this point, the port city of Hainan has implemented a special economic zone (reduced tariffs and simplified bureaucracy) in order to attract foreign investors in the logistics, e-commerce and tourism sectors (ITR, 2020).

According to the literature on the social impacts of the digitalisation of the circularity of urban metabolism, digital technologies guarantee high standards of efficiency, quality and timing in the sharing of goods and services (Upadhyay et al., 2021). In general, the web portals identified and analysed as shareNL, Platform31, Made in Moerwijk, KledingBank Den Haag and Lekkernassuh aim to raise citizens’ awareness of circular economy practices and at the same time integrate people with social and economic difficulties in the urban community. However, there are several behavioural, psychological, and motivational barriers to the digitalization of circularity of urban metabolism (Wu, 2020). 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 (Chen, 2021). Furthermore, the lack of: (a) confidence in digital technologies (Jang et al., 2021); (b) motivations or incentives to co-design or co-create circular urban policies (Gravagnuolo et al., 2021); (c) awareness of the importance of user participation and monitoring (Edelmann et al., 2021); (d) certainty in the use of digital devices due to security and privacy issues (Wu et al., 2018), and (e) familiarity with fixed and mobile digital platforms (Battistini et al., 2020) are factors that discourage users from actively participating in the digitalization of the circularity of urban metabolism.

In social terms, the obstacles to the digitalisation of the circularity of urban metabolism are mainly related to the highly departmentalized and non-integrated bureaucratic governance structure, which prevents any digitalization strategy (Poponi et al., 2021). 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 (Pitidis et al., 2020). Section 6 "Future perspective of Urban Metabolism Circularity: Sensor City" (D'Amico et al., 2020b) focused on the development of urban projects in partnership with technology giants such as Google, Ericsson, Huawei, Alibaba, Microsoft, Deutsche Telekom, and so on, explains that it is possible to have conflicts between public institutions and companies in the management of sensitive data and information, making the balancing of urban governance a challenge for policymakers from a regulatory, ethical and administrative point of view. In this regard, the review and analysis on circular cities (Section 4) 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 (Kim et al., 2021).

In domain 5.2.3 "Environment", digital technologies provide a wide range of data and information on air temperature, wind speed, humidity, tidal and current flows, and so on, which allow logistic operators to elaborate forecasts on visibility in order to ensure a safe entry of the ship into port and to determine the economic impacts on fuel consumption (Široka et al., 2021).

Despite the abovementioned benefits, the pervasive use of technology within urban metabolism presents a multitude of data management issues that embrace: (a) the security standard (Andrade et al., 2021); (b) the level of assimilation of heterogeneous data collected by different stakeholders (Kintscher et al., 2021) and processes with different protocols (Chen et al., 2020b), and (c) the competence of urban planners, administrators and managers to evolve individual feedback into circular urban policies (Zhang et al., 2021).

The development of the circularity of urban metabolism through digital technologies in line with the needs of citizens, local authorities, companies, organizations, etc. requires a significant amount of urban data, monitored and analysed in real time according to the needs of the stakeholders involved (Certomà et al., 2020; De Guimarães et al., 2020). For example, in a survey, the citizens of the well-known German tourist city, Heidelberg, identified traffic as the most urgent problem to be solved. In this way, the efforts of local policymakers have focused on how to improve mobility towards intermodal solutions.

In parallel, it is necessary to ensure a certain level of data quality (Serrao-Neumann et al., 2019). Data collection sensors can produce incorrect, partial or missing values as they use different standards or protocols, generating inconsistencies and differences between the data. For example, CityPulse described by Puiu et al. (2016) is a real-time monitoring framework supported by the European Union (EU) that processes, integrates and adapts uncertain and incomplete data through quality of information techniques in order to develop reliable information capable of satisfying user requests. In this regard, the urban project represents a practical model of how to move from vertically to horizontally interconnected services (see www.ict-citypulse.eu/page/). In this regard, the domain 5.2.5 "Telecommunications" refers to the development of network infrastructures that permit a remote and real-time transfer of data and information between the various stakeholders involved (Sumić et al., 2015). However, the circularity of urban metabolism based on sensor networks can provide unreliable communications due to incorrect data transmission. Specifically, the incorrect transmission of urban data does not only require time, but also retransmits the information flows, which negatively affects the quality of the data (Jiang, 2020). As a result, the quality of data and the technologies to overcome problems of inconsistency, partially, and unreliability should be considered in the development and implementation of sensor city projects (Babar et al., 2019; Engin et al., 2020).

As regards the integration of different types of data, collected, processed and analysed by local authorities, companies, utilities, citizens and organizations, one of the main tasks of policymakers is to implement infrastructures, models, and networks capable of connecting data deriving from different urban sectors, promoting better communication between the various stakeholders involved (Yigitcanlar, 2010). For example, the dashboard implemented by Alibaba, illustrated in Figure 16, requires an information flow and a systemic communication between government, security and emergency service institutions.

Ensuring maximum privacy protection of sensitive data is indispensable for developing the circularity of urban metabolism based on sensors, video surveillance cameras, monitoring stations, cloud computing, and so on. Data security issues not only have isolated effects, but also often affect a wide range of urban metabolism dimensions. Thus, data security is treated as a fundamental issue in the management of urban circularity (Sadgali et al., 2018; Borrion et al., 2019; Laufs et al., 2020). Through the collection of large amounts of data that analyse human behaviour, it is possible to influence not only the fight against crime through sensors that analyse movements or facial expressions, but also urban governance in terms of planning and the attractiveness of the city (Cagliero et al., 2015; Rothkrantz, 2017; Sajjad et al., 2020). Nonetheless, the corresponding interventions are particularly controversial in terms of privacy, emphasizing ethical requirements in the urban safety planning process (Parra et al., 2017; Calzada, 2018). Therefore, integrating traditional and cybernetic urban security aspects is necessary to guarantee a secure and digitalised development of the circularity of urban metabolism (Carter, 2020; Kumar et al., 2020).

Thus, we sustain that the design, installation, formatting, implementation and remodelling of digital technologies must be conducted taking into account the economic, social and environmental dimensions of urban metabolism and at the same time proactively involving stakeholders in urban circularity initiatives. This holistic and participatory approach is emphasised by the theoretical and managerial literature on urban metabolism and our multiple case study analyses concerning circular cities (Section 4), port cities (Section 5) and sensor cities (Section 6). Specifically, the frameworks proposed in Figure 4 and Figure 13 explain the importance of a multidimensional and integrated perspective and the initiatives to digitalise the circularity of urban metabolism identified and analysed agree with this approach.

8. Conclusion

The definition of smart urban metabolism combines the aspects of circularity related to traditional urban metabolism with the needs of innovative urban contexts to better address the social, economic, environmental and technological challenges of current urbanization and the growing datafication of urban processes and operations. In this sense, real-time monitoring stations for water and energy consumption, tracking sensors for waste management, GPS systems for locating vehicle flows, participatory urban governance web platforms, disseminated digital literacy in all segments of the urban population, artificial intelligence and cloud computing technologies for the remote and categorized control of peaks, malfunctions or failures, and so on, aim to improve the quality and efficiency of the circularity of natural and artificial resources of urban metabolism. Consequently, an integrated and multidimensional approach to urban metabolism and smartness becomes highly strategic for policymakers, managers, planners, and entrepreneurs in order to plan, track, monitor, analyse and interpret urban circularity performances.

The Thesis investigated the social, economic and environmental benefits deriving from the circularity of urban metabolism enabled by digital technologies, in order to develop a smart urban metabolism framework capable of supporting the decision-making processes of smart and sustainable development. This was done by addressing the three objectives set during the elaboration of the thesis. The first objective was to identify digital technologies capable of fuelling and improving the circularity of urban metabolism. The second objective refers to the need to design and implement urban technological infrastructures such as sensors, monitoring stations, tracking systems, and so on. Finally, the third was to highlight the social, economic, environmental and technological challenges that emerge from the digitalisation of the circularity of urban metabolism. The results of the study, explained in the five papers that constitute the research, provided the following observations to the questions raised in relation to the three stated objectives:

1. The proposed concept of smart urban metabolism is able to overcome the limitations that the traditional notions of urban metabolism and urban smartness have had to face.
2. In order to analyse and interpret the circularity performances of the social, economic, environmental and technological flows that characterise urban metabolism, it is necessary to equip the policymakers with digital technologies able to continuously and in real-time collect these metabolic flows.
3. The digitalisation of the circularity of urban metabolism can collide with numerous institutional, psychological, financial, ethical and legislative barriers.
4. The continuous suggestions, feedback, proposals, ideas and recommendations collected through digital platforms and dashboards improve the categorization of the urban services and increase the active involvement of the stakeholders, providing a greater sense of belonging and a greater commitment in the decision-making process.

5. Smart Urban Metabolism can activate innovative strategies and practices of urban planning and regeneration by introducing a detailed and dynamic spatial-time perspective of the social, economic, environmental and technological flows of urban metabolism.

As regards the first objective, Papers I, II, IV and V confirm that there is a plethora of digital technologies capable of improving the circularity of urban metabolism. Specifically, the aforementioned papers demonstrate the importance of a technology-driven approach to circularity in the environment, energy, water and wastewater, waste, health, safety, education, leisure, economy, mobility, telecommunications and governance. Therefore, the significant advantage of Smart Urban Metabolism over the traditional version of urban metabolism is that it provides a dynamic and multidimensional perspective. In this sense, the continuous feedback in real time returns data on urban metabolism with high spatial and temporal resolution, compared to static and medium and long-term statistical data.

With regard to the second objective concerning the need to develop technological urban infrastructures such as sensors, monitoring stations and tracking systems, the digitalisation of the circularity of urban metabolism was tested and analysed in Paper III with reference to the circular cities of Porto, Prato, The Hague, Kaunas, Oslo and the Flanders region, which form the European Partnership on Circular Economy. The cities considered have defined a wide range of urban metabolism circularity initiatives enabled by digital technologies. In this regard, the "Circular Resource Efficiency Management Framework" implemented by the European Commission and used in the testing phase led to the identification of the key points of Smart Urban Metabolism. These include the process of mapping economic, social, environmental and technological flows, the development of brokerage and engagement activities of the stakeholders involved and the monitoring and evaluation of the initiative adopted.

With regard to the third objective, the digitalisation of the circularity of urban metabolism has produced a multitude of social, economic, environmental and technological challenges. In this sense, Paper V provides insights into the "sensorization" of urban contexts, confirming that numerous critical issues persist. For example, the partnerships stipulated with the technology giants brought to the fore technical aspects such as the qualitative and quantitative robustness of the urban data collected, the integration of a vast type of data processed following different protocols and standards, cyber security and, finally, the ability of policymakers to integrate and interpret this mass of disordered data and transform them into innovative urban policies. In sum, Smart Urban Metabolism can accelerate the need for a new typology of policymakers, able to combine knowledge of data scientists and urban planning. The results of Paper V confirm that there are numerous ethical, psychological, legislative, institutional, and behavioural challenges that become evident only by analysing in detail the Smart Urban Metabolism.

The multi-disciplinary and trans-disciplinary focus of Smart Urban Metabolism entails the need to implement holistic and integrated approaches, in order to improve the understanding and awareness of the increasingly complex social, economic, environmental and technological urban causalities.

In terms of future perspectives, most of these aspects can lead to numerous managerial implications inherent in the development of the digitalization of the circularity of urban metabolism. In this sense, to better understand the emerging human-technology-nature interactions, it is necessary to equip our cities with infrastructures based on the “City Brain” model, capable of planning, processing and evaluating aspects such as behavioural psychology, disruptive technologies, data science, industrial ecology and advanced urban economy, in order to fuel the advancement of citizens’ wisdom through continuous and real-time feedback and to foster the systemic and holistic integration of all social, economic, environmental and technological dimensions of smart urban metabolism.

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