City in the loop: assessing the relationship between circular economy and smart sustainable cities

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Abstract

Research frame: *The concept of a smart city is closely related to sustainability. The circular economy is one of the most interesting facets of the latter. Nevertheless, no substantial effort has been made so far to establish the link between the circular economy and smart cities.*

Purpose of the paper: *Through the conceptual systemic perspective and quantitative means, the study investigates how the concepts of the smart sustainable city and the circular economy are interconnected.*

Methodology*: After assessing the related scholarly literature to highlight the systemic nature of the connection between a smart sustainable city and a circular economy, we analyze the relationship between the two by operationally quantifying both concepts on the macro level and the level of the single components of smartness and circularity. Operationalizations are based on the relative frequencies with which certain EU cities are mentioned in scholarly documents related to smartness and the circular economy and indexed on Google Scholar. Regression analysis and principal component analysis are used as the main analytical tools.*

Findings*: We find a significant positive relationship between a city's smartness and circularity. While the presence of specific smart city-related technologies like AI, Big Data, and IoT are less important for the proliferation of circular economy initiatives in a city, the same is not true for the overall presence of an advanced ICT infrastructure. Alternatively, waste management is the element of the circular economy that contributes the most to sustainable urban smartness.*

Research limits: *The analysis is performed on a dataset consisting of 193 EU cities. Therefore, the results cannot be applied to cities outside the EU. Moreover, the indices that operationalize sustainable smartness and circularity are empirically valid but require more in-depth statistical validation.*

Practical implications: *The study suggests city managers and administrators to treat the smart sustainable city concept holistically. Indeed, circular economy initiatives could significantly affect the implementation of smart sustainable urban initiatives.*

Originality of the paper: *Although the literature treats the two concepts extensively, no attempts to quantify the relationship between smart sustainable cities and circular economy have been made until now. We hope this study will shed additional light on the complex systemic nature of the investigated domains.*

Key words: smart city; smart sustainable city; circular economy; Google Scholar, city management

1. Introduction

The development of an urban area is intrinsically related to the rate of its investment in the implementation, use, and expansion of smart technologies (European Commission, 2010; Gouvea *et al.*, 2018). The effective disposition and use of smart technologies can increase the innovative growth rate of cities (Gouvea *et al.*, 2018). Furthermore, these technologies are the binding elements of urban sustainability (Gouvea *et al.*, 2018; UNECE, 2015). The role played by smart technologies such as ICT, AI, IoT, and Big Data (Nica *et al.*, 2020; Bifulco *et al.*, 2016; Quan *et al.*, 2019; Bibri, 2018) in the development of smart sustainable cities cannot be underestimated (European Commission, 2010). Nevertheless, in discussing sustainability and smartness - and consequently sustainable practices and smart solutions for cities - we should distinguish between sustainable cities and smart cities (Treude, 2021). Recent studies have attempted to incorporate sustainability into the smart city concept to "smarten up" sustainable models used in cities (Al Nuaimi *et al.*, 2015; Batty *et al.*, 2012; Bibri, Krogstie, 2017; Kramers *et al.*, 2014; Neirotti *et al.*, 2014; Shahrokni *et al.*, 2015). One optimal way of doing so consists in defining the pillars of sustainability of a city and assessing smart technologies' contribution to these pillars.

Moreover, sustainable urban development is not feasible by considering only finite resources and the limited capacity to recycle waste (Bonviu, 2014). Indeed, the natural renovation of resources is not capable of substantial improvements. Consequently, it cannot guarantee sufficient resources for future generations in the light of intergenerational justice principles. Alternatively, an economy based on these principles seeking solutions to the above-mentioned issues functions as a circular economy.

According to a traditional vision, the circular economy also concerns a production and consumption model based on reusing and recycling materials, thus contributing to the extension of the product's lifecycle (Awuah, Booth, 2014). We can also define the circular economy as a regenerative system in which recycling and renewable energy production methods minimize resource input, waste, emissions, and energy leakage (Geissdoerfer *et al.*, 2017).

The circular economy is beneficial for the creation of more sustainable processes in different areas. In urban development, cities can implement relevant initiatives to turn themselves into sustainable circular smart systems. Although the circular economy's application in cities is actively encouraged by many scholars, there is a need to measure and analyze its environmental impacts and correlations in relation to other urban matters (Aceleanu *et al.*, 2019).

Although there are many studies within the literature assessing the contribution of sustainability to smart cities and the application of circular economy in pursuing sustainable development goals, there exists a substantial lack of studies that assess the interconnection of elements of these concepts in a concrete manner. Circularity is an integral part of the notion in some definitions of a sustainable smart city. Thus, some researchers might argue that the sustainable smart city intrinsically includes the concept of circularity. This actually means that the word "circular" can be left out of the definition without any substantial loss. However, there are several reasons why the notion of circularity should be explicitly emphasized.

First, even if some sustainable smart city concepts intrinsically include circularity, this is not the case for all of them, as they do not specifically emphasize circular economy indices. In their study on sustainable smart cities, Kramers *et al.* (2014) argue that only a few definitions include explicit environmental sustainability objectives such as circularity.

Second, there are real cases of technological cities aiming to become smart cities that have failed to solve circularity issues due to linear technology. Or worse, their technological texture has contributed to more pronounced sustainability issues (Hotta, Aoki-Suzuki, 2014).

Third, the analytical mapping of smart cities that was initiated by the EU (Mapping Smart Cities in the EU, 2014) has found that "smart mobility" is the most common aspect of smart cities, which share 21% of all smart initiatives, respectively. Other areas of sustainability within the technological perspective are neglected (Janker, Mann, 2020).

Fourth, none of the present smart city concepts sets up a baseline for circularity and its pillars. Moreover, while a sustainable smart city concept might do just fine without defining circularity, the issue becomes problematic for a smart circular city (Schipper, Silvius, 2019).

In this article, we argue for the importance of circular economy practices in implementing Sustainable Development Goals (SDGs) in Smart Sustainable Cities (SSCs). We present an exploratory analysis of the relationship between the smart sustainable cities concept and the circular economy using data on the 393 most populated urban areas of the EU. In this paper, the concept of smart sustainable cities is addressed from the perspective of smart technologies like AI, ICT, IoT, and Big Data (Nica *et al.*, 2020; Bifulco *et al.*, 2016; Quan *et al.*, 2019; Bibri, 2018). The circular economy is proxied by recurring to the most critical elements of the circular economy related to the smart city concept (Korhonen *et al.*, 2018; Moraga *et al.*, 2019). Besides enriching the currently scarce literature on smart sustainable cities, this study provides policymakers in the urban domain with valuable insights on the dynamics of diverse smart and sustainable development initiatives and their relationship to circular economy principles for EU cities.

2. Theoretical background

2.1 From 'smart city' to 'smart sustainable city'

To outline the smart sustainable city concept, it is necessary to review different available smart city conceptualizations.

It is evident, from the literature review, that there exists no universally accepted definition of the smart city. This is also due to the fact that the concept may be applied in different areas (Schaffers *et al.*, 2012; Zhuhadar *et al.*, 2017; Chong *et al.*, 2018; Ismagilova *et al.*, 2019). In light of the objectives of this study, a city is considered "smart" when it possesses the characteristics of a complex ecosystem (Lusch, Spohrer, 2012) in which sustainable partnerships and cooperation strategies must be implemented among the main stakeholders (Schaffers *et al.*, 2011). This promotes the sustainable management of the cities' resources to improve the inhabitants' well-being and quality of life (Bifulco *et al.*, 2016; Pinna *et al.*, 2017; Ismagilova *et al.*, 2019). These considerations are consistent with the definition of smart city that was formulated by Li *et al.* (2016), who highlight that "smart cities aim to provide a more efficient, sustainable, competitive, productive, open, and transparent place to live". This is also reflected in the study by Gascó-Hernandez (2018), who believes that "smart city is an umbrella term for how information and communication technology can improve the efficiency of a city's operations and its citizens' quality of life while promoting the local economy". More specifically, "a city is designated as smart if it balances economic, social, and environmental development and if it links up to democratic processes through a participatory government. SC involves the implementation and deployment of information and communication technology (ICT) infrastructures to support social and urban growth through improving the economy, citizens' involvement, and government efficiency" (Yeh, 2017). From this point of view, it is possible to monitor, understand, verify, evaluate, and plan cities through ICT to improve urban sustainability (Bibri, Krogstie, 2017).

Based on the definitions mentioned above, we can conclude that smart cities aim at sustainable development, which can be implemented through the active participation of the population and the exploitation of available technologies. Accordingly, a smart city and sustainability are interconnected because a non-sustainable city is, by definition, far from being "smart". However, the concepts of smart city and sustainable city should not be considered synonymous (Ahvenniemi *et al.*, 2017). As highlighted in the study by Ahvenniemi *et al.* (2017), who elaborates on the definition formulated by Castells (2000), "a city can be defined as sustainable if over time its conditions of production do not destroy the conditions of its reproduction". In this context, since a smart city is considered as a constellation of actors (Treude, 2021), in order to achieve sustainability it is essential to understand all the existing relationships between individuals, and then the social dimension, their activities and so the economic dimension, the environmental dimension, and the cultural dimension (Tregua *et al.*, 2015; B (Tregua *et al.*, 2015; Bibri, Krogstie, 2017; Engel *et al.*, 2018; Martin *et al.*, 2018; Treude, 2021). This is consistent with Akande *et al.* (2019), who argued that in order to implement the concept of a smart sustainable city, stakeholders must use ICT to support environmental sustainability. In this perspective, precise systemic analysis is configured because the objectives of a system can generate consequences for other systems (Barbier, Burgess, 2017).

Although the environmental and social impact of contemporary cities-as regards the exploitation of resources, the production of waste, and the generation of emissions-has be proven, it is essential to address a dynamic value co-creation of a long-term approach based on sustainability (Bulkeley, Betsill, 2005). Moreover, the challenges that cities must face include the reconfiguration of land management models, and therefore of all available resources, through participatory governance (Caragliu *et al.*, 2011).

As argued by Akande *et al.* (2019), the study of the principles of smart sustainable cities is grounded in the effects and implications of ICT and infrastructure on urban sustainability (Kramers *et al.*, 2014; Al-Nasrawi *et al.*, 2016). This is made possible through the development of integrated frameworks to measure the sustainable smartness of cities (Ahvenniemi *et al.*, 2017).

Previous studies have sought to understand the association between smartness and environmental sustainability using regression analysis. For example, Wu and Raghupathi (2018) performed country-level research to examine this relationship and found that smartness is positively correlated with sustainability and can promote environmental sustainability. However, Higón *et al.* (2017) reported a contrasting result upon identifying a non-linear relationship between technological development and environmental sustainability in an inverted U-curve shape.

In the two following sections, the effect of a circular economy on a city's smartness as a crucial sustainability factor will be measured.

2.2 The application of circular economy models in the smart sustainable city

As can be inferred from findings in the literature, the smart sustainable city qualifies as a concept because, besides satisfying the requirements of a smart city, it relates to a territorial context that uses ICT and sustainable urban development practices to improve the well-being and quality of life of its citizens (Fedele, Romeo, 2020).

To achieve this goal, infrastructure digitization, in particular, should be used to develop circular economy models. Indeed, gathered data should be used to identify "potential productive uses of waste streams in real-time" (Martin *et al.*, 2018). On the other hand, for a sustainable future of cities to unfold, the circular economy can answer the challenges that urbanities face by taking the prescriptions published in 2019 by the OECD (Bibri, Krogstie, 2017; Bonato, Orsini, 2018; Pevcin, 2019; Yigitcanlar *et al.*, 2019) into account. As indicated by Romano *et al.* (2020), "many cities are implementing circular economy strategies to maintain a healthy and regenerative economy, while promoting environmental sustainability and livability. […]. The circular economy precisely provides the problem context needed for testing, refining, and extending the systems approach in cities. […]. Cities are concerned with the transition towards the circular economy: first, as already discussed, cities are laboratories for innovation and have the bottom-up entrepreneurial impetus and links to citizens to generate the social, environmental, and economic benefits of such innovations and experimentations, including new forms of businesses and partnerships. Second, considering the increasing trends of decentralization of public services in OECD countries, subnational governments have greater responsibility for local public services such as transport, solid waste, water, and energy, which are key to the well-being of citizens. Third, governance at the urban level focuses on the realities of the city and the impacts of policies on the lives of citizens".

The future circularity orientation of smart sustainable cities is desirable for many reasons. For example, waste can be managed to generate new resources and it can even be transformed into resources that take on significantly more than their original value (Thompson, 1979; De Jong *et al.*, 2015; Deakin, Reid, 2018; Yigitcanlar *et al.*, 2019). Circular economic processes can be implemented through the reuse, recycling, and regeneration of materials, production, use of renewable energy, and joint regeneration of cultural heritage and the landscape of cities within a win-win perspective. The circular economy that is applied in smart sustainable cities can be considered a "creative" strategy. Indeed, it integrates the creation of economic value, which is implemented through consonant interactions among companies, environmental protection, and the reduction of social exclusion, starting from the city's/territory's historical-cultural roots.

Romano *et al.* (2020) sustain that in order to achieve these goals, it is necessary to apply the 3P model based on:
- coordination between public and private entities, including the business world, in view of the goal of circularity;
- coordination across policies to make sectors complementary through interactions that are appropriately planned during the design and implementation of urban policies;
- coordination across places because different territorial contexts (urban, rural, etc.) should not be considered as isolated systems but rather as global areas in which materials, resources, and products are exchanged.

The authors highlight that "the variety of actors, sectors, and goals makes the circular economy systemic by nature. It implies a rethinking of governance models based on multi-stakeholder and multi-sectoral approaches. For the circular economy to happen, policies need to be aligned, stakeholders informed and engaged, legal and regulatory frameworks updated and supportive of innovation. Also, technical, human, and financial resources need to be adequate; new capacities need to be built; and progress and results need to be monitored and evaluated to stimulate economic growth, social well-being, and environmental sustainability" (Romano *et al.*, 2020).

In the context of the relationship between smart sustainable cities and the circular economy, adopting a systemic approach is also necessary since a multiplicity of actors, sectors, and goals are involved. In this scenario, interdependencies, circular processes, and implemented synergies increase entrepreneurship, resilience, and therefore the growth and development, of smart sustainable cities. Furthermore, smart sustainable cities can be considered vital systems because they act as dynamic, complex systems, that are capable of transforming themselves and adapting to the continuous pressure of change deriving from the external environment. They can also modify their physical structure of space, organization, and functions by combining infrastructures, services, etc., while maintaining their own identity. To face globalized economic competition, energy needs, and ecological-social challenges, smart sustainable cities must produce synergistic and efficient interactions based on circular economic models that stimulate citizens' creativity (Fusco Girard, 2013; Yigitcanlar *et al.*, 2019). From this perspective, many European cities have included objectives relating to the transition to a circular economy in their agenda in the attempt to reduce systemic entropy through cultural projects aimed at empowering civil society (Talamo *et al.*, 2019).

3. Methodology

We devised a quantitative study to investigate the relationship between urban propensity towards smart sustainable city initiatives and circular economy initiatives,. The subset of EU cities was selected as the starting point of the analysis. We chose EU cities for two main reasons. Firstly, there exists a certain homogeneity at the supranational level in terms of the types of initiatives, which are typically reified in the form of regulations, directives, decisions, recommendations, and opinions (Gargiulio *et al.*, 2013; Paskaleva, 2011; Domenech, Bahn-Walkowiak, 2019, Hartley *et al.*, 2020). However, such homogeneity is not only legislative; rather, there is also a higher degree of cultural homogeneity among EU Member States due to their geographical proximity and shared burdens of history (Akaliyski, 2017). This is important, as the methodology we propose is not entirely immune to local specificities. By removing the problem of heterogeneous contexts, we hope to render the derived indices comparable across the countries. Secondly, given the status of "developed countries" that is detained by most EU Member States (Rozmahel *et al.*, 2013), EU cities are proximal candidates, as they are both sustainably smart and actively implement circular economy initiatives. To study how these two are interconnected, we need to analyze cities that are currently making substantial progress towards both goals.

A total of 27 countries were selected for the analysis (Great Britain was excluded, given its recent withdrawal from the EU). The dataset we created was built by drawing on the most recent edition of the free-to-use version of the World Cities Database (2020). As stated by the creators of the database, "cities for all non-U.S. countries come from the National Geospatial-Intelligence Agency. […] The basic population data comes from Natural Earth Data" (World Cities Database, 2020). Overall, we identified 4804 cities within the EU. The number is not exact, as different countries usually have different legislative criteria for distinguishing cities from minor urban centers (Macionis, Parrillo, 2004). Also, the criteria the database creators adopted to define a city is also not clear. Out of 4804 EU cities, we selected urban centers with over one hundred thousand inhabitants as the starting point of the analysis. We realize that this may seem like an arbitrary criterion, and some critical high-tech cities might have been left out of the analysis. However, as most technological innovation and adoption happen inside larger urban areas (Makkonen *et al.*, 2018), the cut-off point of one hundred thousand inhabitants adheres to a strong rationale. 393 such cities were identified in the EU.

The additional gathering of data was performed through the Google Scholar search engine. For each city in the sample, we performed a set of Google searches. All of the searches were performed with the "in-title" specifier to count frequencies only when a search term appeared in the title of scholarly publications.

First, we used the names in English of each city as search queries. We thus obtained an approximate number of all academic papers and other related scientific literature for each urban center containing the related city names in their titles. We labeled it as *all Google results for a city*. Then, for each city, we carried out additional Google Scholar searches (with the "in-title" specifier) by looking for a city's name paired with a specific keyword. Each keyword identified a specific technological component of a smart sustainable city or a particular facet of circular economy. We identified four keywords for a smart sustainable city subset (Internet of Things, ICT, Big Data, Artificial Intelligence) and three keywords for a circular economy subset (Waste Management, Renewable Energy, Recycling). While the latter denotes the most critical elements of the circular economy (Korhonen *et al.*, 2018; Moraga *et al.*, 2019), the former identifies the most frequently implemented technologies in smart sustainable cities (López, Bolívar, 2018). We termed the number of Google Scholar results for each of those searches *all 'keyword' Google results for a city,* where 'keyword' is a specific indicator among the seven that were previously mentioned. To determine related indices that measure a city's performance in the core aspects of sustainable smartness and circular economy, we applied the following set of formulas to each of the 393 cities in the sample:

$$\boldsymbol{'keyword'\ index\ =\ \frac{'keyword'\ Google\ results\ for\ a\ city}{all\ Google\ results\ for\ a\ city}}$$

The result consisted in the set of micro indices (Artificial Intelligence index, IoT index, Waste Management index, etc.) measuring how well a particular city is doing in those specific aspects of sustainable smartness and circular economy. Lastly, two additional indices, i.e., *Smart City Google results for a city* and *Circular Economy Google results for a city,* were calculated following the same logic (using "Circular Economy" and "Smart City" keywords). In contrast to the seven aforementioned indices, these two do not measure the amount of academic interest towards specific components of a city's sustainable smartness and circular economy. However, they served to identify an additional number of articles related to both the smart sustainable city and circular economy aspects of an urban center in order to count the articles that are not identifiable by more specific keywords.

To quantify the overall predisposition of a city towards smart sustainable city initiatives, we applied the following formula:

$$\boldsymbol{Sustainable\ Smartness\ index\ =\ \frac{\sum 'smart\ sustaibnable\ city\ keyword'\ Google\ results\ for\ a\ city}{all\ Google\ results\ for\ a\ city}}$$

Where the *smart sustainable city keyword Google results for a city* represent the number of search results for a particular smart sustainable city-related keyword (Smart City, Internet of Things, ICT, Big Data, Artificial Intelligence) paired with the name of an urban center on Google Scholar.

To quantify the general predisposition of a city towards circular economy initiatives, we applied the following formula:

$$Circular\ Economy\ index\ =\ \frac{\sum 'circular\ economy\ \ keyword'\ Google\ results\ for\ a\ city}{all\ Google\ results\ for\ a\ city}$$

Where the *circular economy keyword Google results for a city* represent the number of search results for a particular circular economy-related keyword (Circular Economy, Waste Management, Renewable Energy, Recycling) paired with the name of an urban center on Google Scholar.

To eliminate cities introducing a significant distortion in the dataset, we calculated the two macro indices only when the sum of five *'smart sustainable city keyword' Google results for a city* and four *'circular economy keyword' Google results for city* indices was more or equal to four. The cut-off point was not arbitrarily set but rather derived from an empirical observation: in such cases in fact, the denominator of the formulas was consistently low (which was often true for less known urban centers), and the results were distorted in an upward manner, inflating the significance of a city based on its sustainable smartness or circular economy initiatives. Of the initial 393 cities, the two macro-indices were calculated for 193 cities.

Overall, we considered the population, the two macro indices of Sustainable Smartness and Circular Economy, and the seven micro indices related to the individual components that contribute to a city's sustainable smartness and its circular economy initiatives of each city.

The indices operationalize sustainable smartness and its components, as well as the extent of circular economy initiatives for each specific city. The biggest issue here is understanding how closely an operational definition matches reality. Indeed, it seems that the indices more closely capture the amount of academic interest in different aspects of a city's sustainable smartness and circular economy. Is academic interest correlated with the actual number of smart sustainable city and circular economy initiatives? Do cities with a significant presence of academic institutions generate more Google Scholar searches on average? The methodology, indeed, requires additional statistical validation.

Nevertheless, an empirical observation revealed that cities with a high Sustainable Smartness index have a substantial number of ongoing or planned sustainable smart city projects. This, for example, is the case of Varna, a Bulgarian seaside city scoring the highest in the Sustainable Smartness index. The city is an urban center that substantially invests in sustainable smart city initiatives and has the potential to become one of the first real European smart cities (Kostadinova Popova, Malinova Malcheva, 2020). The second "sustainably smartest" city, as defined by the index, is Funchal, the central city on Madeira Island (Portugal) that is famous for its smart projects for tourism (Rodrigues, Virtudes, 2019). The third "sustainably smartest" city in the dataset is Oulu (Finland), commonly recognized as a critical center of innovation in the EU (Rantakokko, 2012).

The same empirical validation applies to the Circular Economy index, with cities in Poland (Zabrze, Wałbrzych) and Croatia (Split, Płock)-all strategic centers of circular economy initiatives in the EU-leading the list (Zielińska, 2019; Smol *et al.* 2020; Andabaka *et al.*, 2018; Sverko Grdic *et* *al.*, 2020). The weak point of the methodology is represented by Barcelona, the city that produced the highest number of Google Scholar results related to sustainable smartness and is considered one of the leading European cities in terms of its smart city initiatives (Bakici *et al.*, 2013). Nevertheless, its Sustainable Smartness index is at the end of the first percentile of the related distribution due to the high denominator.

Both macro and micro indices have the apparent advantage of being relative, and thus expressed by pure numbers. This makes the comparison between various cities in relation to such heterogeneous dimensions possible. By definition, the indices vary in the range between zero and one. Zero denotes a city with no related academic literature containing its name in the titles, thus defining the city's lowest possible smartness/amount of circular economy initiatives. One represents an ideal case in which all the academic city-related topics concern either a smart sustainable city and its components or circular economy and its components. It operationalizes the city's highest possible smartness/amount of circular economy initiatives.

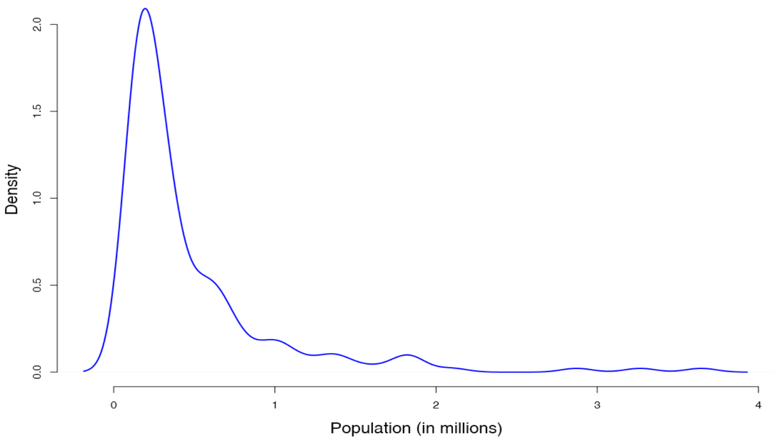
To understand how the indices of Sustainable Smartness and Circular Economy are related, we performed regression analysis. The European cities we chose to investigate do not come from a random sample. Therefore, the models in the next section are not applicable to all urban realities. Accordingly, any conclusion herein can be extended to cities in similar contexts and with similar characteristics to major EU cities. On the other hand, not striving for statistical inference simplifies the analysis, as the distribution of residuals is not conditioned by a set of stringent assumptions.

Finally, to understand how the individual components of a smart sustainable city contribute to the number of circular economy initiatives of a city and how different pillars of a circular economy are related to the city's smartness, we analyzed the spatial distribution of indices along the two most significant dimensions of principal component analysis (PCA). The results and their discussion are reported in the following sections.

4. Results

Out of 193 EU cities were identified as potential smart sustainable cities with substantial investments in the circular economy, and the majority have a population of one million or fewer inhabitants. The distribution is asymmetrical and right-skewed, with an average number of inhabitants equal to 0.472 million and a median equal to 0.2783 million inhabitants. The kernel density estimation of the cities' distribution according to their populations (bandwidth = 0.09529) is shown in Figure 1.

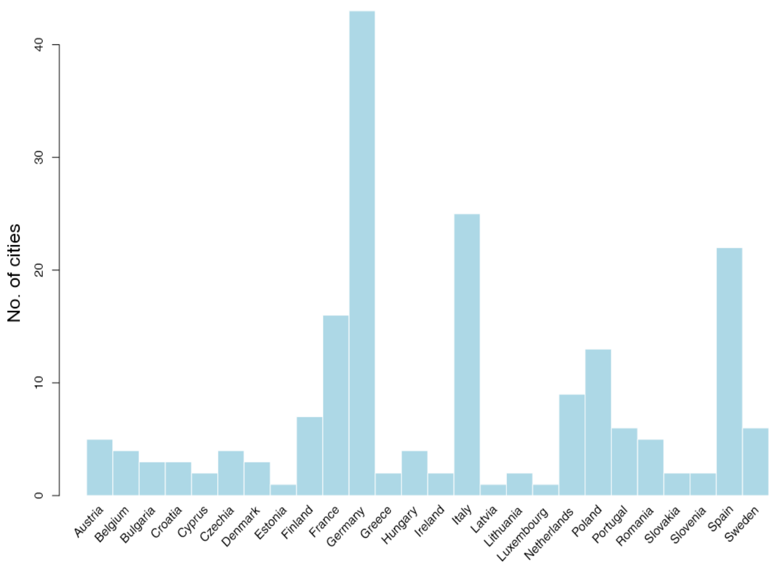
Fig. 1: Kernel density estimation of the cities of the dataset according to their populations



Source: own elaboration

Of the EU States contributing to the dataset, most cities are German (43), with Italy and Spain taking second and third place, respectively (25 and 22 cities). However, , the numbers reflect the EU Member States' geographical and demographical composition and underlying socio-cultural aspects more than correlating with the relative amount of smart sustainable city and circular economy initiatives in each country. The bar graph in Figure 2 reports the countries' distribution within the sample.

Fig. 2: Distribution of countries in terms of the numbers of cities in the dataset



Source: own elaboration

A simple linear regression between the Circular Economy index and the Sustainable Smartness index was performed.

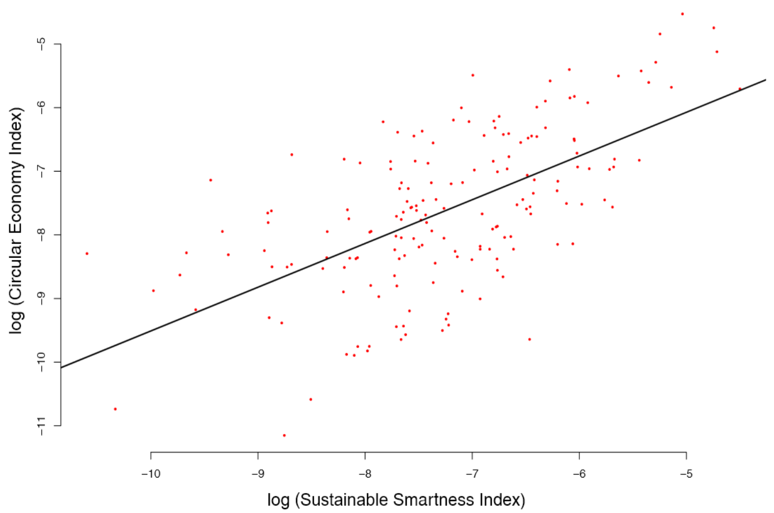
$$Circular\ Economy\ index = 0.0005015 + 0.4571193 * Smartness\ index$$

The resulting model revealed the existence of a moderate-to-strong positive correlation between the two indices (p-value for the slope equal to 2.28e-13). The R-squared index equal to 0.2419 suggests that approximately 24 percent of the Circular Economic index variation is related to the variation of the Sustainable Smartness index. However, due to the relative nature of the indices (varying between zero and one), the interpretation of the above relationship is problematic. To capture the nested dynamic between the indices, we applied logarithmic transformations to both sides and performed another linear regression. The following expression captures the resultant log-log relationship between the indices:

$$log\ (Circular\ Economy\ index) = -2.63422 + 0.68755 * log(Smartness\ index)$$

The expression, which denotes the relationship between the two indices in terms of elasticity (p-value for the slope equal to 2e-16), indicates that a 0.68 percent increase in the Sustainable Smartness index is necessary to obtain a percentage increase in the Circular Economy index. Figure 3 shows the scatter plot and the regression line representing the log-log relationship between the indices.

Fig. 3: log-log relationship between the Circular Economy index and the Sustainable Smartness index



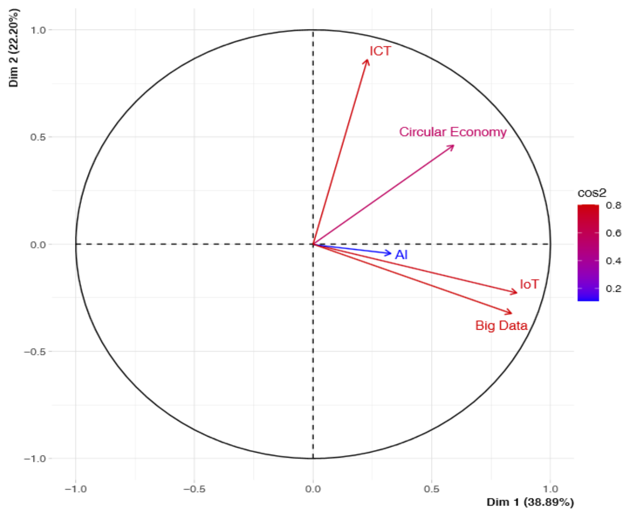
Source: own elaboration

Finally, to understand which components of sustainable smartness contribute the most to the Circular Economy index and vice versa, as well as which elements of the circular economy contribute the most to the Sustainable Smartness index, we performed a principal component analysis (PCA).

Firstly, four specific smart city-related indices (Internet of Things index, ICT index, Big Data index, Artificial Intelligence index) and the general Circular Economy index entered the analysis as active variables. The PCA generated five dimensions, with the first two capturing more than 60 percent of the cumulative variance. Figure 4 shows the distribution of variables within the correlation circle. The coordinates of active variables are the squared correlation ratios between each active variable and the two dimensions of the plane; cos2 denotes each active variable's quality of representation on the two most significant PCA axes. By analyzing the contribution of variables to the plane's definition, we noticed that they were positively correlated with the first dimension. Alongside the second dimension, however, the ICT index and Circular Economy index were positively correlated, while others were negatively correlated. Accordingly, the first dimension may be defined as the overall propensity towards smart and circular economy initiatives. The second dimension distinguishes between specific indices that are closely related to smart sustainable cities (Artificial Intelligence index, Internet of Things index, and Big Data index), and negatively correlated with the second dimension and the more general indices of Circular Economy and ICT. It suggests that specific technologies like AI, Big Data, and IoT are less important for the proliferation of circular economy initiatives in a city compared to the general presence of an ICT infrastructure.

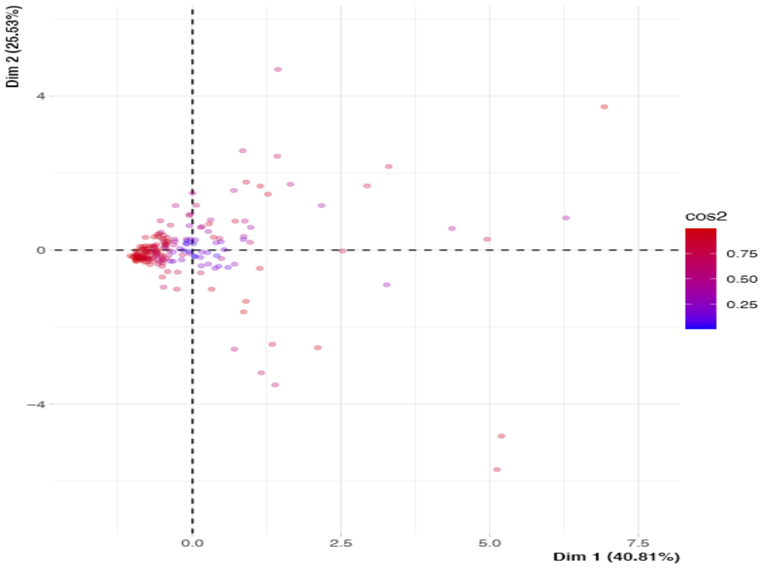
According to the PCA, cities on the right side of the graph are generally more innovative from the point of view of sustainable smart city initiatives. In Figure 5, the distribution of all the urban centers alongside the two most significant dimensions of the PCA factor map is shown.

Fig. 4: Squared correlation ratios between individual components of sustainable smartness and the Circular Economy index



Source: own elaboration

Fig. 5: Distribution of individual cities of the dataset along the two most significant dimensions of the PCA



Source: own elaboration

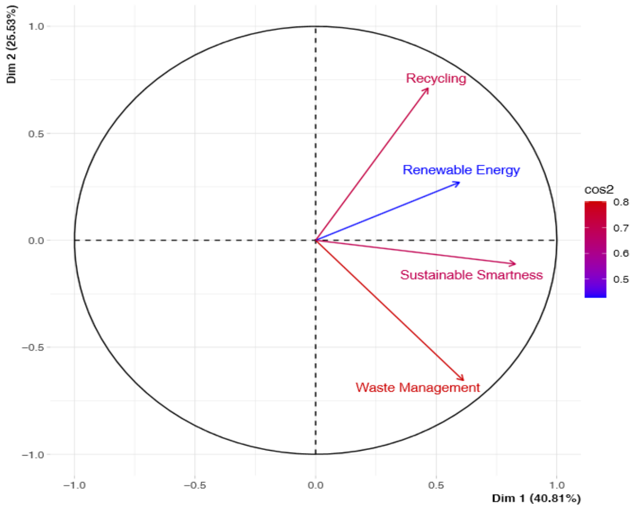
As seen in Figure 5, most of the EU cities in the dataset (clustered around the origin of the axes) rated average in terms of their smart city initiatives. However, some EU cities (on the right) are already very proactive about their smart sustainable future.

Secondly, three specific circular economy-related indices (i.e. Waste Management index, Recycling index, and Renewable Energy index) and the general Sustainable Smartness index entered the analysis as active variables. The PCA generated four dimensions, with the first two capturing more than 66 percent of the cumulative variance. The PCA graph of the variables inside the correlation circle is shown in Figure 6.

Again, all the variables were positively correlated with the first dimension. As regards the second dimension, the Recycling index and the Renewable Energy index were positively correlated, while the Sustainable Smartness index and the Waste Management index were negatively correlated. Thus, the first dimension may be defined as the general propensity towards smart and circular economy initiatives. We did not manage to find a specific descriptor for the second dimension. However, it clearly shows that the element of the circular economy contributing the most to sustainable urban smartness consists in waste management.

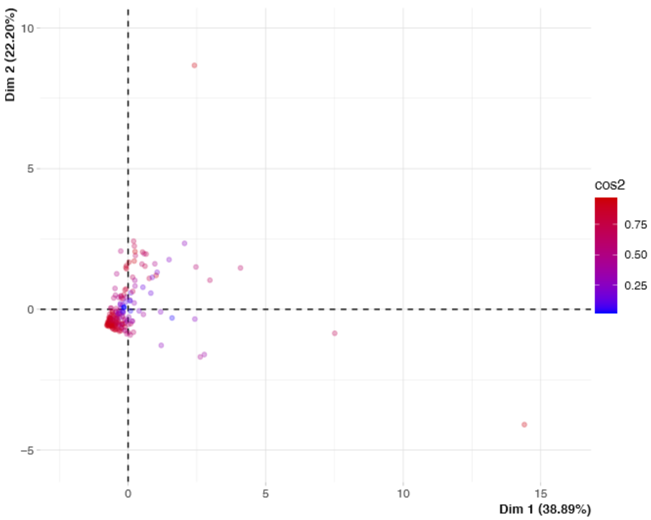
According to the PCA, urban centers on the right side of the graph are generally more innovative in terms of urban circular economy initiatives. The EU cities' distribution alongside the two most significant dimensions of the PCA is shown in Figure 7. Most of the cities in the dataset are clustered around the origin of axes, and therefore perform neither well nor badly in terms of circular economy initiatives. Some cities, however, are very innovative.

Fig. 6: Squared correlation ratios between individual components of the circular economy and Sustainable Smartness index



Source: own elaboration

Fig. 7: Distribution of individual cities of the dataset along the two most significant dimensions of the PCA



Source: own elaboration

5. Discussion and conclusions

As can be deduced from the study's results, we may assume that smart cities are also sustainable. Both sustainability and ICT can be viewed as the two enabling pillars of a city's smartness (Bifulco *et al.*, 2016). The opposite is, however, debatable. For example, we may think of an environmentally sustainable city without a substantial ICT infrastructure. To overcome the issue and shift the focus towards major problems within the literature, some authors recommend using the term "smart sustainable city" (Ahvenniemi *et al.*, 2017). The term elevates both smartness and sustainability to the same conceptual level, making them equally important for researchers. Too often in fact, previous research efforts overlooked the sustainability aspects of urban development, making it the proverbial "elephant in the room". On the other hand, as the first two decades of research on smart cities have revealed, the (more "thrilling") technological aspects were increasingly addressed by scholars. However, those contributions lacked cohesion and were significantly heterogeneous (Mora *et al.*, 2017).

Only recently have sustainability issues in smart cities gained the necessary attention from scholars. Starting from suggestions to rescale the plans of smart cities from large urban realities to eco-friendlier smart villages (Visvizi, Lytras, 2018), proposals of bottom-up smart city initiatives "that facilitate participation and collaboration among city stakeholders" (Veeckman, Van Der Graaf, 2015), and attempts to study the quality of life within smart cities (Coenen *et al.*, 2014), the novel urban literature is thriving with sustainability topics of every kind. The application of circular economy principles to smart cities is undoubtedly part of this trend, as even a brief assessment of the related literature may demonstrate (Petit-Boix, Leipold, 2018; Del Borghi *et al.*, 2014; Aceleanu *et al.*, 2019; Schipper, Silvius, 2019).

The methodology that was developed in the present study allowed us to rank the biggest cities in the EU according to the number of smart sustainable city initiatives and urban circular economy initiatives. Whether the indices of Smartness and Circular Economy perfectly capture the real situation is left to the further analysis of the compatibility between operational definitions of smartness and circularity (as defined by both indices) and the empirical reality. On the other hand, the indices allowed us to rank the cities in the dataset according to a universal criterion. Thus, the indices were not developed asthe most precise or proximal. This comes as no surprise, given how heterogeneous the perception of a smart city in the literature is (Yigitcanlar *et al.*, 2018).

The results of the regression analysis are interesting. The moderate-to-strong positive linear relationship between smartness and circularity reveals the close interconnectedness of technology and environmental sustainability. It also confirms the assertion by Bifulco *et al.* (2016) about the importance of sustainability for smart cities. Among the specific technological components of a smart sustainable city, only ICT seems closely related to the Circular Economy index. This makes sense, as the general presence of an ICT infrastructure in a city seems to account for its circularity. As for the contribution of specific components of circularity to a city's smartness, only the Waste Management index positively correlates with the Sustainable Smartness index on both PCA dimensions. This may be due to the critical importance of waste management for a city.

From a managerial point of view, the obtained results suggest a set of important implications. Firstly, environmental issues should not be neglected during the planning and implementation of smart city initiatives as they are, in fact, closely and positively connected. Indeed, it is not uncommon to highlight this relationship by appealing to a "smart sustainable city" concept. Secondly, although most large European urban centers are ready to implement circular economy and smart city initiatives, only a minority of them scored highly on both indices. The others are clustered near the origin of the axes. Upon observing the PCA maps of individual cities, it becomes clear that smartness issues were addressed more frequently than circularity issues. We advise city planners and managers to consider circular economy initiatives more willingly while planning for a city's smartness. Not only may they produce benefits of their own but, given the positive relationship between circularity and smartness, they would induce an indirect positive effect on the latter through the implementation of the former. Thirdly, the presence of a well-developed ICT infrastructure would undoubtedly benefit the future circular economy initiatives of a city. While planning for both circularity and smartness, city managers should consider the synergetic relationships between the two.

Given that the dataset was not based on a random selection of cities, there is an obvious limitation to our analyses. The conclusions and suggestions above apply to cities of considerable size in the EU, with more than one hundred thousand inhabitants, that are already pursuing smartness and circularity initiatives. The generalization of the results is impossible unless the city in question is similar to a generic large urban center in the European Union.

Regardless of the high face validity of the Sustainable Smartness and Circular Economy indices, more in-depth statistical validation of both is needed. Further replication studies should also be performed to assess the reliability of the indices. The principal component analysis was used to uncover the latent relationship among the indices and describe them inductively. However, to validate the model, a more formal and structured analysis of its components is needed. This may be achieved in future studies by applying a more formal and standardized statistical framework such as structural equation modeling.

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