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Investigating the environmental dimension of the integrative framework for smart sustainable cities: empirical evidence and theoretical consolidation

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To Liam
For the world is your oyster

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ACRONYMS

AI	artificial intelligence
CC	circular city
ESG	environmental, social, and governance
ESGE	environmental, social, governance, and economic
EU	European Union
GC	green city
HP	hypothesis
ICT	information and communication technology
IoT	Internet of Things
LSA	latent semantic analysis
NCA	necessary condition analysis
PCA	principal component analysis
QC	quantum city, quantum computing
QCM	quantum communication
QT	quantum technology
RQ	research question
SC	smart city
SDG	sustainable development goal
SEM	structural equation modeling
SGC	smart green city
SMC	smart circular city
SSC	smart sustainable city
SST	smart city technologies
STST	society-technology-space-time continuum

1 INTRODUCTION

1.1 Three problems in smart city research and practice

The notion of the smart city is still as ambiguous and epistemologically intricate a concept to investigate as ever. Even nowadays, when a lot has been said and done to reify it by providing real-life examples of how a smart city should look like, especially when it comes to its heterogeneous sustainability aspects (Haarstad, 2017), it is still often treated as an idealistic hyperreality, where the quality of life of inhabitants is improved considerably by mere means of the information and communication technology (ICT) integration (Pieroni & Iazeolla, 2016). This is both simplistic and misleading. Hence, the primary goal of the thesis, its impetus, and guiding principle boils down to searching for the satisficing answer to the three "unanswered questions" of broader epistemic and ontological scope within the smart city literature. It is precisely by delving into these three cardinal issues that the overall structure of the work is organized. Indeed, the remaining chapters of the thesis offer, in one form or another, a potential solution to the issues described in the Introduction.

1.1.1 Issue 1. Heavy techno-centricity of smart cities

A significant proportion of smart city scholars criticize, in one form or another, the techno-centricity of a smart city concept, which is mainly perceived and socially re-produced by the general public but also by some practitioners worldwide (Shwayri, 2013; Yigitcanlar, Han, et al., 2019). The techno-centricity view of smart cities prioritizes technology for the sake of it. It neglects, partially or entirely, smart city implementations that are more sustainable and oriented toward the actual well-being of city inhabitants. An emblematic example of such a naive approach is Songdo, a South Korean smart city that is currently barely inhabited and feels more like a ghost town than a thriving urbanity (Shwayri, 2013; Yigitcanlar, Kamruzzaman, et al., 2019).

As exemplified by Songdo, technology alone cannot create and, more so, sustain urban smartness. The latter arises primarily from the mindset of city inhabitants, city administrators, and managers, as well as local, state-level, and supra-state-level policymakers (i.e., the European Union) (Morse, 2009). This view has been emphasized by the growing number of smart city and sustainable city scholars. For example, Han and Hawken (2018) argued that discourses on smart cities have long overemphasized technological capability and development, simplifying a broader understanding of smart cities to a one-dimensional model.

According to the authors, for the concept to exert a durable and lasting impact on future cities, the technology adopted therein must also strive to contribute to the development of a city's unique cultural identity and the simultaneous technology-driven improvement of inhabitant's well-being (Han & Hawken, 2018).

Scholars also argue that the business value potentially offered by the emphasis on mere technology is negatively affecting the smart city agenda worldwide (Yigitcanlar et al., 2018). In this regard, major engineering, hi-tech, construction, and consultancy companies play a leading role in the development and social re-production of smart city agendas and policies, which raises the risk of a conflict of interest between academia and practitioners (Wiig, 2015). Noy and Givoni (2018) point out that, in the context of a so-called private smart city, "business actors are expected, even required, to be concerned primarily with the commercial goals of their companies and with profitability. However, it becomes a problem if these same actors and companies are the ones who set the agenda, drive and largely determine transport policy and planning and are the ones who lead public transport policy and research institutions."

Beyond the initial investment cost, many smart city stakeholders are concerned with the future update and upgrade requirements that might make them forever dependent on the related solutions offered by the hi-tech companies (Kitchin, 2014; Yigitcanlar, Kamruzzaman, et al., 2019). The requirement of thousands (if not millions) of IoT sensors integrated into a smart city infrastructure that will eventually necessitate the update and replacement due to commercial malpractices such as planned obsolescence is deterring a significant amount of urban planners, managers and administrators from pursuing smart city goals (Kitchin, 2014; Macke et al., 2019). In this regard, Lyons (2018) argues that the smart city concept actually comes with caution, as large private organizations are exerting a considerable influence in pursuit of goals that are not always aligned with those of urban stakeholders concerned with social and environmental sustainability.

To summarize the heterogeneity of techno-centricity critiques, the current smart city agendas are still largely driven by concerns for economic growth and innovation rather than by environmental sustainability (Haarstad, 2017). The techno-centric view limits smart city development as it gives rise to the conflict between short-term competitiveness, private organizations' profit, and long-term sustainability (Herrschel, 2013). According to Joss et al. (2022), techno-centric smart city initiatives and practices are not capable of driving concrete environmental sustainability outcomes. Moreover, it is not at all clear what tangible

environmental milestones should be reached, even indirectly, as a byproduct of a technology-only smart city development. Indeed, according to Trindade et al. (2017), the lack of convincing policy commitment to sustainable urban development in smart cities can be chiefly traced back to their heavily techno-centric view. Similarly, as pointed out by Ramaswami et al. (2016), a real-life smart city implementation putting too much emphasis on its technological dimension is not able to integrate multisectoral social ecosystems adequately. For smart cities to achieve their full potential, the related discourses and narratives must move past hi-tech fascination and incorporate sub-systems of different orders while also considering urban stakeholders with diverse needs, goals, and desires (Ramaswami et al., 2016).

Anthopoulos (2017) pointed out that sustainability is not typically treated as a mandatory constituent of smart cities within the techno-centric approach. Stratigea et al. (2017) argued that the excessive focus on technology and the lack of holistic approaches toward urban sustainability leads to a smart city concept that is largely impoverished and mono-dimensional, presenting serious limitations and gaps when it comes to sustainability goals. Haarstad (2017), while aiming at the conceptualization of a sustainable city, examined the role of sustainability in the smart city discourses. The scholar emphasized the lack of attention to sustainability in the smart city agenda, arguing that the latter is driven more by concerns for economic growth and innovation rather than by environmental sustainability (Haarstad, 2017). On the other hand, sustainable city development is a multi-faceted topic, and environmental sustainability (e.g., city greenness, green city, circular city, eco-city) is one the most intricate and researched aspects of it (Arbolino et al., 2018; Moldan et al., 2012). In fact, Trindade et al. (2017) point out that the smart city concept is largely impoverished if the sustainability dimensions are not considered. In this regard, a narrative shift can be readily identified happening around the year 2021, in which sustainability concerns became the most prominent within the smart city research, and the previous fascination with technology for technology's sake is no longer at the forefront of the smart city agenda.

This tendency towards sustainability and, specifically, environmental issues is easily detectable through common bibliometric techniques when assessing the totality of scientific production on the topic of smart cities. In this regard, on the 26th of April 2024, a search was conducted on Scopus. To perform the broadest but also the most context-specific search possible, the only keyword searched was "smart cit*" (the asterisk at the end allows for the possibility to include both *city* and *cities* as units of search). When no restrictions were put on

the language, type of documents, or area of research, a total of 38342 scholarly documents were identified with either “smart city” or “smart cities” in titles or keywords[1]. However, when restricted to the conference and journal articles only in the English language, the number became 30540. Then, the final search results were restricted to the “business, management, and accounting” category[2]. In total, 2006 smart city-related scholarly documents were identified, and the associated metadata was then downloaded.

An interesting observation emerges by comparing the distribution of the documents as identified by both queries (Figure 1.1).

Indeed, both in the case of all smart city-related articles and when those were restricted to the domain of business, management, and accounting, a defining year in which the interest in the smart city concept started to pick up was 2013. Until then, relatively few articles were published explicitly mentioning smart cities in titles or among keywords. In both cases, the interest in smart cities steadily grew in the years to follow before reaching the limits of growth in around 2020-2021, in the midst of the COVID-19 pandemic. Then, for the following two years, a slight decline in interest in the topic can be detected. It is still not clear, however, whether this decline is indicative of a general trend, as two years are too few to comfortably make a generalization of this kind (2024 should still be excluded from the analysis, given the date when queries were made). Hence, three distinct periods in the development of the research area can be identified so far. First, a nascent phase, which is so far the longest, from 1985 to 2013. Then, from 2013 to 2021, there was a period of rapid growth in the interest in smart cities. Finally, from 2021 to now, the topic is still largely discussed (the overall annual growth rate in terms of the number of documents is around 19%), but the interest is starting to diminish.

[1] (KEY(smart cit*)) OR (TITLE(smart cit*))

[2] (KEY (smart AND cit*)) OR (TITLE (smart AND cit*)) AND (LIMIT-TO (SRCTYPE , "p") OR LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "BUSI"))

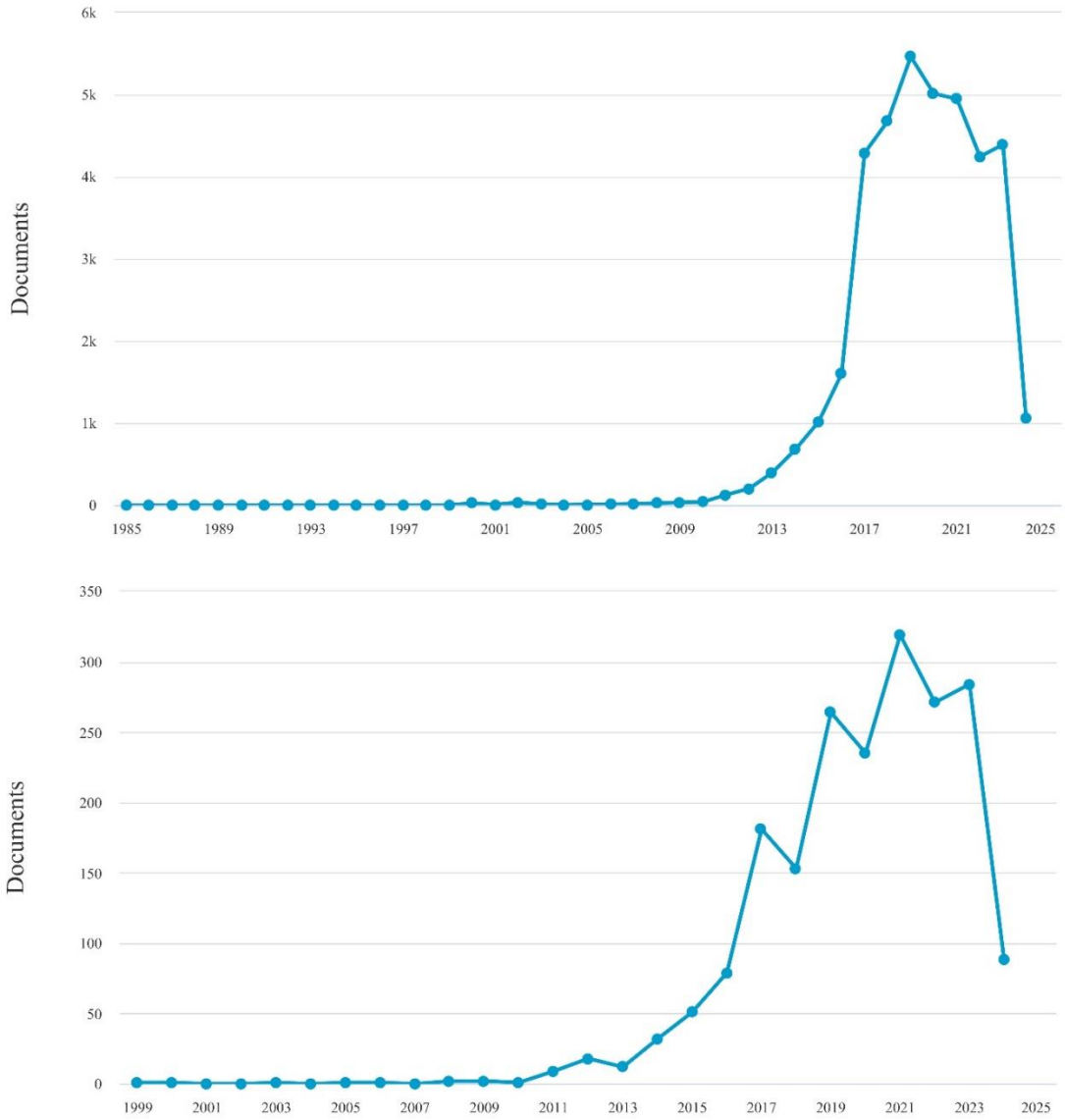


Fig. 1.1 *Smart cities. Distribution of Scopus queries' results by year*

Note: top—all fields; bottom—business, management, and accounting

Figure 1.2 shows the results of the trend topics analysis performed using *bibliometrix* package and *biblioshiny* app in RStudio and considering the keywords used by authors (Aria & Cuccurullo, 2017). Only the past ten years were taken into account since before, the concept of smart city was largely of marginal interest to researchers, and, as Figure 1.1 shows, it only started to gain relevance within academia, including business and management domains, since around 2013.

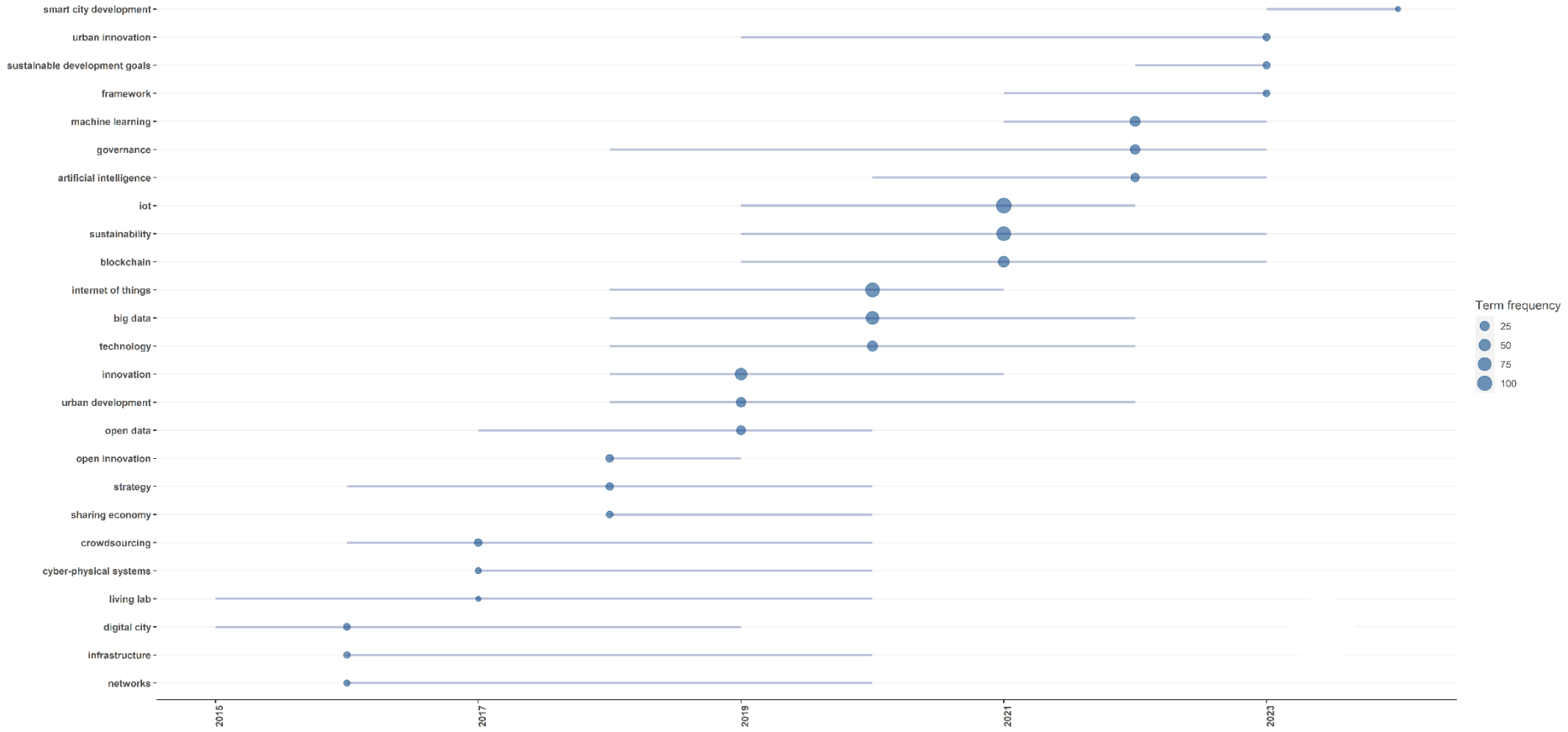


Fig. 1.2 *Smart cities. Trends topic analysis*

The dot's position denotes the average year in which the keyword was the most used. The dot's size represents the overall frequency of that keyword in the abstracts. Two developmental trends appear to be the most relevant. First, there is a marked shift in discourses from topics centered on mere technological fascination and innovation (i.e., *networks*, *infrastructure*, *digital city*) to topics that are more centered on sustainability and sustainability-related practices (i.e., *sustainability*, *sustainable development goals*). The shift seems to coincide with the peak of the COVID-19 pandemic (around the year 2020), which is also the time period when the research interest in the topic of smart cities has seen a reverse in the growth trend.

In terms of the change in smart city discourses, the shift can be readily described as the so-called "sustainability turn." In this case, the decline in the scholarly interest in smart cities is not surprising, as some researchers could have preferred to reconceptualize their research of smart cities in terms of metaphors and conceptual frameworks that are similar, although more sustainability-related and nuanced, like a smart circular city, smart sustainable city, sustainable city, and so on. In this scenario, those terms were not detected by the restrictive Scopus query used here; hence, the reversal of interest toward smart cities around 2021-2021 (see Figure 1.1) can be more readily explained by researchers not losing their interest in a smart city metaphor but rather reconceptualizing the metaphor itself through the lenses of sustainability. The second trend, in line with the recent AI craze, is, unsurprisingly, the predominance of the related keywords in the upper half of the chart (e.g., *machine learning*, *artificial intelligence*), denoting another narrative shift around 2020-2021

To cross-validate the results of the trends topic analysis, a thematic evolution analysis was performed through *bibliometrix* R package by means of the *biblioshiny* app (Aria & Cuccurullo, 2017). Again, the keywords *smart city* and *smart cities* were excluded from the analysis, as they were most frequent and tautological to the scope of the analysis, thus potentially distorting the results and diminishing the presentational clarity of the graph. Two hundred fifty most frequent keywords entered the analysis. The minimum cluster frequency per thousand documents was set to five, the minimum weight index equal to 0.1, and the inclusion index weighted by word occurrences. Finally, a Leiden clustering algorithm was applied (Traag et al., 2019).

Figure 1.3 summarizes the results of the thematic evolution analysis. Specifically, two periods were chosen as cutoff points according to the above considerations on the publication trends. First, the year 2013, when the interest in the topic of smart cities began to grow substantially,

and then the year 2020, at the beginning of what was termed here a "sustainability turn." Figure 1.3 shows how a set of smart city-related themes has evolved across the two subperiods. The thickness of the lines is proportional to the inclusion index associated with each keyword. A thematic evolution is considered as such if the related keywords are present in both associated thematic networks (Chen et al., 2019).

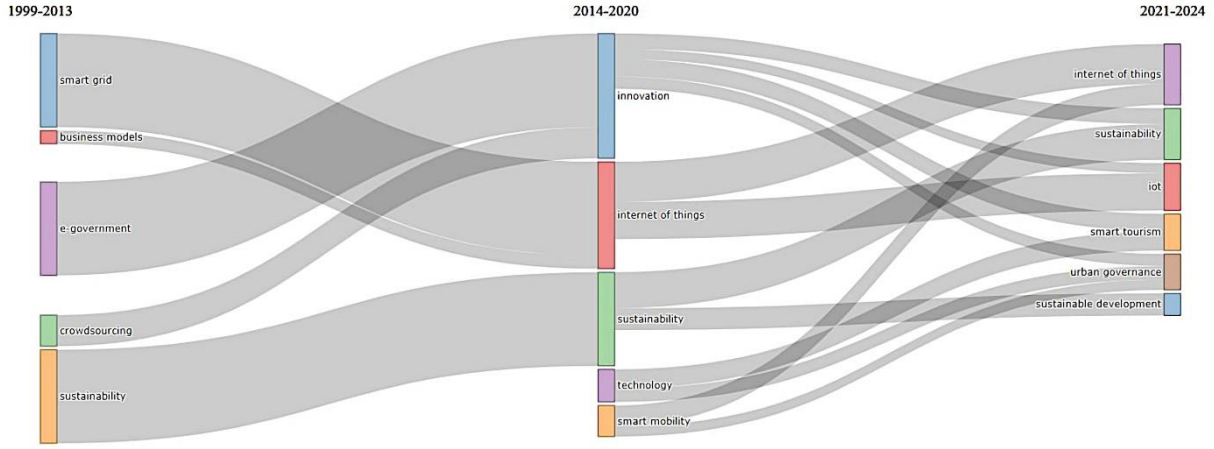


Fig. 1.3 *Smart cities. Thematic evolution analysis*

Overall, the thematic evolution analysis confirmed the hypothesized "sustainability turn" in smart city discourses. Indeed, until 2013, the topic of sustainability was treated in a more or less monolithic manner. Since 2014 and onward, it has begun to evolve into a more nuanced category of sustainable development. Some innovation-related topics popular during the 2014-2020 period have also morphed into the sustainability domain around 2021. Conversely, the preponderant role of IoT-related keywords during both the 2021-2024 and the 2014-2020 periods confirms its pivotal role for the smart city discourses and narratives over time. Moreover, according to the thematic evolution analysis, IoT-related topics have previously evolved from that of smart greed, a popular area of study during the 1999-2013 period.

To conclude, the smart city metaphor and the related discourses are quite recent in academia and date back to the middle of the eighties. Moreover, those were not discussed in relation to management and business literature until the end of the nineties. In both cases, however, the topic was somewhat niche and marginal and mostly centered on the general theme of introducing technological innovation in cities (the techno-centricity period). This was the case until the early 2010s when the interest in the concept started to grow, and the concept's thematic breadth became larger, centered around topics of blockchain and the related e-

government and local participation. The narrative turn in smart city discourses happened again in the midst of the COVID-19 pandemic, with more focus being put on sustainability issues than ever before (what is termed here a "sustainability turn") but also on emerging AI technologies (such as machine learning and deep learning) and their usage in the context of cities (the more techno-centric perspective of the two). At this point in time, the academic interest in strictly defined "smart cities" starts to diminish, most likely due to the emergence of closely related sustainability-oriented concepts such as circular cities and sustainable cities. In all the cases above, however, the topic of the Internet of Things appears central and binding to the entire smart city narrative starting from the early 2000s.

1.1.2 Issue 2. Practice complexity of smart cities

At its core, the smart city concept relies on integrated digital technologies for collecting, measuring, elaborating, broadcasting, and sharing urban-generated data to pursue efficient and effective city governance and management and to ensure quality services to its inhabitants as well as maximize the objective of social well-being. In principle, smart city development can happen in both greenfield and brownfield manner. Hence, smart cities leverage both existing but also created ad-hoc infrastructures, organizations, and urban policies to deliver a higher quality of living to all of their inhabitants, stimulate an attractive investment climate, and promote a more eco-friendly city environment (Macke et al., 2019). In other words, when reified, smart cities are a set of complex integrated systems of social and technological orders, including but not limited to information and communication infrastructures, social and business infrastructure, and emerging artificial intelligence technologies (Albeverio et al., 2007). The said systems must work cohesively and in synergy to generate sufficient quality-driven data for feedback and decision-making loops that are useful to city designers, planners, legislators, and managers (Albeverio et al., 2007; Yigitcanlar et al., 2018).

Managing urban complexity has always been the primary challenge for urban stakeholders as it requires a holistic approach that can efficiently deal with the entanglements of socio-technical structures (Arida, 2002). Moreover, the complexity and intricacy of urban systems are only expected to increase over time due to rapid urbanization and population growth and the related differentiation of heterogeneous city functions (Colding, Wallhagen, et al., 2020). In this regard (and as emphasized above), smart cities are highly complex systems of systems, including various economic, societal, environmental, governance, technical, and technological systems as well as their sub-systems (Albeverio et al., 2007).

Sustainable urban development practices aiming at establishing smart and sustainable communities are the only way to support socio-economic development and endure looming environmental challenges while guaranteeing a prosperous urban environment for humans and non-humans alike (Macke et al., 2019; Yigitcanlar, Kamruzzaman, et al., 2019). However, the ambiguity of what constitutes a truly "smart" city, and the heterogeneity of related definitions create an issue, mainly for urban policymakers and managers. Likewise, these misconceptions and confusion are detectable in the academic literature, especially the heavily techno-centric perspectives prior to the year 2020, as revealed through the thematic bibliometric assessment of the field in the previous sub-section. A possible reason for the confusion might be the semantics, in particular the word *smart* itself, as considerably diverse ways of identifying and measuring city smartness exist (Lara et al., 2016). Some researchers perceive smartness in a sense isomorphic to smart growth (Lara et al., 2016). Others interpret smartness simply as digital or intelligent cities (Kitchin, 2014).

Noy and Givoni (2018) found that, despite all the empirical evidence arguing otherwise, the predominant belief amongst hi-tech organizations is still that smart technologies constitute the main factor of sustainable urban development. Conversely, as seen in the previous sub-section, complexities related to the reification of smart cities are pushing urban policymakers, planners, and managers to opt for short-term goals by relying on technological solutions heavily promoted and controlled by high-tech companies or by opting out of smart city project entirely (Colding, Wallhagen, et al., 2020). Although applying complexity-embracing metaphors to accomplish urban sustainability and smart city development is possible (Arida, 2002; Barile & Saviano, 2010), the majority of urban stakeholders ignore (or are not aware of) those alternative ways of framing the smart city challenges. As Colding et al. (2020) pointed out, "whether the [smart city] model is a new panacea for urban sustainability or instead opens up for a future of unmanageable complexity is an open question that deserves more argues."

To summarize the major points of the complexity problems related to smart cities, Yigitcanlar et al. (2015) pointed out that a simplified view of smart city practice fails to produce either concrete or promising sustainable urban development outcomes. Monfaredzadeh and Berardi (2015) emphasized the friction between sustainability and competitiveness. Similarly, Marsal-Llacuna et al. (2015) revealed a lack of holistic sustainability initiatives, performance monitoring, and assessment measures, indicating that the performance of smart cities is not adequately monitored, which might be a contributing factor to their underperformance when it

comes to sustainability. A lack of key performance indicators and feedback systems concerning smart city initiatives was also pointed out by Hara et al. (2016). In particular, the authors argued that smart cities fail "to produce triple-bottom-line sustainability … development and application of comprehensive key performance indicators are also absent in practice" (Hara et al., 2016). Framing a typical smart city as a solution for sustainable mobility and decarbonization, Zawieska and Pieriegud (2018) have argued that meeting the greenhouse gas emission reduction targets set by the EU is highly challenging, as current smart cities need to stimulate further in-depth transformation of their transportation and energy sectors. Yigitcanlar et al. (2018) argued whether typical smart city policies lead to significant urban sustainability at all. By studying the impact of urban smartness on sustainability outcomes in a set of UK cities, the authors emphasized substantial gaps between policy and reality, limiting sustainability achievements in smart cities to mere greenwashing practices (Yigitcanlar et al., 2018). Silva et al. (2018) hypothesized that the implementation of sustainable smart city practices is particularly complex as it is challenged by means of design, implementation, and operation cycles. Finally, Ibrahim et al. (2018) suggested that the underlying complexity of sustainability-related issues has been mostly ignored in smart city planning and development. According to the authors, a smart sustainable city reification is a continuous, long-term, complex set of processes that require radical socio-technical changes to be introduced and to be planned effectively and efficiently (Ibrahim et al., 2018).

1.1.3 Issue 3. Ad-hoc conceptualizations of smart cities

The passage toward smart sustainable cities is not only limited to the issues of heavy techno-centricity and practice complexity of smart cities but also due to apparent conceptualization problems. In particular, there is still a lack of comprehensive and holistic frameworks, rendering the entire research area overly fragmented (Ahvenniemi et al., 2017).

It is easy to frame the concept of smart cities by mainly emphasizing neoliberal economic growth, the role of already affluent inhabitants, neglecting environmental concerns, and failing to provide actual alternatives to the prevailing consumerism (Martin & Peine, 2021; Yigitcanlar et al., 2018). One of the reasons for the failure to conceptualize smart cities successfully is due to heterogeneous entities such as governments, academia, and private organizations lacking an agreement on what a smart city is (Ben Letaifa, 2015; Pacione, 2009). For example, while, in theory, the smart city concept readily integrates the sustainability goals, in practice, the notions of "smartness" and "sustainability" have often

been reduced to mere "greenwashing" narratives (Balducci & Ferrara, 2018).

Very often, rather than reifying visions of the good city, the focus of smart city stakeholders shifts to emphasizing techno-centric solutions (Herrschel, 2013). In line with the properties of a quantum urban metaphor described in Chapter 3, the intrinsic conflicts within the smart city conceptualization could be viewed as a set of dualities. These include short-termism vs. long-term goals, profit-driven vs. equilibrium-driven, business-friendly vs. environmentally friendly, elitist vs. inclusive, carbon economy vs. climate-neutral economy, and so on (Yigitcanlar et al., 2018). Different ad-hoc conceptualizations of smart cities have been criticized in the smart city literature. For example, according to Bibri (2018), the inability of existing smart cities to adequately address socio-economic and environmental issues can be traced back to the lack of systemic, integrative, and holistic thinking. Similarly, the lack of solid knowledge-based smart city conceptualization has also been framed as a grave "sin of omission" (Ahvenniemi et al., 2017).

Mundoli et al. (2017) argued that the notion of urban smartness should be more than a catchy prefix for all things urban. According to the authors, the reconceptualization of a smart city as a complex urban ecosystem is a must in order to avoid definitions that are overly narrow and restricting (Mundoli et al., 2017). Moreover, as stated by Ramaswami et al. (2016), in addition to the comprehensive, inclusive, and integrative views of smart cities, it is also essential to "focus the attention on the [higher-order] systems-level decisions that society faces to transition toward a smart, sustainable, and healthy urban future."

To summarize the ad-hoc conceptualization problem, smart city notions are fragmented too granular, and lack a systemic outlook (Ahvenniemi et al., 2017). Indeed, the poorly conceptualized (Yigitcanlar et al., 2018), misconceptualized (Bibri & Krogstie, 2017), and incomplete (Cugurullo, 2018) smart city notions can, in practice, contribute to the deterioration of human and nature relations therein (Colding & Barthel, 2017). The planning, developing, and managing of smart cities that are both ecologically and technologically sound necessitate a reconceptualization of smart cities as multi-faceted urban ecosystems (Mundoli et al., 2017). Moreover, the lack of a universally accepted conceptualization of smart and sustainable cities points to the gap between the smart city and sustainable city frameworks, indicating a need for a more holistic reconceptualization of the smart city notion (Ahvenniemi et al., 2017), primarily through the incorporation of further urban developmental drivers, including sustainable urban development principles, into a multidimensional smart city framework (Yigitcanlar et al., 2018). There is, in fact, a high degree of variance between what

a smart city should be and the state of current sustainable development practices (Martin & Peine, 2021). Considering the inability of the heavily techno-centric smart cities to deliver sustainable changes, each such smart city practice is, by definition, ad-hoc (Chang et al., 2018). It is in this regard that Bibri (2018) emphasizes the lack of systemic thinking to address environmental sustainability challenges in smart cities. Finally, according to Balducci and Ferrara (2018), sustainability, while often being seen only as an ancillary topic in smart cities research, is, indeed, strongly related with other smart city dimensions as a strategic component to promote the good quality of life of its inhabitants.

1.2 Three research questions and the outline of the thesis

While running the risk of being repetitive, before outlining the ways in which the thesis deals with the three fundamental problems in smart city research and practice, it is worth recapitulating them, albeit very briefly.

The heavy techno-centricity problem states that more often than not (especially when it comes to practice), smart cities are regarded as technological poles, worthy of consideration only because of the technology itself. Hence, the mere (one may also add, blind) fascination with technology could lead to a neglect of social, environmental, and other aspects of urban sustainability. Hence, rather than having a liveable city, the results are ghost towns of the likes of Songdo (Yigitcanlar, Han, et al., 2019), fascinating as they are, where no one actually wants to live.

The practice complexity problem focuses on the growing challenge of planning, developing, and managing smart cities as systems of systems of complex socio-technical orders. The outcomes of the issue are two-fold. On the theoretical side, there is still a lack of a shared, universally accepted definition of a smart city. It is, indeed, highly unlikely that such a consensus could ever emerge. On a practical side of the spectrum, growing urban-related complexity and uncertainty could only 1) push urban decision-makers toward solutions that are overly simple and short-term or 2) deter them from pursuing smart city goals in their entirety.

Finally, the ad-hoc conceptualization problem emphasizes the need for more complex, integrative, holistic, and systemic ways of thinking about smart cities while at the same time avoiding simplistic one-size-fits-all solutions, so far, the most popular among smart city practitioners.

Obviously, the three problems are highly interconnected. More so, they could actually be considered as different facets of the same underlying issue in smart city research and practice: simplification for the simplification's sake and the unwillingness to treat the complexity as an opportunity rather than a threat—which is also a typical way of proceeding when the goal is a mere isolation of causes and effects, typical of the so-called Newtonian city conceptualizations (see Chapter 3 for more details). As shown later in the thesis, such simplistic approaches could be detrimental when it comes to socio-technical reality as complex as a smart city.

Overall, the thesis is structured around the three fundamental smart city problems described in this chapter. Each of the following three chapters, indeed, is an attempt to offer a solution to one of the three problems. When it comes to the related research questions (or, given their breadth, they could as well be framed as research goals), these are:

RQ1: What is the best alternative to a techno-centric view of smart cities, the one that does not compromise the well-being of heterogeneous groups of urban stakeholders?

RQ2. What is the best way, in theory and practice, to deal with the issue of complexity in smart cities?

RQ3. What is the most systemic, holistic, and integrative way of conceptualizing a smart city?

Again, it is important to emphasize that each of the three smart city-related problems could perceived as stemming from a single cardinal issue: the underlying simplification vs complexity duality. Accordingly, each of the following chapters, while emphasizing the answers to one of the three research questions at a time, actually deals with all of them to a certain degree. Indeed, this is also in line with the complexity-embracing ethos that this thesis seeks to promote. Overall, each of the following chapters is composed of three analytical blocks, denoted as Study 1, Study 2, and Study 3, respectively, in every chapter. The analytical block of Chapter 2 mainly focuses on RQ1, the analytical block of Chapter 3 focuses on RQ2, and the analytical block of Chapter 4 primarily investigates RQ3 as well as sums up and integrates the findings of the preceding chapters.

More specifically, In Chapter 2, a more sustainable alternative to a techno-centric view of smart cities is proposed. This is, in the first instance, a so-called smart green city, which is itself a fundamental component of a smart sustainable city conceptualization. In the second instance, a so-called smart circular city concept is also outlined as a particularization of a smart green city in which circularity principles are practiced and enhanced by conventional

smart city means. Hence, Chapter 2 is mainly centered around issues of environmental sustainability. However, the other three components of a smart sustainable city are also briefly mentioned (social, governance, and economic), and the conceptual framework for the latter is proposed (albeit not empirically evaluated). The chapter starts with a literature review, outlining the abovementioned smart city and smart circular city conceptualizations and hypothesizing a structure of set relations between them. Then, the hypothesized structure is assessed in the three studies based on the analysis of indices devised to measure urban smartness, greenness, and circularity for both EU cities and worldwide.

Chapter 3 is mainly centered on the issue of complexity, which it addresses both in terms of theory and practice through the notion of a quantum city. In particular, the chapter is divided into three macro-sections: one theoretical and two empirical and explorative. The goals of the first one are two-fold: to review the most significant and influential city-related conceptualization and narratives of the past, showing how their attempts toward simplification and isolation of causal structures might hinder and harm the urban development and management and offering an alternative point of view that actively encourages to embrace complexity as the central ontological property of a city. The latter constitute the so-called urban quantum metaphor. The subsequent section consists of an in-depth, mixed-methods systematic review of urban quantum technologies performed in order to outline the concept of a quantum city, which is itself a reification of the urban quantum metaphor through the introduction of quantum technology in smart cities. Finally, the concluding section looks at the potential contributions of quantum technologies to conventional smart city implementations like ICT, IoT, blockchain, and AI. Again, this is done through a combination of quantitative and qualitative methodologies.

Chapter 4 summarizes and integrates the preceding considerations and results in an attempt to offer the most holistic and inclusive outlook on the environmental pillar of smart sustainable cities. Like the two previous chapters, it is divided into three analytical macro sections. In particular, it elaborates more in-depth on the results of Chapter 2 by tracing the narrative evolution of the circular city concept through advanced bibliometric techniques and then by investigating which components of circularity and smartness are necessary for a circular city to emerge by means of necessary condition analysis. Finally, it relates smartness and quantum technologies through an ad-hoc semantic analysis technique based on structural equation modeling, showing which components of smartness are the most influential and are influenced by the two classes of quantum technologies deemed important within an urban

context.

Finally, Chapter 5 acts as the overall conclusion of the thesis. In there, the holistic conceptualization of environmentally sustainable smart cities based on the results of all nine analytical sections of the thesis is outlined and discussed, emphasizing the intricate relationship between smartness, circularity, and quantum technologies. Moreover, the implications for theory and practice are also presented, and the limitations of the work along with reflections on the possible future research directions are outlined.

This thesis is the result of three and a half years of academic work and reflections that have, in part, resulted in the publication of journal and conference papers as well as one book chapter. Accordingly, some sections of the thesis are largely based on the already published research work and, in particular, those parts of it to which the author of this work has directly contributed. In equal measure, the remaining part of the analyses are new and never published contributions or heavily edited, critically re-assessed, and expanded parts of the said published works. In particular, the following scholarly documents have contributed to the creation of the thesis.

Journal articles:

- Bashirpour Bonab, A., Fedele, M., Formisano, V., & Rudko, I. (2023). In complexity we trust: A systematic literature review of urban quantum technologies. *Technological Forecasting and Social Change, 194,* 122642. https://doi.org/10.1016/j.techfore.2023.122642
- Bashirpour Bonab, A., Fedele, M., Formisano, V., & Rudko, I. (2023). Urban quantum leap: A comprehensive review and analysis of quantum technologies for smart cities. *Cities, 140*, 104459. https://doi.org/10.1016/j.cities.2023.104459
- Bashirpour Bonab, A., Bellini, F., & Rudko, I. (2023). Theoretical and analytical assessment of smart green cities. *Journal of Cleaner Production, 410,* 137315. https://doi.org/10.1016/j.jclepro.2023.137315
- Formisano, V., Iannucci, E., Fedele, M., Bashirpour Bonab, A. (2022). City in the loop: assessing the relationship between circular economy and smart sustainable cities. *Sinergie Italian Journal of Management. 40(2),* 147-168. https://doi.org/10.7433/s118.2022.07

Book chapters:

- Formisano, V., Fedele, M., Bashirpour Bonab, A. (2022). Technology and Innovation:

Solution for Uncertainty in Quantum Cities. *Innovazione e Management, Omaggio a Salvio Vicari, Egea-Bocconi Editore*, p. 529-539, ISBN 978-88-238-5186-3

Conference papers:

- Fedele M., Rudko I., Bashirpour Bonab, A., (2024) Tracing the change in discourses on sustainability in smart cities through the latent semantic analysis of smart city sustainability reports, *R&D Management 2024 - Sweeden.* Accepted manuscript, forthcoming
- Formisano, V., Fedele, M., Bashirpour Bonab, A., Rudko I., (2022). The more, the better: Towards a holistic assessment of city brand personality and image, *Sinergie-SIMA 2022 Management Conference*, in *Boosting knowledge & trust for a sustainable business*, p. 245-264, ISBN 97888943937-8-1
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- Formisano, V., Iannucci, E., Fedele, M., Bashirpour Bonab, A. (2021). The Analytical assessment of the Relationship Between Technological Aspects of Circular Economy and Smart Sustainable Cities, *Sinergie-SIMA 2021 Management Conference*, in *Leveraging intersections in management theory and practice*, p. 207-223, ISBN 97888943937-7-4
- Formisano, V., Fedele, M., Bashirpour Bonab, A. (2021). Knowledge management and circular economy: novel solutions to cope with uncertain times, *IFKAD 2021– International Forum on Knowledge Asset Dynamics*, in *Managing Knowledge in Uncertain Times*, p. 183-206, ISBN 978-88-96687-14-7

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2 RELATING CIRCULARITY, SMARTNESS, AND GREENNESS: AN EMPIRICALLY BASED CONCEPTUALIZATION OF ENVIRONMENTAL PILLAR OF SMART SUSTAINABLE CITIES

2.1 Introduction

According to the estimates provided by the UN (*United Nations Department of Economic and Social Affairs*, 2018), while the number of inhabitants worldwide is exhibiting substantial growth, 68% of the world's population will live in cities by 2050. Indeed, from anthropological, sociological, psychological, economic, and political points of view, cities are the most important loci of human (co-)existence, both as physical and symbolic/discursive spaces (Macionis & Parrillo, 2010).

During the past century, after the conceptualization by Ebenezer Howard (2003) of the so-called "Garden Cities of Tomorrow," urbanism—as a set of practical urban solutions and academic urban-related discourses—has been increasingly centered on the futuristic visions of cities (Yigitcanlar et al., 2018). Unsurprisingly, from the point of view of contemporary urbanism, a smart city is currently one of "the hottest topics" out there, as even the superficial skimming of related academic journals reveals (e.g., Alizadeh & Sharifi, 2023; Arku et al., 2022; Guenduez & Mergel, 2022). Considering the current and projected rates of technological progress, the smart city concept constitutes an essential framework for implementing an advanced and sustainable polity (Zuniga-Teran et al., 2020). According to Joshi (2019), major economic and social crises are essential for introducing novel technologies in cities. Likewise, Zhou et al. (2014) believe that the smart city concept has evolved in a series of phases, each caused by a major crisis and the accompanying technological advancements: from the industrial city, as a consequence of the economic crisis of 1857 and the related second industrial revolution, to the digital city and informational city concepts resulting from the third industrial revolution (also known as the first digital revolution) in the second half of the 20th century. For Zhou et al. (2014), the primary catalysts of the modern-day conceptualization of a smart city are the economic crisis of 2008 and the forthcoming second digital revolution.

While the preoccupations with technology are evident in the case of a smart city, the scholars of the concept often tackle sustainability issues only implicitly. Conversely, nowadays, researchers have developed a broad range of more explicit sustainability-related urban metaphors competing for discursive primacy in understanding how a sustainable city of the

future should look like: e.g., the eco-city, the dispersed city, the car-free city, the compact city, the regional city, the network city, the 15-minute city (Pacione, 2009). All of these, however, have their historical roots in the concept of a green city (GC). The latter stems from the belief that urban planning should be more mindful of natural regions and their resources when developing a city (Pacione, 2009). Unlike the novel urban metaphors, the green city metaphor mainly emphasizes the environmental aspect of urban sustainability (Pacione, 2009).

From the "green city" perspective on urban management, the sustainable development of a city is not feasible considering the finite resources and the limited capacity to recycle waste (Castagna et al., 2014). This means the natural reconstruction of resources cannot be substantially improved if the standard way of "doing things" persists. Consequently, city managers cannot guarantee enough accessible resources for future generations according to the principles of intergenerational justice. On the other hand, an economy based on such principles targeting solutions for the abovementioned issues can be considered to function as a circular economy. According to a common view, the circular economy is primarily concerned with a production and consumption model based on the reuse and recycling of materials to contribute to the extension of the product's lifecycle (Awuah & Booth, 2014). Moreover, it can also be defined as a regenerative system in which resource input, waste and emission, and energy leakage are minimized by recycling and renewable energy production methods (Geissdoerfer et al., 2017). The circular economy can benefit different areas of city development and management by creating more sustainable urban processes. Accordingly, some cities began implementing relevant initiatives to turn themselves into sustainable circular systems or so-called circular cities (*Europe 2020*, 2013). Conversely, although the application of a circular economy in cities is actively encouraged by many scholars, measuring and analyzing its environmental impacts is necessary (Aceleanu et al., 2019). In this regard, while many studies are contributing to assessing the sustainability of smart cities or the application of circular economy therein, there is a substantial lack of research that evaluates the interconnections between constitutive elements of the concepts mentioned above (circularity, greenness, and smartness) in a concrete and insightful manner.

2.1.1 An outline of the chapter

The chapter's primary goal is to showcase the practical and theoretical usefulness of developing a consolidated framework of a smart sustainable city (Nitoslawski et al., 2019; Schluter et al., 2022), highlighting the positive synergizing effects of the combination of

further technological development/adoption and the greater focus on environmental, social, governance, and economic concerns by policy-makers, urban managers, and planners. In doing so, the chapter emphasizes the most critical aspect of sustainability, chiefly its environmental pillar. Indeed, the attention of urban and managerial scholars is often directed toward the "more exciting" technical aspects of introducing innovative technologies in smart cities (see the fundamental techno-centricity problem as outlined in the Introduction). At the same time, environmental sustainability concerns are frequently treated as epiphenomenal (i.e., expected to be necessarily solved with further technological improvements). This chapter argues that the two approaches—one focused on technology and one focused on environmental concerns—will only benefit from further integration (Branny et al., 2022). Consequently, it focuses on the need for more holistic and systemic approaches in urban studies and city-related business and management fields by exploring nested dynamics between urban environmental sustainability and technology.

Recent research strived to incorporate sustainability in smart city approaches to smarten up sustainable models used in cities (Al Nuaimi et al., 2015; Batty, 2011; Bibri & Krogstie, 2017; Kramers et al., 2014; Neirotti et al., 2014; Shahrokni et al., 2015). One optimal way of doing so is by defining the sustainability pillars of a city and assessing the contribution of smart technologies to these pillars. As the chapter's primary focus is the environmental pillar of sustainable smart city development, to bridge the epistemic gap, after outlining a comprehensive definition of a smart green city and smart circular city through the analysis of the related urban literature, the chapter adopts quantitative means to operationalize the "smartness," "greenness," and "circularity" of a generic medium-to-large city (worldwide, for the "greenness" and within EU area for the "circularity" aspect) and to investigate how the three are related within the more broad conceptual framework of a smart sustainable city.

This chapter is structured as follows. The Literature Review section holistically outlines and provides conceptual definitions of smart city (SC), green city (GC), smart green city (SGC), circular city (CC), and smart circular city (SCC). In doing so, it is argued that all the concepts are interconnected but ought to be kept conceptually distinct. They are connected in a sense that all converge into the notion of a smart sustainable city (SSC). They are all distinct in the sense that we can think of a city that is smart but not green, green but not smart, circular but not smart, and smart but not circular.

The quantifiable evidence for the dynamics described above is provided in subsequent sections of the chapter. In particular, after outlining the research hypothesis on the

relationships between the abovementioned concepts, three separate quantitative studies are presented to back up the hypotheses. In Study 1, the methodological and analytical framework is proposed to emphasize the connections between city greenness and smartness within the perspective of the so-called "smart green cities" by 1) operationalizing smartness and greenness in a way to render cities worldwide comparable; 2) determining the indices of smartness and greenness for the world's biggest cities (with more than one million inhabitants); 3) performing correlational, principal component, and hierarchical clustering analyses to determine how the greenness of contemporary big cities is related to their smartness and how both are related to city size (in terms of the overall population). The analyses performed herein are essential for three reasons. First, as emerges from the literature review, no attempts to relate city greenness and smartness have been made on the macro-level of analysis (cities worldwide as units of analysis). Indeed, the chapter offers a holistic perspective transcending a typical country-level analysis, as it offers a world-system inter-regional point of view on sustainable urban development. Second, the methodology used in the chapter is novel and insightful, providing a unique way to effectively rank cities worldwide regarding the amount of greenness and smartness initiatives they adopt. Third, the results are important to policy-makers, smart city managers, and planners, as they highlight the critical tradeoff between urban growth, the related increase in technological development/adoption, and the ecological sustainability of future smart cities.

Study 2 highlights the role of circular economy practices in implementing the Sustainable Development Goals (SDGs) in smart cities. This is primarily achieved through an exploratory and correlational analysis of the relationships between smart cities and the so-called "circular cities" by analyzing 393 of the most populated urban areas within the European Union (EU). In the context of this chapter, the smart city concept is operationalized from the perspective of the introduction, development, and usage of smart technologies like AI, ICT, IoT, and big data (Bibri, 2018; Bifulco et al., 2016; Nica et al., 2020; Quan et al., 2019) in the EU cities, while the circular economy is proximally operationalized by looking at the critical constitutive elements of circular economy within the EU cities (Korhonen et al., 2018; Moraga et al., 2019).

Finally, Study 3 elaborates on the definitions and conceptualizations proposed in the previous two studies by relating the concept of smart green cities (Study 1) and smart circular cities (Study 2). In particular, by means of the necessary condition analysis, Study 3 shows that circularity is the necessary (but not sufficient) condition for a smart green city to emerge.

Thus, Study 3 establishes the hierarchical linkage between smart green cities and smart circular cities.

In the last section of the chapter, the findings from the three studies are summarized. Additionally, the concluding section discusses how the results fit into the broader integrative framework of smart sustainable cities. While this chapter focuses on the environmental pillar of smart urban sustainability, a need to understand and operationalize the other three aspects of smart sustainable cities (economic, social, and governance) in future studies on the topic is also emphasized. Hence, the chapter concludes by outlining a comprehensive conceptualization of a smart sustainable city based on the revised ESG framework. Specifically, to comprehensively define a smart sustainable city, the chapter considers three pillars of sustainable development based on the sustainability framework of ESG (environmental, social, and governance). An additional economic pillar of sustainable development is also considered (environmental, social, governance, and economy; the so-called ESGE framework) (Pagano et al., 2018; Tanguay et al., 2010). The chapter argues for the proper integration of the four sustainability pillars in smart city design, planning, and development to achieve sustainable urban growth effectively. From this point of view, a thriving smart city can also be categorized as a smart environmental (or smart eco) city, a smart social city, a smart governance city, and a smart economic city. The notion of a city's "greenness" and "circularity" is closely related to the first type, a smart environmental city, and those constitute a primary focus of this work.

2.2 Literature review

2.2.1 Toward a holistic definition of a smart city

A brief scoping review (or even skimming the related literature on any academic search engine) is sufficient to conclude that, up to date, no universally accepted definition of the smart city exists. This is primarily because the concept is 1) partly a shared socially constructed discourse practice (Haarstad, 2017) and, as such, 2) is applied in many different areas of research and practice (Chong et al., 2018; Ismagilova et al., 2019; Schaffers et al., 2011; Zhuhadar et al., 2017). As no unique, universally accepted definition of a smart city exists, some of the most important of existing definitions are reported in Table 2.1. A careful assessment of definitions reveals considerable heterogeneity in how scholars and institutions envision a smart city.

According to	A smart city is	Main focus
(Hall et al., 2000)	"a futuristic urban center in which all the structures and infrastructures are made safe, secure, green, and efficient by integrating novel digital technologies."	futurism, technology, environment, security
(Odendaal, 2003)	"a city that invests in ICT-related opportunities to promote its affluence and influence."	technology, affluence
(Partridge, 2004)	"a city that actively adopts innovative means to build a society that leverages technology to make the lives of its members better."	technology, affluence
(Komninos, 2006)	"an urban environment centered on education and innovation, combining the creativity of its inhabitants with digital infrastructures."	technology, education, creativity
(Caragliu et al., 2011)	"a city in which investments in social capital and traditional and modern (ICT) infrastructure contribute to sustainable economic growth and enhance the quality of life."	technology, social capital, sustainable growth, affluence
(Su et al., 2011)	"the authentic approach toward the smart planet, applied to a specific region, to improve the integrated informational and management systems of a city."	holistic view, technology, urban management
(Neirotti et al., 2014)	"a city characterized by the ubiquitous use of information and communication technologies in various urban fields to help inhabitants efficiently use its limited resources."	technology, efficiency
(Yigitcanlar et al., 2018)	"an idyllic model for contemporary cities, sustainable and harmonized notion of the economic, societal, environmental, and institutional domains."	utopia, sustainability
(Gong et al., 2019)	"an urban area network that solves traffic, environmental, and energy issues by relying on multiple ICTs."	technology, environmental sustainability
(Ahad et al., 2020)	"a hopeful project adopted globally to make the lives of the urbanites more convenient and inclusive."	utopia, holistic view, affluence, sustainability
(Nunes et al., 2021)	"a concept that emerges in response to the major problems created when specific regions start to attract a higher number of inhabitants."	response to urban problems, sustainability
(Kutty et al., 2022)	"a complex urban ecological system built to optimize challenges and improve the residents' quality of life with the ubiquitous use of data."	ecology, data, affluence
(Cheng et al., 2022)	"a novel urban innovation model that can exert a significant influence on urban green development."	environmental sustainability, technology

(Savastano et al., 2023)	"an area in which ICTs are largely used to increase operational efficiency, quality of services, and the well-being of citizens."	technology, affluence, sustainability

Table 2.1 *Heterogenous definitions of a smart city*

The careful analysis of main themes and topics emerging from the definitions above reveals a gradual shift in smart city discourses (Haarstad, 2017) from a more technologically focused emphasis in the 2000s to an implicit preoccupation with sustainability issues prominent in recent scholarly contributions (Virtanen et al., 2020). This is, indeed, a so-called "sustainability turn" in smart city discourses, as detected through bibliometric means in the Introduction.

Following the above dynamics of the conceptual evolution of a smart city concept, within the framework of this thesis, a city is considered "smart" when it has the characteristics of a complex ecosystem (Lusch & Spohrer, 2012) in which sustainable partnerships and cooperation strategies among the relevant stakeholders must be implemented (Schaffers et al., 2011). This ensures the promotion of a process of sustainable management of the resources in the city in order to improve the well-being and quality of life of its inhabitants (Ismagilova et al., 2019). These considerations are consistent with the definition of a smart city formulated by Li et al. (2019), highlighting that "smart cities aim to provide a more efficient, sustainable, competitive, productive, open and transparent place to live." This is also reflected in the research of Gasco-Hernandez (2018), stating that "A 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. Smart city involves the implementation and deployment of information and communication technology infrastructures to support social and urban growth through improving the economy, citizens' involvement, and government efficiency" (Yeh, 2017). Hence, in this regard, through ICT, it is possible to monitor, understand, verify, evaluate, and plan cities to improve urban sustainability (Bibri & Krogstie, 2017).

The assessment of commonalities between heterogeneous definitions of a smart city allows for the formulation of a more comprehensive and integrated definition in line with the specific goals of the thesis. Accordingly, a smart city is defined here as *an organic urban system that integrates data, resources, policies, and people through technological means to achieve*

aware, sustainable development.

2.2.2 Toward a holistic definition of a green city

In this chapter, the concept of a green city is reconceptualized in line with that of an eco-city (Roseland, 1997). Indeed, initially, and for decades to follow, the concept of a green city was strictly aligned with that of Garden Cities, as devised by Howard (2003). Hence, in this regard, greenness merely implies the integration of cities into the existing natural landscape, which is only a "shallow" way to envision environmental sustainability. Conversely, a deeper understanding of city greenness implies a more holistic understanding of the term.

Given the recently agreed-upon centrality of sustainable development in smart cities (as captured by some of the newest conceptualizations in Table 2.1), one may conclude that a typical smart city is, by definition, green. However, the two terms should be kept conceptually distinct. Generally, urban "greenness" is reified through environmentally sustainable technology development and adoption, but it can also be deployed through other means, like planting trees alongside sidewalks and, in general, expanding the number of green public spaces like parks and other green recreational areas (Li et al., 2016; Sauve et al., 2016). Hence, technology's positive and direct impact on the environment and natural resources (Ahad et al., 2020) is only a part of the global effort to ameliorate the ever-expanding relationship between nature and humans (Odame et al., 2020). In other words, the notion of "green" captures many different aspects of the synergetic development of nature and the social world, not necessarily limited to the technological dimension (Bishop, 2021; Cezarino et al., 2020). Moreover, an excessive focus on the positive aspects of technological innovation may itself be unsustainable. Indeed, for example, as Antwi-Afari et al. (2021) point out, an excessive emphasis on the perceived benefits of innovativeness may hamper the measurement of the development levels of cities of the Global South and, therefore, hinder their sustainable development.

A green city prioritizes environmental sustainability by integrating parts of a city with natural green areas to balance nature and polity (Liu et al., 2022; Macke et al., 2019). Subadyo et al. (2019) define eight primary attributes of a green city: green planning and design, green building implementation, green waste, green transportation system, green water and energy utilization efficiency, green environment, and green community. Likewise, according to Fatimah (2012), the following eight attributes must (co-) exist for a city to be considered

green: green planning and design, green open spaces, green communities, green buildings, green waste, green energy, green water, and green transportation/infrastructure. Another study (Azis et al., 2019) conceptualizes six attributes of a green city. These are green open space, green transportation, green buildings, green energy, green water, and green waste.

Ahad et al. (2020) adopt the term "environmentally sustainable city" or the so-called "eco-city" to describe an archetypal green city. Additionally, Mori and Christodoulou (2012) argue that a green city is an environmentally sustainable city in which development is based on an effort by the current generation to improve a city's environment for generations to come. Similarly, in their effort to identify constituents of a smart sustainable city through principal competent analysis of survey answers of respondents from Kumasi (Gnana), Antwi-Afari et al. (2021) identified four sustainability guidelines for such a city: developing smart policies for smart living, applying sustainable principles for sustainable development, enforcing sustainable practices into the smart city concept, and developing effective plans for continuous improvement.

Regardless of the perspective, being "green" appears to be a necessary (but not sufficient) attribute of a city striving to become sustainable. Several cities worldwide are already well equipped to adhere to major green city initiatives, including green planning and decision-making systems, green regulations and policies, and professional staff supporting the implementation of green urban development. In addition, the importance of smart solutions for urban mobility emerges as a common topic for the conceptualizations of both smart (Macioszek et al., 2022; Macioszek & Cieśla, 2022) and green cities (Azis et al., 2019; Subadyo et al., 2019). Irrespective of the above considerations, however, the concept of a green city has never managed to gain the same level of popularity among scholars and practitioners as that of a smart city. For the purpose of the thesis, and in line with the evidence from the literature, we define a green city as *a city that prioritizes environmental sustainability by integrating natural green areas with urban infrastructure through dedicated policies, urban planning, and urban management efforts aimed to balance nature and urban development while considering future generations' needs.*

According to the evidence provided above, the following hypothesis is formulated:

HP1 There is a positive relationship between city smartness and city greenness.

2.2.3 Toward a holistic definition of a smart green city: an integrated approach

A smart green city is a holistic concept. As Figure 2.1 shows, this implies that all three semantic units composing the term (*smart*, *green*, and *city*) and, therefore, the concepts they denote must be dynamically integrated to form a harmonized entity, a smart green city. Without synergies between the three components, a city may quickly regress toward another polluted but technologically advanced urban center or a mere green city immersed in the stunning natural landscape but relying on old and inefficient technological infrastructure.

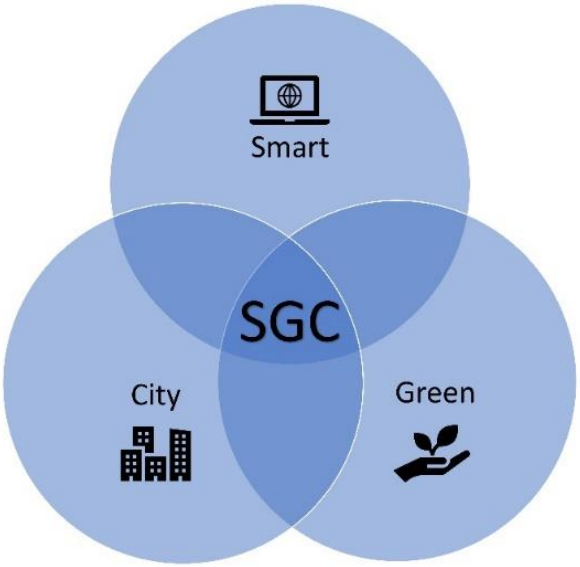


Fig. 2.1 *An integrated approach to smart green cities*

Greenness is integral to some smart city definitions (see Table 2.1 and the bibliometric assessment in the Introduction). Thus, scholars might argue that the smart city concept is identical to the smart green city because environmental sustainability has already been incorporated into the former. Indeed, according to Razmjoo et al. (2022), smart city technologies and implementations such as the Internet of Things improve energy and traffic management, the resilience of buildings, and, in general, diminish the environmental impact of urban areas when they are adopted. However, there are several reasons why greenness can benefit from being emphasized and differentiated from the notion of smartness.

Firstly, even if some smart city concepts inherently include environmental sustainability, this is not true for all the definitions. Kramers et al. (2014) argue that only a relative minority of definitions contain explicit environmental sustainability objectives. Secondly, there are real-life examples of technologically advanced cities struggling with environmental sustainability

goals (Zhang et al., 2018). Thirdly, the analytical mapping of smart cities performed by the EU (*Europe 2020*, 2013) revealed that smart mobility is the most common smart city implementation, constituting 21% of all smart city initiatives. The other "greenness"-related goals are often neglected (Janker & Mann, 2020). Lastly, none of the proposed smart city definitions (Table 2.1) explicitly mention an environmentally sustainable city. While scholars of smart cities might do just fine without integrating the aspects of greenness in their definitions, the issue becomes of utmost importance for a smart green city (Brilhante & Klaas, 2018; Palumbo et al., 2021).

In this chapter, the conceptualization of a smart green city is based on the six attributes of green cities identified by Azis et al. (2019) while also considering all the above-mentioned issues and concerns. Like in the case of a smart city definition, for the purpose of the chapter, a smart green city is holistically defined as *an organic urban system integrating data, resources, policies, and people through technological means to achieve an aware, environmentally sustainable development in transportation, buildings, energy, open spaces, water, and waste management areas.*

According to the above evidence from the literature, the following hypothesis is formulated:

HP2 A smart green city is a distinct category of cities that exhibits the traits of both green and smart cities.

2.2.4 Toward a holistic definition of a circular city

A circular city is an urban metaphor intrinsically connected to that of a green city, be it the original "cities in the parks" or Garden Cities conceptualization by Howard (2003) or a more recent re-conceptualization of greenness in the form of eco-city (Roseland, 1997). Indeed, the notion of a green city, as defined in the thesis, is closely aligned with the latter but also integrates some of the aspects of the former. In this regard, a circular city is simply a particularization of a green city concept, and, as such, it instantiates a part of green city characteristics. In particular, the concept of a circular city is closely aligned with that of urban metabolism (Stren et al., 1992), intended as "the sum total of the technical and socio-economic process that occur in cities, resulting in growth, production of energy and elimination of waste" (Kennedy et al., 2007). A circular approach to how the said processes and the related resources are managed in cities is believed to "significantly reduce the consumption of finite resources globally" (Williams, 2019).

For the purpose of this sub-section of the literature review, the most common and agreed-upon definitions of a circular city are listed in Table 2.2. Readers who are interested in more in-depth reflections and considerations on the concept, as well as its contextual parameters, are advised to reference the dedicated sections of Chapter 4 of this thesis.

According to	**A circular city is**	**Main focus**
(Kennedy et al., 2007)	"the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste."	urban metabolism, elimination of waste, energy production, sustainable growth
(Taylor Buck, 2017)	"the application of circular metabolism in cities, including biomimetic urban design approaches."	urban metabolism, biomimetics
(Marin & De Meulder, 2018)	"a city in which urban centers become consumers of waste and generators of the resources necessary for their maintenance through optimized and prolonged life cycles."	holistic approach, waste management, sustainability
(Prendeville et al., 2018)	"a city in which circular economy principles are practiced, involving the participation of inhabitants, businesses, and researchers to achieve a future-poof city."	holistic approach, long-term sustainability
(Girard et al., 2019)	"a city that reduces the number of inputs by reusing materials, energy, water, nutrients, and others in order to preserve natural, manufactured, and social capital."	reduction of waste, sustainability
(Skar et al., 2019)	"a city relying on complex interactions of resource flows, urban dwellers, and urban space for regenerative management of these flows through reduction, reuse, and recycling."	complexity, holistic approach
(Williams, 2019)	"a framework seeking to provide an urban-responsive approach to the management of resources."	resource management
(Paiho et al., 2020)	"a city based on closing the resource loops as far as possible after liner efficiency improvements, resource sharing, servitization, and virtualization efforts have been exhausted."	resource management, last resort solution
(Baganz et al., 2020)	"an urban concept envisioning city as a regenerative and restorative system that aims to eliminate waste and make resources management more efficient over time."	holistic approach, restoration, regeneration, resource management
(Marjanović et al., 2022)	"a city in which a set of activities, sectors, services, resources, lifestyles, and practices are integrated into circular economy practices in such a way that it has a contextualized and	holistic approach, sustainability, integration

	socially inclusive circular system."	
(Horn & Proksch, 2022)	"implementation of circular approaches to urban resource consumption and production to render the global management of finite resources more efficient."	consumption, production, holistic approach, efficiency

Table 2.2 *Heterogenous definitions of a circular city*

One thing in common among the heterogeneous definitions presented above is the holistic approach most authors implicitly or explicitly invoke. In this regard, Prendeville et al. (2018) emphasize the importance of the participation of all city stakeholders, including institutions, businesses, inhabitants, and researchers, in bringing about circularity initiatives, both from the side of production and consumption (Horn & Proksch, 2022). Hence, while the circular approaches go beyond the mere technological dimension (Marjanović et al., 2022), the outlined holistic goal of societal integration around the notion of circularity is hard to imagine without relying on the sociological compression of time and space that recent integrated ICT solutions for cities offer (Bifulco et al., 2016; Kramers et al., 2014). In this regard, while circular cities are not necessarily smart, and smart cities are not necessarily circular, a clear conceptual connection between the two supposedly exists (Viglioglia et al., 2021) (as is proven in the concludion chapter of the thesis).

For the purpose of the analyses in this chapter, and based on the assessment of major circular city definitions in Table 2.2, a circular city is defined here *as a city that embodies regenerative and sustainable practices, aiming to minimize waste, optimize resource use, and enhance resilience through circular economy principles by integrating the collaboration among city stakeholders for self-sustaining, inclusive, and eco-friendly environments, preserving natural capital for long-term prosperity.*

Given the above consideration on the importance of a holistic approach and collaboration when it comes to the successful deployment of circular cities and the potential role of ICTs and other smart city implementations in bringing about such collaboration by facilitating communicative practices among stakeholders, the following hypothesis is advanced:

HP3 There is a positive relationship between city circularity and city smartness.

2.2.5 Toward conceptualizing a smart circular city: an integrative approach

As can be inferred from the literature, a smart green city qualifies as empirically valid and

distinct because, besides satisfying the requirements of a smart city concept, 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.

From this perspective, circularity-oriented smart green cities are 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 (de Jong et al., 2015; Deakin & Reid, 2018; Thompson, 2017; Yigitcanlar, Kamruzzaman, 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 (Castagna et al., 2014; Williams, 2021). Infrastructure digitization, in particular, should be used to develop circular economy models within smart urban areas. Indeed, gathered data should be used to identify "potential productive uses of waste streams in real-time" (Martin et al., 2018). Additionally, for a sustainable future for cities to unfold, the circular economy should answer the challenges that urbanities face by taking into consideration the prescriptions published in 2019 by the OECD (Bibri & Krogstie, 2017; Pevcin, 2019; Yigitcanlar et al., 2018).

Overall, a potential nested relationship exists between the two conceptualizations: a smart green city and a smart circular city. In this regard, a plausible claim is that all truly smart green cities have all the infrastructural potential to go circular. Indeed, smart green city initiatives and projects appear to play a crucial role in promoting the circular economy and related sustainability outcomes (Damianou et al., 2019). For example, Damianou et al. (2019) give an overview of how the impact of smart sustainable city initiatives (focusing primarily on environmental, "green city" pilar of sustainability) promotes circular economy therein, particularly in the water and wastewater management, waste management, and energy sectors. When it comes to the "smartness" aspect, Viglioglia et al. (2021) emphasize the central role of ICTs in promoting circular economy principles. Similarly, the use of blockchain combined with the well-developed IoT infrastructure is cardinal for the effective transition from linear to circular economy types in a city (Damianou et al., 2019).

Hence, a necessity logic appears to apply when it comes to the relationship between a smart green city and a smart circular city. In particular, being a smart green city constitutes a necessary (but not sufficient) condition for a proper smart circular city to emerge. Consequently, the relationship depicted in Figure 2.2 also implies a sufficiency condition: indeed, being a smart circular city appears to be a sufficient (but not necessary condition) to

be considered a smart green city. In fact, according to Damianou et al. (2019), true smart circularity would necessarily require proper smart green city infrastructural support to emerge—hence, it is hard to envision a smart circular city outside the framework of a smart green city. On the contrary, a city that relies heavily upon circularity principles but is not technologically advanced will surely be considered a green city, but not a proper smart green city (Figure 2.2).

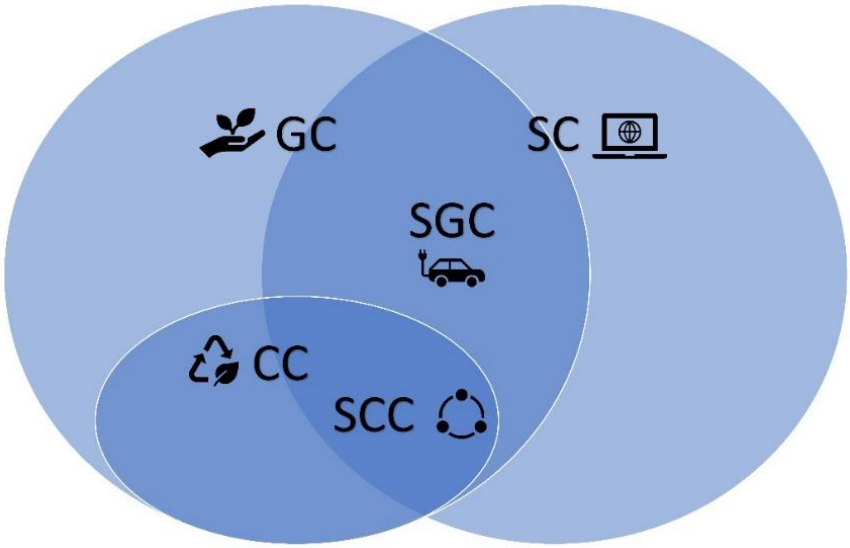


Fig. 2.2 *An integrated approach to smart circular cities*

Note: GC—green city; SGC—smart green city; SC—smart city; CC—circular city; SCC—smart circular city

The circular economy initiatives applied within smart green 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 (Geissdoerfer et al., 2017). In the context of the relationship between smart green cities and the circular economy, adopting a systemic, holistic approach is also necessary since a multiplicity of actors, sectors, and goals are involved (Nunes et al., 2021). In this scenario, interdependencies, circular processes, and implemented synergies increase entrepreneurship, resilience, and, therefore, the growth and development of smart green cities (Nunes et al., 2021).

To face globalized economic competition, energy needs, and ecological-social challenges, smart circular cities must produce synergistic and efficient interactions based on circular

economic models that also stimulate citizens' creativity (Fusco Girard, 2013; Yigitcanlar, Han, et al., 2019). From this perspective, many European cities have included objectives relating to the transition to a circular economy in their agenda in an attempt to reduce systemic entropy through cultural projects aimed at empowering civil society (Talamo et al., 2019). In the context of this thesis, a smart circular city is defined as *a city that integrates smart city infrastructure and sustainable urban development practices to enhance citizens' well-being and quality of life by implementing circular economy principles.*

According to the evidence from the literature provided in this subsection, the following hypotheses are formulated:

HP4 A smart circular city is a distinct category of cities that exhibits the traits of both smart and circular cities.

HP5 Being a smart green city is a necessary condition for a smart circular city to emerge.

2.3 Study 1: Exploring the relationship between smart cities and green cities

2.3.1 2.3.1 Methodology

2.3.1.1 *Reasons for the analysis and data collection*

The primary reason for the analyses in Study 1 is to provide the conceptualization of a smart green city (SGC) with a solid empirical basis upon which future studies can be conducted. Indeed, for the proposed definition of smart green city to hold (see the Literature Review section), it is essential to show that, on the one hand, smart cities and green cities are distinct concepts, as being "smart" is not a necessary condition for "greenness," and, on the other hand, smart city and green city initiatives can be implemented in tandem and with mutual benefits (as is expected in a typical smart green city).

As a simple unrestricted query on Scopus shows (*TITLE ("smart green city")*), the topic of smart green cities—as a specific environmentally-focused instance of smart sustainable cities—is mainly unexplored and novel (the first article dates back to 2011). Chiefly, no empirical effort has been put in place to validate the concept on the inter-regional level of analysis. Indeed, most studies on smart green cities assume the localized perspective of one city/one region/one area (Antrobus, 2011; Hossain et al., 2018; Kim et al., 2012).

To address the abovementioned epistemic gap, both the smartness and greenness of a city are operationalized here according to the amount of online media attention the related smart and

green urban initiatives have received from the (online) press. This is done in order to create context-free indices and render cities around the world comparable. Then, correlational and principal component analyses are performed to understand the relationship between urban smartness and greenness and their relationship to general urban growth.

To avoid the difficulties of satisfying a stringent set of assumptions necessary for statistical inference (Poole & O'Farrell, 1971), and given the relatively small population size of big cities with more than a million inhabitants (defined here as megapolises), the entirety of the statistical universe of over-one-million-inhabitants urban centers worldwide is analyzed. This is primarily done because 1) most of the technological innovation is concentrated in big cities—thus, they are the proximal candidates for becoming the first true SGCs; and 2) according to the data from the World Cities Database (*World Cities Database | Simplemaps.Com*, 2020), up to 26% of the world's population already lives in cities with over one million inhabitants.

Therefore, the inferential model

$$greenness = \alpha + \beta * smartness + \varepsilon$$

where ε represents a random error term, can be substituted with the descriptive statistical equation derived from the analysis of the entirety of the world's megapolises became

$$greenness = a + b * smartness$$

where *a* and *b* are the two linear parameters estimated through the ordinary least squares (OLS) approach; consequently, *a* is interpreted as a baseline level of smartness in a city with no greenness, and *b* is interpreted as the strength and direction of the linear relationship between smartness and greenness of a generic megapolis.

The data was gathered relying on the newest version of the World Cities Database. As stated by the database creators, all data for non-U.S. cities comes from the National Geospatial-Intelligence Agency, while the data for US cities is taken from the US Central Bureau and US Geological Survey (*World Cities Database | Simplemaps.Com*, 2020). A subset of 498 cities with over one million inhabitants was identified and selected. There are different methods to estimate a city's population (Macionis & Parrillo, 2010; Pacione, 2009). However, for the purpose of the analyses, the metropolitan area was considered instead of the city proper. Nevertheless, even if the other estimation method were adopted, the analytical outcomes would have been similar, as only a handful of cities would have been excluded from the analyses (around the threshold of one million inhabitants).

2.3.1.2 *Smartness and greenness: operational definitions*

Different methods exist to operationally define greenness and smartness. For example, Giffinger and Pichler-Milanović (2007) adopt a six-dimensional typology to classify European cities according to the level of smart city development (smart economy, smart people, smart governance, smart mobility, smart environment, and smart living). Similarly, Zygiaris (2013) uses six levels of analysis to identify and classify smart sustainable cities (innovation, application, integration, instrumentation, interconnection, environment, and the city itself). One of the recent contributions to the methodology is that of Antwi-Afari et al. (2021). The authors used principal component analysis to identify four sustainability guidelines for a smart, sustainable city (developing smart policies for smart living, applying sustainable principles for sustainable development, enforcing sustainable practices in a smart city, and developing effective plans for continuous improvement).

However, given the scope of the chapter's analyses, any context-dependent method can be detrimental to its goals. In fact, the chapter outlines a comprehensive viewpoint on sustainable urban development that goes beyond a country-level analysis because it intends to provide a Wallersteinian world-system inter-regional point of view on the topic (Ritzer & Stepnisky, 2021). Therefore, ideally, the two indices should make cities worldwide comparable in terms of smartness and greenness. Accordingly, they should be independent of a city's specific geographical, social, and economic contexts.

Consequently, the two indices were devised based on the number of search results in the Google News section, equating media coverage with the approximate number of smart and green urban initiatives implemented therein. In short, the more frequently different green and smart initiatives of a city are discussed in the online press, the higher its smartness and greenness should be. To derive the indices of smartness and greenness, the following formulas were used:

$$Smartness \text{ index} = \frac{results\ for\ "smartness"}{total\ results}$$

$$Greenness \text{ index} = \frac{results\ for\ "greenness"}{total\ results}$$

where *results for "smartness"* and *results for "greenness"* indicate the number of Google News results for a specific city concerning the news articles on green and smart initiatives implemented (or that are going to be implemented) therein (Schraven et al., 2021).

In particular, for greenness, the name of each city in the dataset was separately searched in combination with the following keywords*: environmentally sustainable, green space, green transportation, green buildings, green energy, green water,* and *green waste* (for example, *Tokio green space, Tokio green transportation,* and so on). For smartness, each city's name combined with the following keywords was separately searched: *technology, IoT, AI, ICT, big data,* and *blockchain* (for example, *London big data, London, IoT,* and so on). The keywords for both searches were identified based on the analytical literature review results as reported in the previous section. The variable *results for "greenness"* is the sum of search results related to "greenness" keywords for each city in the sample. Likewise, the variable *results for "smartness"* indicates the sum of results for "smartness" keywords for each specific city. The variable *total results* is the total number of news articles concerning a specific city (by merely searching its name on Google News).

The advantages of the two indices are as follows:

- they are relative (ranging between zero and one). Zero indicates the complete absence of news articles related to the greenness or smartness initiatives in a specific city, while one indicates the hypothetical situation in which all city-related news articles are related to greenness or smartness initiatives;
- both are pure numbers. Therefore, different cities worldwide can be compared without having to deal with context specificity, ensuring that the units of measurement do not influence the resulting analyses.

2.3.2 Analyses and results

According to the World Cities Database (2019), nearly 26 percent of the world's population resides in cities with over one million inhabitants. Figure 2.3 shows the respective boxplot depicting the distribution of cities in the sample according to the population.

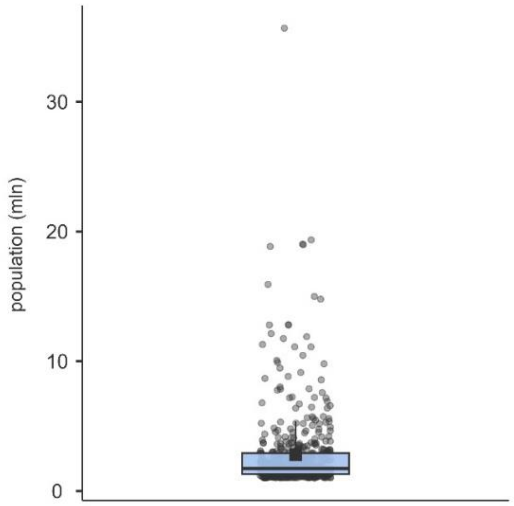


Fig. 2.3 *Relating smartness and greenness. A visual summary of the population distribution (in mln)*
Note: dots represent single data points (cities worldwide). The black square represents an arithmetical average

The kernel density estimation (N = 498, bandwidth = 0.3176) of the analyzed cities according to their populations (Figure 2.4) shows a marked right-skewness, with the average number of inhabitants equal to 2.8 and the median equal to 1.7 million (a slight rightmost fluctuation corresponds to the city of Tokyo, the biggest one in the dataset). Overall, China has contributed to the right-skewness of the density distribution the most (Figure 2.4), as the majority of Chinese cities in the dataset have a population between 1 and 1.5 million inhabitants, and around one-fifth of the world megapolises in the dataset are Chinese (see Figure 2.5).

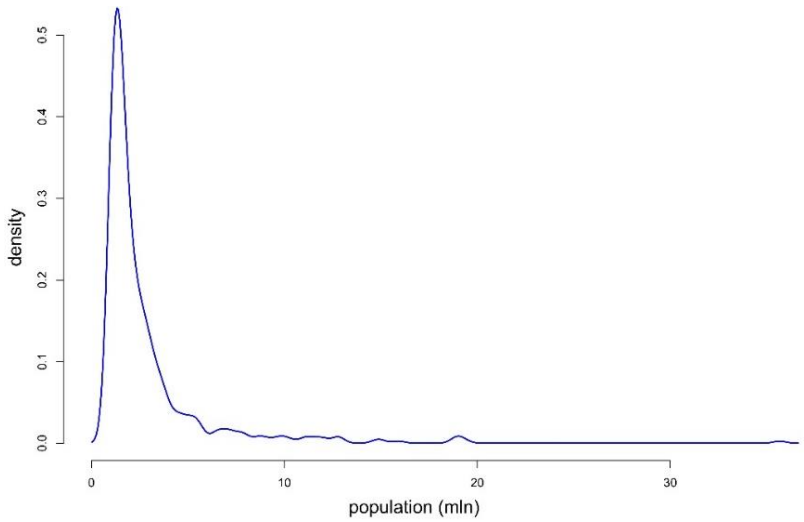


Fig. 2.4 *Relating smartness and greenness. Kernel density estimation of the population of the world's megapolises (over one million inhabitants)*

Among the countries represented in the sample, four have contributed the most to the dataset: China (109 cities), the United States of America (50 cities), India (44 cities), and Brazil (21 cities). These countries alone contain roughly 45 percent of all the world's megapolises. The bar plot showing all the countries with more than five cities with a total population of over one million inhabitants is shown in Figure 2.5.

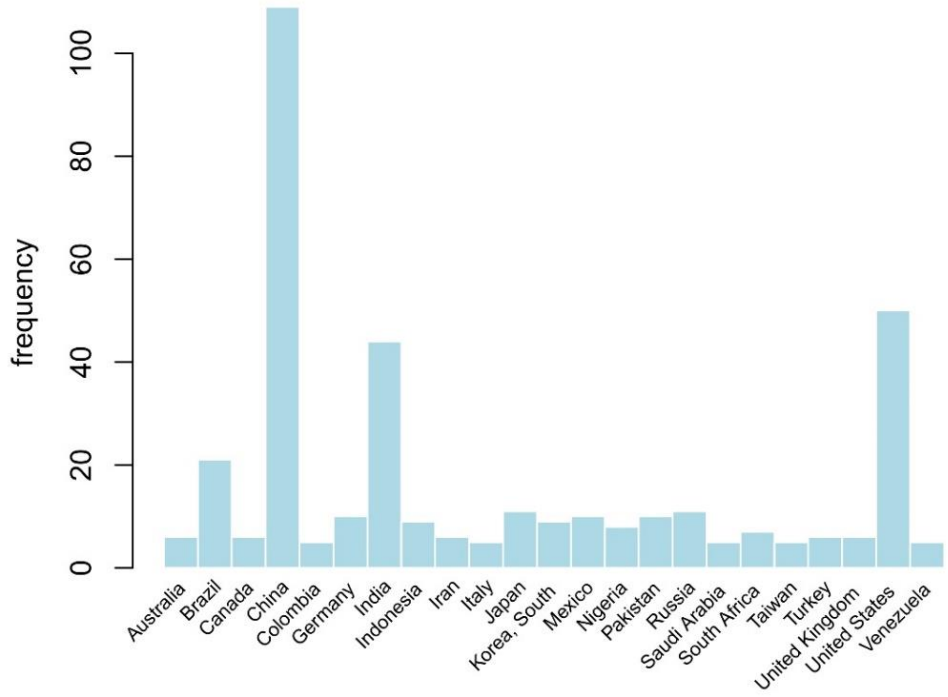


Fig. 2.5 *Relating smartness and greenness. Countries with more than five megapolises (over one million inhabitants)*

After obtaining the indices of greenness and smartness for all 498 megapolises according to the formulas reported in the previous sub-section, a linear regression was performed to understand the relationship between the greenness and smartness of a generic big city. As the statistical universe of megapolises (defined here as metropolitan areas with more than one million inhabitants) coincided with the sample, the assumptions of Gauss-Markov did not need to be satisfied nor checked for the model to retain its validity, as the model in question was gained by descriptive and not inferential means. The following equation captured the relationship between *Smartness* and *Greenness* indices:

$$Greenness \text{ index} = 0.003 + 0.352 * Smartness \text{ index}^{3}$$

[3] For intercept: SE = 0.0002862; t = 10.915; p-value < 2e-16
For independent variable: SE = 0.0656; t= 5.364 p-value = 1.253-07

The equation reveals the positive relationship between the indices of *Greenness* and *Smartness*. The R-squared index is equal to 0.054, suggesting that roughly 5.4 percent of a big city's greenness is related—in some form or another—to its smartness. While the number may seem small, for such a complex phenomenon as a large city, with multiple other factors potentially contributing to its greenness, 5.4 percent represents a substantial amount of explained variance.

Given the difficulty of interpreting the angular coefficient of the above model, a logarithmic transformation of both indices was performed to quantify the nature of this relationship more accurately. The resulting linear model is reported below:

$$log_greenness = -4.57 + 0.26 * log_smartness$$ [4]

The R-squared index for the second model is equal to 0.18. In this case, an angular coefficient of 0.26 represents the relationship between greenness and smartness that can be interpreted in terms of elasticity: for a one percent increase in a city's greenness, its *Smartness* index should rise by 0.26 percent. Figure 2.6 shows the related scatterplot with the regression line for the log-log transformed model.

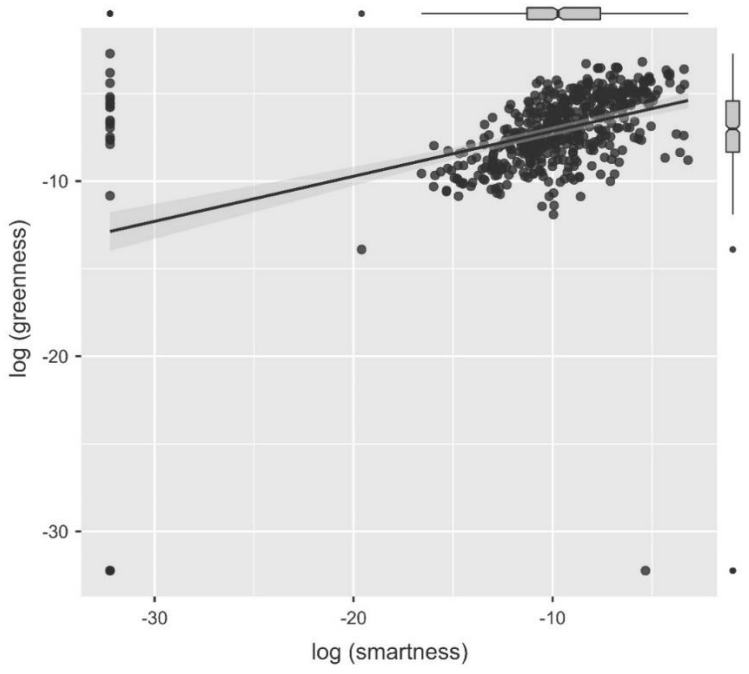


Fig. 2.6 *log-log relationship between a city's smartness and greenness*

[4] For intercept: SE = 0.29294; t = -15.6; p-value < 2e-16
For independent variable: SE = 0.02481; t= 10.38; p-value < 2e-16

To verify whether a city's population can significantly influence its smartness and greenness, the hypothesis of independence between pairs of categorical variables was tested (four *greenness* categories against four *size* categories; four *smartness* categories against four *size* categories). Accordingly, two qualitative categorical smartness and greenness-related variables (*smartness categorical* and *greenness categorical*) were created according to the four quartiles of the related continuous distributions. Therefore, four categories for each variable were derived ("not green" < 0.000243, 0.000243 < "less green" < 0.0008994, 0.0008994 < "green" < 0.0044335, "very green" > 0.0044335; and "not smart" < 0.00001261, 0.00001261 < "less smart"< 0.00005999, 0.00005999 < "smart" < 0.0004997, "very smart" > 0.0004997). The cut-off thresholds were established according to the values of the first, second, and third quartiles for both indices. The same procedure was performed for the *population categorical* variable, creating four categories ("less populated" < 1.28 million, 1.28 million < "moderately populated" < 1.73 million, 1.73 million < "highly populated" < 2.92 million, "very highly populated" > 2.92 million), once again, established according to the values of the first quartile, median, and third quartile.

To begin with, the contingency table relating to categorical smartness and greenness indices was assessed as a form of robustness check of the above regression results. Indeed, in line with the regression results, two indices were associated (p-value < 2.2e-16; df = 9, X-squared = 177.64). More specifically, as shown in the balloon plot in Figure 2.7, "very smart" cities tend to score highest in *greenness.* On the contrary, cities not considered smart (as operationalized through the *smartness* index) also tend to be the least "green."

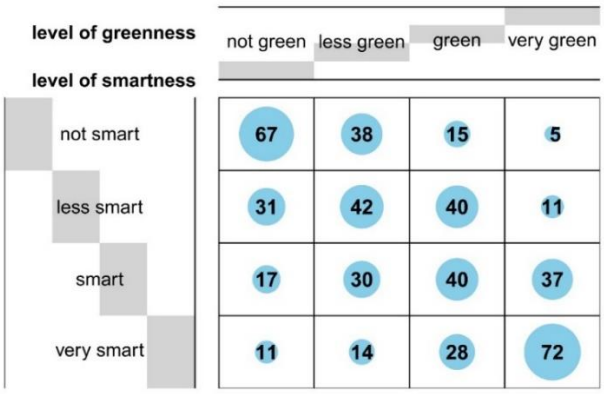


Fig. 2.7 *Association between smartness and greenness categories*

Then, two Pearson's chi-squared tests were performed on the obtained contingency tables to

test associations between smartness and population, as well as greenness and population. The first test (p-value = 1.004e – 05; df = 9; X-squared = 39.337) rejected the null hypothesis of independence between smartness and population size. For the second test (p-value = 0.047; df = 9; X-squared = 17.07), the null hypothesis of independence between greenness and population size was also rejected at a 0.05 percent level. Thus, for the two tests, it can be concluded that significant relationships exist between the two indices and the population size. Figures 2.8 and 2.9 show the respective balloon plots reporting joint frequencies for the three categories. As can be seen in the figures, most populated cities tend to concentrate where greenness is not that high, and, on the contrary, the majority of "very green" cities are not "very highly populated." The situation is somewhat specular in the case of the *smartness* category, with most populated cities being either "not smart" or "very smart." The latter, indeed, hints at the existence of a hidden variable or the set of variables moderating the relationship between the smartness and the population of a city.

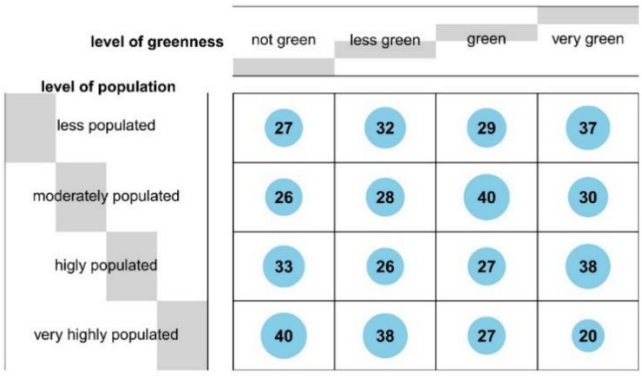


Fig. 2.8 *Association between greenness and population categories*

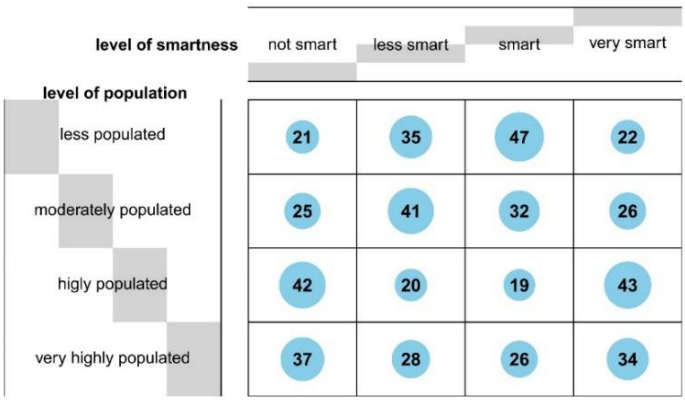


Fig. 2.9 *Association between smartness and population categories*

To better understand the nature of the above relationships, two additional linear regressions were performed in order to evaluate the direction and strength of the relationships between a megapolis's smartness, greenness, and population size. As for the relationship between population and smartness, the regression coefficient was positive (0.000094; SE= 0.000062; t = 3.654; p-value = 0.000286); conversely, the regression coefficient was negative for the relationship between population and greenness (-0.0002; SE = 0.0000902; t = -2.46; p-value = 0.0142), suggesting that a larger city population may be advantageous for smartness but detrimental to greenness.

The results were further confirmed by a principal component analysis (PCA) applied to the three quantitative continuous variables (*Smartness* index, *Greenness* index, and *population*). Given the heterogeneous nature of the indices, all three were scaled to unitary variance before entering the analysis. Three components were identified (equal to the starting number of variables), and the first two captured 76 percent of total inertia (see Figure 2.10). Figure 2.11 shows the correlations of three active variables with the two most significant dimensions. Again, as a form of robustness check, PCA confirmed the hypothesized direction of the relationships, both between the *Smartness* index and the *Greenness* index and between the latter two and the *population*.

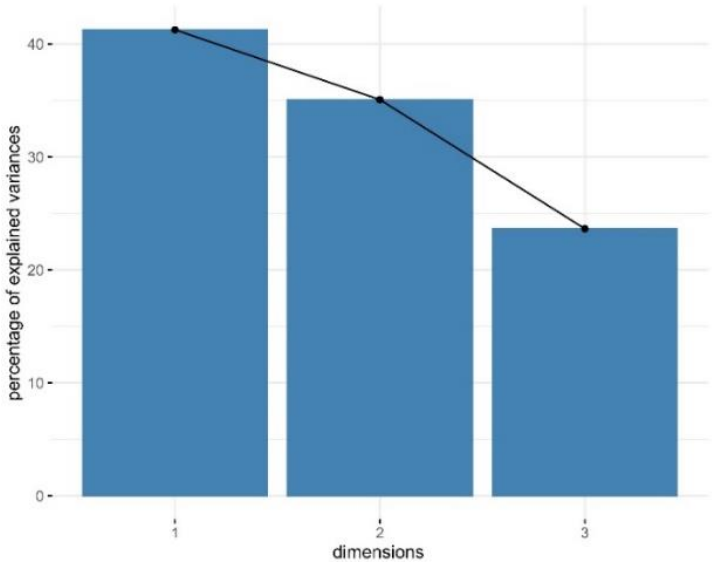


Fig. 2.10 Relating smartness and greenness. Scree plot

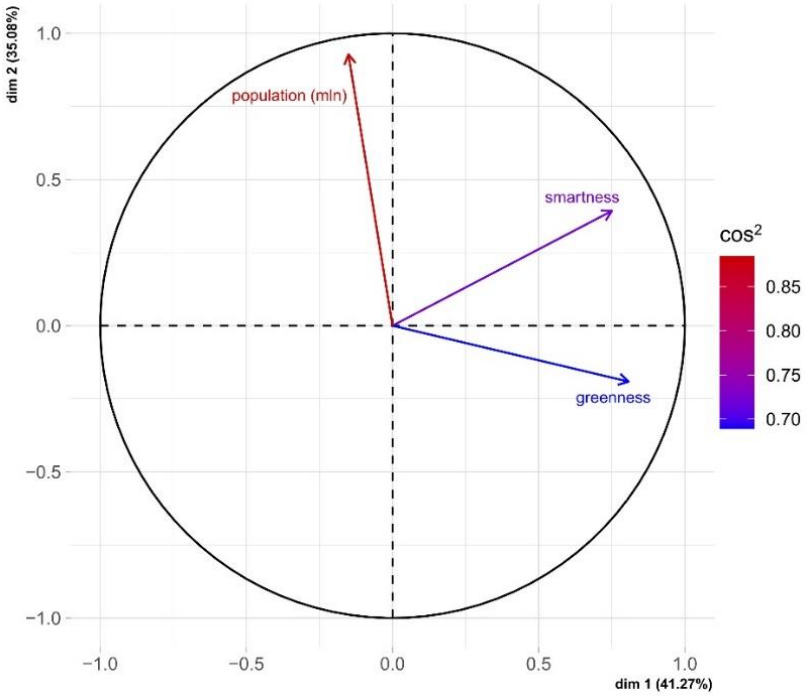


Fig. 2.11 *Relating smartness and greenness. PCA active variables*

Note: cos² denotes the quality of the representation of variables on the plane

As revealed by the PCA, cities scoring high on the horizontal axis (the first component) were more likely to have higher indices of both *Smartness* and *Greenness*. Cities with high values of the second component (vertical axis) were those with larger populations. Once again, smartness and greenness appear to be positively correlated (along the horizontal dimension). However, greenness is negatively correlated with a city's population (along the vertical dimension). Conversely, smartness is positively related to a city's size (along the vertical dimension). The results, therefore, suggest a likely moderating effect of population on the relationship between the city's greenness and smartness.

According to the most straightforward interpretation of the PCA results (Figure 2.11, Dim 1), the coordinates of cities along the first principal component were interpreted as the expression of the joint smartness and greenness of a generic big city. As a result, the coordinates of the first PCA dimension were fetched from the analysis and then standardized (mean-centered and scaled to unitary variance). The resulting distribution (Figure 2.12) is the proximal operationalization of a *Smart Green City (SGC)* index. The distribution is asymmetric, with a marked skewness to the tight, suggesting the real-life presence of a few singular instances of cities that could be considered proper reifications of the concept of a smart green city.

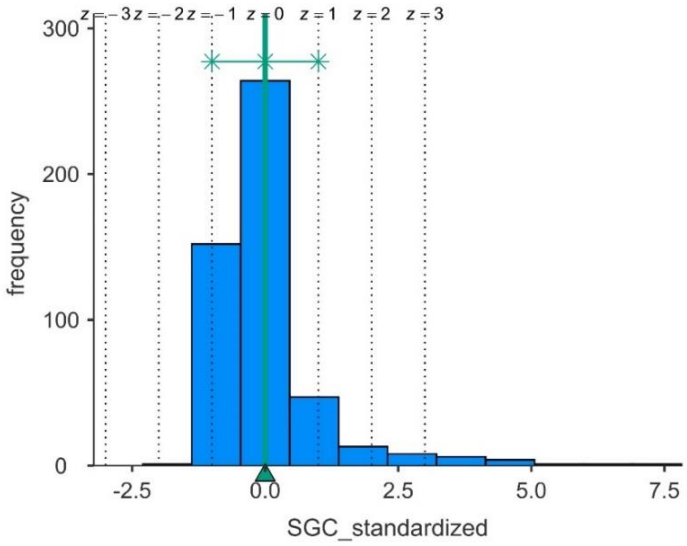


Fig. 2.12 *The distribution of Smart Green City index*

To provide another form of robustness check and to better identify those real-life examples of ideal types (in a strictly Weberian sense) of smart green cities, hierarchical agglomerative clustering was performed on the three PCA dimensions. In particular, the Euclidean distance was chosen to measure the similarity between individual data points (i.e., cities in the dataset). Ward's linkage method was used to ensure partitioning with small within-class variability and high between-class variability. Figure 2.13 shows the resulting cluster dendrogram projected onto the first two PCA dimensions (with dots denoting individual papers). The partitioning of cities into four clusters was deemed optimal by the R package used for the analyses (Factoshiny). In particular, the function first built a hierarchical tree. Then, the sum of the within-cluster inertia was calculated for each partition. The suggested partition was the one with the higher relative loss of inertia [i.e., (i(clusters n+1)/i(cluster n))]. As a result, additional inertia gains from considering the fifth cluster and onward were inconsequential.

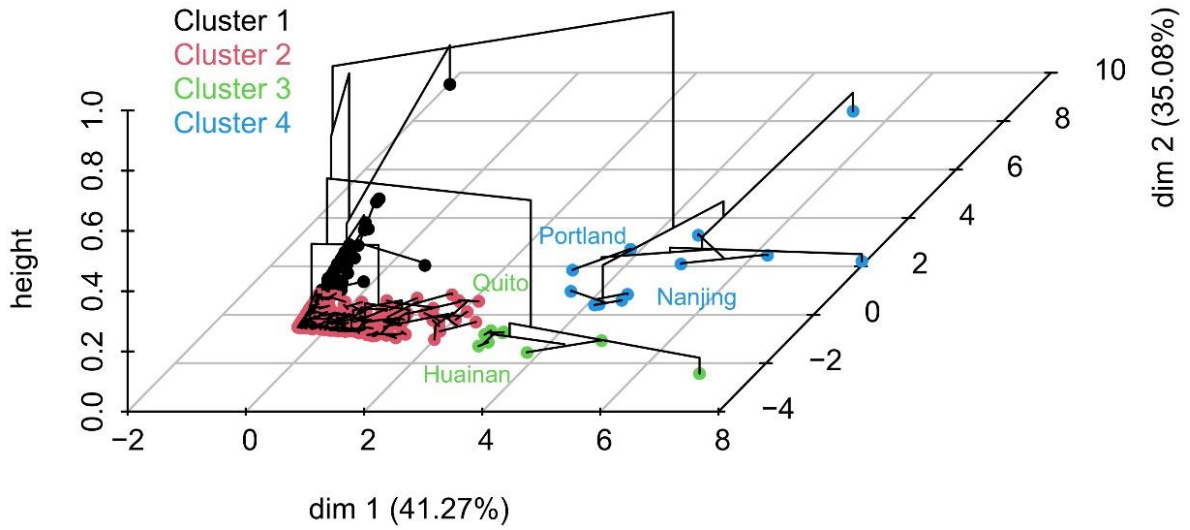


Fig. 2.13 *Relating smartness and greenness. Cluster dendrogram projected on the first two PCA dimensions*
Note: Dots represent the actual distribution of cities over the factor map. Most individual city names are omitted for better presentational clarity

According to the results, Cluster 2 (red) turned out to be the most numerous, followed by Cluster 1 (black) and Cluster 4 (blue). Cluster 3 (green) was the least numerous, with only nine cities therein. In terms of the related composition, Cluster 1 is primarily defined by cities that are highly populated (17.2; p-value < 0.05) but also not particularly green (-2.65; p-value < 0.05) or smart (-1.54; p-value < 0.05). Specifically, the numbers between the parenthesis are to be interpreted in the following manner: being highly populated significantly increases the probability of a city being part of the cluster. On the contrary, both smartness and greenness slightly diminish the chance of a city being part of the cluster. Hence, overall, Cluster 1 is composed of cities that are highly populated but also not smart and not green. Those are, for example, New York, Mexico City, Delhi, Sevilla, Moscow, and Paris.

Similarly, Cluster 2 is defined by cities that are less green (-6.22; p-value < 0.05), less smart (-7.82; p-value < 0.05), but also relatively smaller (-14.6; p-value < 0.05). As an example, Cluster 2 contains the following cities: Sūrat, Riyadh, Chittagong, Baoding, Alexandria, The Hague, and Chelyabinsk. Hence, considering the numerosity of both clusters, it is safe to conclude that most cities worldwide with more than a million inhabitants cannot and should not be considered either smart, green, or both. Consequently, cities that are smart, green, or both are, as of now, rather an exception from a general trend.

Cluster 3 is defined primarily by cities that are green (15.3; p-value < 0.05) but not smart (-0.12; p-value < 0.05) and less numerous (-0.666; p-value < 0.05). This further confirms the

conceptual distinction between green cities and smart cities and enforces the argument for keeping the two concepts theoretically distinct. In particular, a common characteristic of all the cities in Cluster 3 is their geographical location. While being scattered across the continents, all the archetypical "green" cities (as operationalized through the methodology here adopted) are either deeply embedded into or integrate vast expanses of untouched nature.

An example of both natural landscape integration and embeddedness is Quito, the capital of Ecuador. Located close to the Pichincha volcano, at an altitude of 2820 meters, the city is surrounded by mountains and forests. However, a part of the urban landscape of the city is El Panecillo (0.2303° S, 78.5192° W), a famous hill with a statue of the Virgin Mary at the top. Seamlessly integrated into the city's panorama, it offers a 360-degree view of Quito and is a famous tourist attraction therein.

Another apparent characteristic of identified "ideal types" of green cities is the presence of large-scale sustainability-oriented projects. This is the example of Huainan (China) and its Sungrow Huainan Solar Farm, once the largest floating solar array, with a capacity of 40 MW, built on an artificial lake (32°47′21″N 116°51′13″E) built on the outskirts of the city.

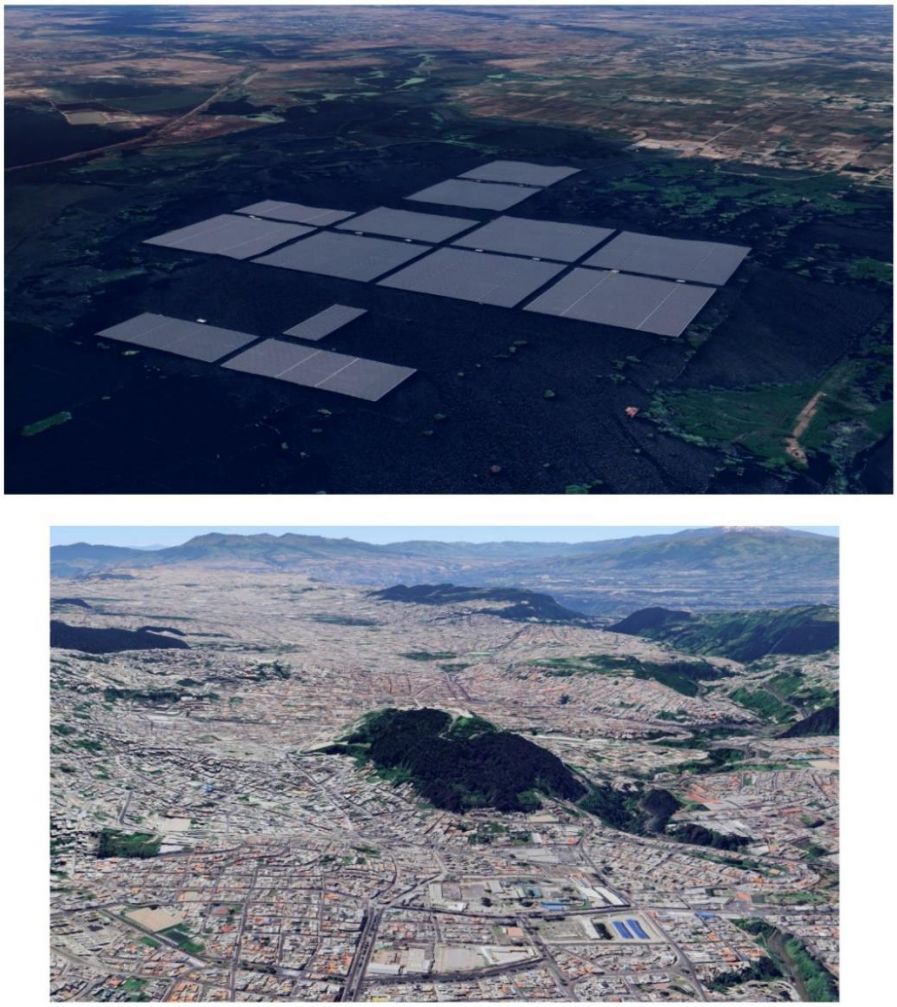


Fig. 2.14 *Green cities. Two examples*

Note: top—Huainan and its solar farms; bottom—cityscape of Quito and the view of El Panecillo. Data openly available on Google Earth

Finally, Cluster 4 is the most interesting out of the four from the perspective of this chapter, as it is composed of cities that are both smart (19.4; p-value < 0.05) and relatively green (4.82; p-value < 0.05). The role of the population in the formation of the cluster is less pronounced but is nonetheless slightly positive (1.14; p-value < 0.05). Given the contributions to the formation of the cluster and the fact that cities composing the cluster scored the highest in the *Smart Green City* index (according to their coordinates along the first dimension of PCA results), those can be readily considered as real-life examples of prototypical smart green cities.

A good example from the cluster is Nanjing (32.0584° N, 118.7965° E), the capital of Jiangsu province of the People's Republic of China, a truly ambitious smart sustainable city (Liu et

al., 2022). Considered a "megacity" with almost ten million inhabitants within the metropolitan area, it has been ranked second in the evaluation of cities with the most sustainable development in the region (Liu et al., 2022). Moreover, it does not shy away from implementing more conventional smart city initiatives related, for example, to ICT expansion (Cai et al., 2020).

Another instance of a city from the cluster (that is not Chinese, as most cities within Cluster 4 turned out to be) is Portland, Oregon (45.5152° N, 122.6784° W). From the point of view of the "greenness" dimension, the city is a good example of a seamless and successful integration of natural and urban (Portney, 2005). Famously, Portland is considered a truly sustainable city and one of the world's best-planned polities, with a reputation as a forward-thinking city regarding land use and public transportation (Abbott, 1997). It is also increasingly interested in implementing smart city initiatives, including facilitating equity in adopting innovative technologies (Lee et al., 2023).



Fig. 2.15 *Smart green cities: urban grids of communist Nanjing (top) and capitalist Portland, Oregon (bottom)*

Note: data openly available on Google Earth

To conclude the analyses, we ran an additional linear regression between the *Smart Green City* index (i.e., the standardized first principal component of the PCA) and the cities' populations (in millions of inhabitants). Contrary to the agglomerative clustering results (see Cluster 4), the analysis revealed a negative relationship (-0.053; SE = 0..1582; t = -3.397; p-value = 0.0007373) between a city's population and the *SGC* index (Figure 2.16). However, the difference is mainly due to the size of the respective cluster because 1) it was small overall, and 2) there was one significant outlier among smart green cities with a population approaching 20 million inhabitants, hence significantly influencing the results As Figure 2.16 shows, when all the cities of the sample are considered, the real relationship between smart greenness and city size tends to be slightly negative.

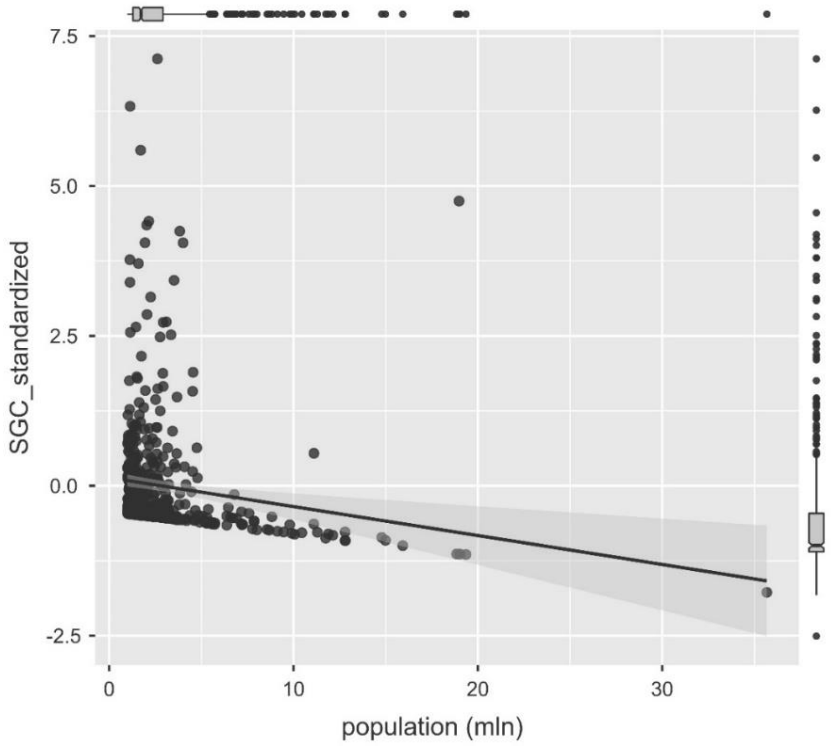


Fig. 2.16 *Relationship between population and SGC index*

Finally, it is important to highlight that the *Smart Green City* index substantially differs from the previously defined indices of *Smartness* and *Greenness*. Indeed, it is not relative but, instead, varies according to the underlying decomposition process of PCA. Thus, it is idiosyncratic to a specific method and a specific sample of cities.

2.3.3 Discussion

In Study 1, to grant the outlined theoretical concepts a more solid ontological, methodological, and epistemic validity, all world cities with more than one million inhabitants were considered for the analyses. Indeed, the study is unique, as it goes beyond the specific country or regional level of analysis and constitutes an inter-regional worldwide evaluation of cities. In order to make heterogeneous cities comparable, existing measures of sustainable smartness (Antwi-Afari, Owusu-Manu, Ng, et al., 2021; Giffinger & Pichler-Milanović, 2007; Zygiaris, 2013) were acknowledged while also deemed unsuitable for the broader scope of the work. Instead, the indices of greenness and smartness were devised based on the relative amount of media attention the sampled cities receive online regarding their smartness and greenness initiatives.

Regarding *HP1* (there is a positive relationship between city smartness and city greenness), correlational, association, and principal component analyses confirmed the hypothesized relationship. All of the results aligned with each other, robustly confirming the hypothesized directionality of the significant relationship. Hence, as a city becomes smarter, its "greenness" is likely to increase.

Concerning the *HP2* (a smart green city is a distinct category of cities that exhibits the traits of both green and smart cities), the results of the principal component and hierarchical clustering analyses performed on the two indices of *Smartness* and *Greenness* and the *population* variable granted the theoretical conceptualization of smart green cities (SGC) a solid empirical basis. In particular, PCA results show that both smartness and greenness are correlated; however, they are correlated only along the most significant PCA dimension. Indeed, the coordinates of that dimension were then used as an operational measure of the *Smart Green City (SGC)* index. Moreover, an agglomerative hierarchical clustering performed on the PCA coordinates revealed the existence of a particular cluster of cities worldwide (Cluster 4) that are both highly smart and green. The result aligns with the recent tendency to conceptualize smart cities from a holistic sustainability-centered perspective (Colding et al., 2020). Indeed, a city can only become greener as newer, more efficient, and environmentally friendly technologies are adopted therein.

By looking at the distribution of cities on the PCA plan, one could also identify green but not smart cities and, vice versa, cities that are smart but not green. In this regard, city population plays a significant role in determining whether a city can be considered either smart, green, or both. The nature of the relationship between a city's size and its greenness and smartness is,

indeed, ambiguous (Ahvenniemi et al., 2017; Vinod Kumar, 2020; Yigitcanlar & Kamruzzaman, 2018). In particular, as city size grows (in terms of the metropolitan area population), so is typically its *Smartness* index. On the contrary, larger populations are negatively correlated with city greenness.

A city's population affects the two indices inversely: while a larger urban population positively affects city smartness—possibly due to the synergic effects of the higher number of ICT hubs and infrastructures—it negatively affects its greenness. The latter impact is also fathomable: as a city grows, it becomes harder to manage effectively, inefficiencies multiply, and finally, the tipping point is reached, inefficiencies more than offset positive effects from increasing technological synergies, and a city hurls down toward environmental catastrophe.

Overall, the results of the analyses (correlational analysis and clustering) suggest that the true relationship between a typical smart green city and city size is most likely curvilinear (e.g., approximating an inverted U curve). From an analytical point of view, this would necessarily entail the existence of a global maximum (i.e., a population size tipping point from which a city can only see its *Greenness* index diminish). It is precisely the emphasis on the awareness of the existence of the tipping point (in terms of a city's population) from which diseconomies of scale may hurdle a city's proper sustainable development that distinguishes the outlined framework of SGCs from similar urban metaphors and concepts in the literature. This awareness is essential to urban scholars, planners, designers, policy-makers, and managers striving for smart, holistic urban sustainability.

2.3.4 Conclusions: implications, limitations, and suggestions for further studies

The notion of a "green city" is usually epistemically and ontologically confused with that of a "sustainable city." However, most definitions of greenness refer exclusively to the environmental pillar of sustainability. While environmental sustainability is usually an essential part of smart city goals, smart technological means (artificial intelligence, the Internet of Things, blockchain, and others) may contribute more to the other pillars of sustainability (social, governance, and economic). Besides, a tech-heavy city may even hinder its environmental goals in order to buttress other sustainability pillars. This alone constitutes the call to action for the precise and unambiguous conceptualization of a smart green city, intended as an urban area where the means of smartness are in a fruitful and synergic relationship with urban ecology.

Smart green city literature is novel and still undeveloped. Indeed, this is one of the first macro-level analyses attempting to conceptualize the phenomenon and argue for its validity, usefulness, and distinctiveness from the more general concept of a smart sustainable city. In doing so, Study 1 provided inter-regional empirical evidence fully supporting this thesis' conceptualization of a smart green city. This, in fact, is its primary contribution to the smart green city and smart sustainable city literature. Another point of interest for smart sustainable city scholars is the methodology. The proposed indices of *Smartness* and *Greenness* have the merit of being relative and pure numbers (hence, independent of the socio-political and cultural contexts and the units of measurement). If, on the one hand, some variability is lost in the process of data collection, on the other hand, the indices are perfectly suitable for an inter-regional, world-system level of analysis.

The primary advice for policy-makers and urban managers/planners is to be more reflective on the role of uncontrolled urban growth. As the results show, city size is detrimental to its greenness. Conversely, it is positively related to a city's smartness. It is hard to tell whether an unambiguous "sweet spot" exists in terms of the optimal city size for the most effective smart green city implementation—most likely not, considering each city represents a distinct and complex reality on its own. Without the pretense of having a definitive answer, a simple visual exploration of Figure 2.16 suggests that cities with a population of up to five million inhabitants are better suited to being smart and green. The implications are straightforward for greenfield urban developments: only a thoughtful limit on urban growth can ensure it will develop as both "smart" and "green." For already existing cities, it may be too difficult (if not too late) to ever strive to achieve SGC status. However, more thoughtful consideration of the role of city size in achieving its environmental sustainability goals can greatly benefit big cities, safeguarding them from the unintended environmental consequences of uncontrolled urban proliferation.

Understandably, the adopted methodology is not immune to critiques. On the one hand, more than actual smartness and greenness, both indices proximally capture the amount of media exposure a city has received regarding its smartness and greenness initiatives. On the other hand, it might be argued that in the information age, media exposure effectively shapes reality. Therefore, the famous conjecture of Descartes, *cogito ergo sum*, can be appositely reformulated as "I am on Google; therefore, I exist." Moreover, the analysis of semantic intra-textual relationships typically provides a good understanding of the relatedness of heterogeneous themes and topics and the direction of current academic interests within

different areas and social science research programs (Arnulf, 2020; Arnulf et al., 2014). Accordingly, although with a certain degree of reservation, it is assumed that the two indices appropriately capture both domains of interest.

The proposed methodology and analyses do not preclude the necessity for a further, in-depth investigation of the external validity of indices. An obvious problem with the methodology is the "black box" nature of Google's search algorithm. Hence, the mechanisms by which results are customized for each user are unclear. Indeed, a simple replication of a city-related Google News search on a different machine led to different results displayed on the first "results" page and a different total number of results. Additionally, the total number of news articles varied slightly on the same machine but on different days. Regardless of the insignificant effect of such differences on the indices of *Smartness* and *Greenness* (the variations were, overall, minor), all the data gathering was performed on the same machine to avoid a systematic measurement error.

The final critical issue is the possibility of bias that more famous cities could have introduced into the dataset. Indeed, these always generated a considerable number of news articles of any kind, so even if indices of *Smartness* and *Greenness* are relative, it is possible that some "noise" was introduced in the analysis. However, almost all the megapolises typically considered "hi-tech" or "green" scored high in terms of the respective *Smartness* and *Greenness* indices. For example, Cali, the third-biggest city in Colombia, has generated the highest number of search results for "greenness" relative to the total results and, therefore, scored highly in the *Greenness* index (first percentile). Indeed, it is famous for its geographic location, with plenty of green spaces within and surrounding the city. One good example of a city scoring highly in both the *Smartness* and the *Greenness* indices is Singapore, a pole of innovation and one of the world's leading smart green cities.

Given the limitless possible factors to consider, contemporary cities are among the most complex and complicated entities to study. The only pragmatic solution seems to be that of simplification, even when it means sacrificing some of the critical variability of the phenomenon. However, simple models can still be effective in capturing significant urban trends while possessing the merits of conceptual clarity and comprehensibility.

The analysis of 498 cities with over one million inhabitants worldwide revealed a positive correlation between the greenness and the smartness of a generic megapolis. It also revealed the potential moderating role of a city's population, weakening the positive relationship between the two as a city grows. Regardless of significant results, the models and

methodology developed herein require further statistical validation. Firstly, more empirical evidence is needed to validate operational definitions of smartness and greenness. The two indices have the merit of being easy to obtain and independent of different urban contexts and units of measurement. However, they may be susceptible to the informational "noise," especially for global (and thus more "famous") cities, which typically generate a substantial amount of heterogeneous news. Secondly, while the considerable merit of the models is their broad scope, an in-depth investigation of the contribution of specific smart technologies to the different pillars of greenness should also be performed in the future. Additionally, smaller urban centers should also be analyzed to obtain a more comprehensive picture of reality. Thirdly, the geographic scope of this chapter's analyses is all-encompassing. However, the analogous methodology could also be applied to single countries or regions (something that has been done in the following study). Additional replication studies are also needed and are welcome.

2.4 Study 2: Exploring the relationship between smart cities and circular cities

2.4.1 Methodology

A quantitative study was devised to investigate the relationship between the propensity of an urban area toward smart and circular economy initiatives. Unlike in Study 1, in which all the big cities worldwide were assessed, the subset of EU cities was selected as the starting point of analysis. The subset of EU cities was chosen mainly for two reasons. Primarily, there is a certain degree of homogeneity on the supra-national level in terms of the types of circular economy and smart city initiatives, usually stemming from EU institutions in the form of regulations, directives, decisions, recommendations, and opinions (Domenech & Bahn-Walkowiak, 2019; Gargiulo et al., 2013; Hartley et al., 2020; Paskaleva, 2011). Not only is the homogeneity of a legislative nature, however. There is also a substantial degree of cultural homogeneity between the EU Member States due to the geographical proximity and shared historical trajectories (Akaliyski, 2017). This is important, as the methodology proposed in this chapter is safeguarded but not wholly immune to geographic considerations. By removing the problem of heterogeneous contexts, the indices of *Smartness* and *Circularity* were derived to be the most neutral and comparable across the EU countries. Moreover, given the socio-geographic status of "developed countries" of the majority of the EU Member States, the cities of the EU are the proximal candidates for being both smart and actively implementing circular economy initiatives. To study how those two dimensions are interconnected on the

macro-geographic level, there is a need to analyze cities that are currently making substantial progress toward both goals.

An entirety of 27 EU member states were selected for the analysis. The dataset was created relying on the updated edition of the free-to-use version of the World Cities Database (*World Cities Database | Simplemaps.Com*, 2020). As stated by the creators of the database, "cities for all non-U.S. countries comes from the National Geospatial-Intelligence Agency. […] The basic population data comes from Natural Earth Data" (*World Cities Database | Simplemaps.Com*, 2020). Overall, 4804 cities were identified within the EU. At this point, it is essential to specify that the total number of EU cities is not (and cannot be) exact, as different countries usually have different normative legislative criteria for distinguishing cities from minor urban centers such as villages and towns (Macionis & Parrillo, 2010; Pacione, 2009). Also, it is not clear what criteria the creators of the database adopted to define what constitutes a city (*World Cities Database | Simplemaps.Com*, 2020). The issue is, however, of secondary importance. Out of 4804 cities of the EU, only those with over one hundred thousand inhabitants within the city proper limits were selected for the analyses. On the one hand, this may seem like an arbitrary cut-off point; hence, some of the critical high-tech cities might have been left out of the analyses. However, as most of the technological innovation and adoption usually happens within larger urban centers (Makkonen et al., 2018), the cut-off point of one hundred thousand inhabitants is not without a substantial rationale. Overall, 393 of cities with more than 100 inhabitants within the city proper limits were identified in the European Union.

The subsequent gathering of data was performed through the Google Scholar search engine. More specifically, for each city with over one hundred thousand inhabitants, a set of Google Scholar searches was performed. Google Scholar was selected as it is currently the largest depository of academic documents and, while not suitable for particularized structured literature reviews, is a great supplementary source for academic information of all sorts (Gusenbauer & Haddaway, 2020). All the searches were performed using the *in-title* specifier, allowing the narrowing of the selection of the results to cases in which search terms appear in the title of academic papers and other related scientific literature. First, only a city name was searched for every city in the sample. As a result, an approximate number of all academic papers and other related scientific literature containing that city name in its title was obtained for each urban center. This result was denoted as the variable *all Google results for a city*.

Then, for each city, additional Google Scholar searches were performed (with the *in-title* specifier) by looking for the name of a city paired with a specific keyword. The selection of keywords was based on the result of the literature review performed at the start of this chapter. Each keyword was chosen to identify a specific technological component of a smart city or a particular circular economy element related to the implementation of circularity initiatives in the urban context. Five keywords were identified for a smart city subset (*Smart City, Internet of Things, ICT, Big Data, Artificial Intelligence*) and four keywords for a circular economy subset (*Circular Economy, 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 conventional smart cities (Lopez-Quiles & Rodriguez Bolivar, 2018). The number of Google Scholar results for each of those searches was termed *all 'keyword' Google results for a city*, where *'keyword'* is a specific keyword among the nine mentioned above. To determine specific indices that measure a city's performance in the core aspects of smartness and circular economy, for each of 393 cities, the following set of formulas was applied:

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

The result is a set of nine micro-level indices: five for a sustainable smart city (*Smart City* index, *Internet of Things* index, *ICT* index, *Big Data* index, *Artificial Intelligence* index) and four for the related circular economy initiatives (*Circular Economy* index, *Waste Management* index, *Renewable Energy* index, *Recycling* index) measuring how well a particular EU city is doing in those aspects of smartness and circular economy. At this point, it is essential to emphasize that, among the abovementioned micro-level indices indices, the *Smart City* index and the *Circular Economy* index do not capture the overall amount of academic interest toward sustainable smartness and circular economy initiatives of a city but serve the purpose of identifying an additional number of articles related to both smart city and circular economy aspects of a generic EU city, in order to factor in the articles not identifiable by the more domain-specific keywords.

In order to quantify the general predisposition of a city toward smart city initiatives, the following formula was used to calculate the macro-index of *Smartness*:

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

where *'smart city keyword' Google results for a city* is the number of search results on Google Scholar for a particular smart city-related keyword (*Smart City, Internet of Things, ICT, Big Data, Artificial Intelligence*) paired with the name of a city.

To quantify the general predisposition of a city toward circular economy initiatives, the following formula was used to calculate the macro-index of *Circularity*:

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

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

To eliminate cities that might have created significant distortions from the dataset, two macro-indices were calculated only when the sum of the five *'smart city keyword' Google results for a city* and four *'circular economy keyword' Google results for a city* variables was more or equal to four. The cut-off point was not arbitrarily set but came from an empirical observation that when the number of Google Scholar search results was small (which was often the case for less-known urban centers), both macro-level *Smartness* and *Circularity* indices were distorted, often by inflating the significance of a city with regards to its sustainable smartness or circular economy initiatives. Accordingly, out of the initial 393 cities in the dataset, the two macro-indices were calculated for 193 cities (approximately 50% of the cities in the initial dataset).

The indices as calculated above operationalize smartness and its components, as well as the extent of circular economy initiatives and their constitutive elements for each specific city in the sample. The biggest concern here is, obviously, how closely an operational definition matches the reality. In fact, what they seem to capture more proximally is the amount of academic interest in the various aspects of a city's smartness and circular economy rather than actual city-related circularity and smartness dynamics. Hence, inadvertently, the following questions should be eventually answered: is academic interest correlated with the real amount of smart city and circular economy initiatives in cities? And: do cities with a significant presence of academic institutions generate more Google Scholar searches on average? In any case, the methodology used herein requires substantial empirical validation in future studies on the topic.

An empirical observation, however, revealed that cities with a high *Smartness* index actually have a substantial amount of ongoing or planned sustainable smart city projects. This is, for

example, the case of Varna, a Bulgarian seaside city scoring the highest in the *Smartness* index according to the methodology. The city is an urban center that is substantially investing in sustainable smart city initiatives and has significant potential to become one of the first true European smart cities (Kostadinova Popova & Malinova Malcheva, 2020). The second "smartest" city, as defined by the index, is Funchal, the main city on Madeira Island (Portugal), which is famous for its smart projects for tourism (Rodrigues & Virtudes, 2019). Similar empirical observations apply to the *Circularity index*, with cities in Poland (Zabrze, Wałbrzych) and Croatia (Split, Płock)—two countries that are the frequently leading circular economy initiatives of the EU—at the top of the respective ranking (Andabaka et al., 2018; Smol et al., 2020; Sverko Grdic et al., 2020; Zielińska, 2019). The weak aspect of the methodology is perfectly illustrated by Barcelona, which is the city that produced the highest number of Google Scholar results related to smartness and is considered one of the leading European cities in terms of its smart cities initiatives (Bakıcı et al., 2013), but its *Smartness* index is located at the end of the first percentile of the related distribution mainly due to the overall high amounts of the Google Scholar results generated for the city in the denominator of the formula.

Like in the case of the methodology in Study 1, both macro-level and micro-level indices have the apparent advantage of being relative and expressed by pure numbers, making the comparison between different cities possible while transcending the issue of heterogeneous units of measurement. By definition, the indices vary between zero and one. Zero denotes a city that has generated no academic literature with its name in academic documents' titles, which operationally defines the lowest possible score in the city's smartness/circularity. One represents an ideal case in which all the academic literature on the city relates to either a smart city and its components or a circular economy and its components. Hence, it operationalizes the highest possible city's smartness or circularity.

2.4.2 Analyses and results

A set of linear regression analyses was performed to understand how the indices of *Smartness* and *Circularity* are related. The analyzed EU cities do not come from a random sample but were instead chosen as the most likely prospective EU smart and circular cities of the future ("the bigger, the better" argument). Therefore, the models proposed in the chapter should not be generalized to all kinds of urban realities, and the related discussion and conclusions concluding Study 2 should only be applied to cities in similar contexts and with isomorphic

characteristics to major EU cities.

Out of 193 analyzed cities, the majority had one or less than one million inhabitants. As can be seen in Figure 2.17, only a few cities in the EU are above the threshold of one million inhabitants, hence classifiable as megapolises of regional significance, comparable to cities analyzed in Study 1 of this chapter.

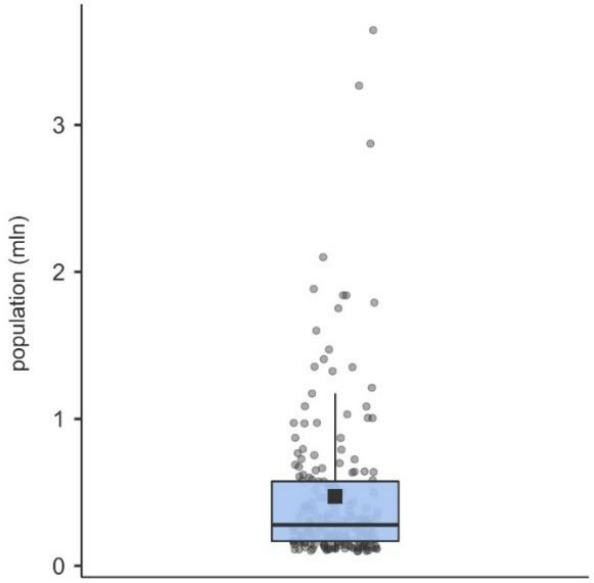


Fig. 2.17 *Relating smartness and circularity. A visual summary the population distribution (in mln)*
Note: dots represent single data points (cities worldwide). The black square represents an arithmetical average

The distribution is clearly asymmetrical and skewed to the right, 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 histogram of the distribution of the cities according to their populations (bandwidth = 0.09529) is shown in Figure 2.18.

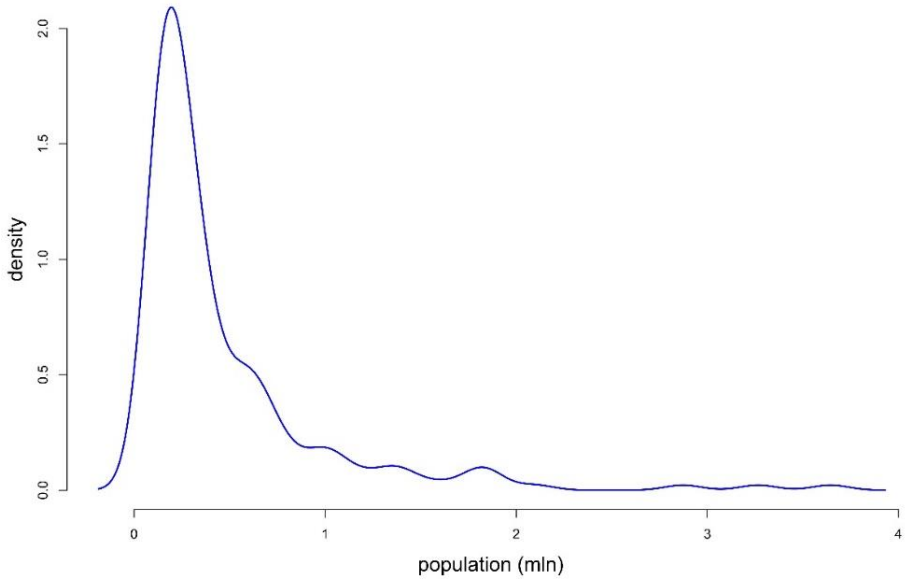


Fig. 2.18 *Relating smartness and circularity. Kernel density estimation of the cities of the dataset according to their populations*

Among all the EU countries contributing to the dataset, most of the cities are German (43), with Italy and Spain occupying the second and third place respectively (with 25 and 22 cities). The bar plot reporting the distribution of all 27 EU member states according to their contribution to the dataset in terms of the number of medium-to-large cities therein is shown in Figure 2.19.

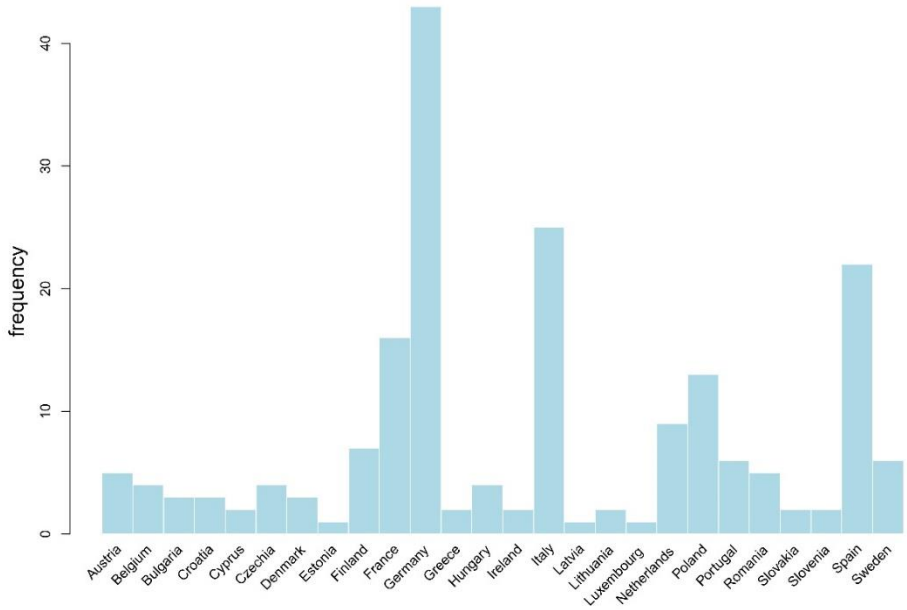


Fig. 2.19 *Relating smartness and circularity. Distribution of countries in terms of the number of cities in the dataset*

A simple linear regression between the *Circularity* index and the *Smartness* index was performed. The resulting model is reported below.

$$Circularity \text{ index} = 0.0005015 + 0.4571193 * Smartness \text{ index}$$

The model revealed the existence of a moderate positive correlation between the two indices[5]. The R-squared equal to 0.2419 suggests that approximately 24 percent of the variation of the *Circularity* index is related to the variation of the *Smartness* index. However, due to the relative nature of indices (which vary between zero and one), the interpretation of the above relationship turned out to be not overly intuitive. To better understand the relationship between the two indices, logarithmic transformations were applied to both, and a log-log linear regression was performed. The resultant log-log relationship between the indices is captured by the following expression:

$$log_circularity = -2.63422 + 0.68755 * log_smartness$$

The expression captures the relationship between the two indices in terms of elasticity. Hence, according to the log-log regression interpretation, a 0.68 percent increase in the *Smartness* index is needed for a percentage increase in the *Circularity* index[6]. Figure 2.20 shows the scatter plot and the regression line for the log-log relationship between the indices.

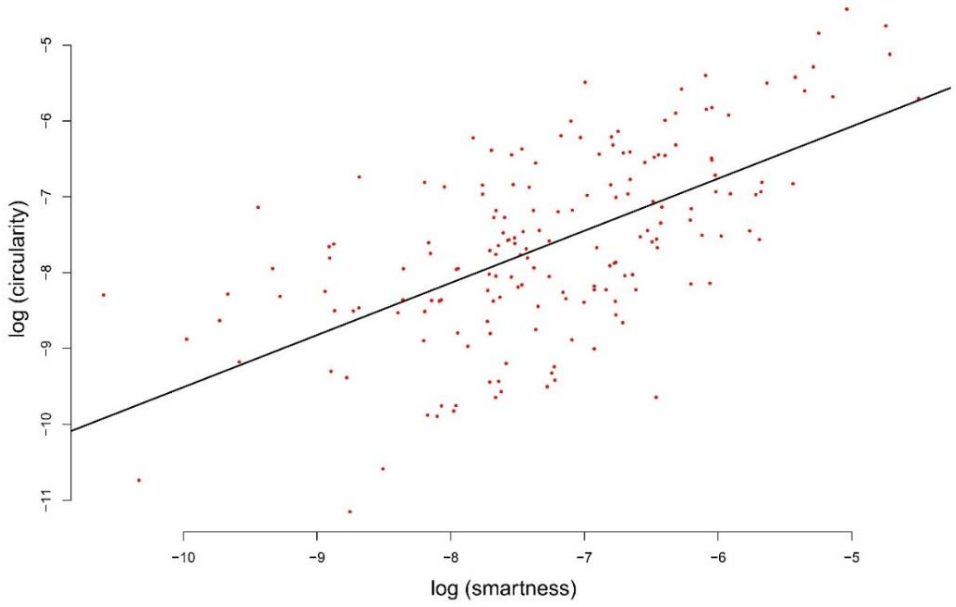


Fig. 2.20 *log-log Relationship between Circularity index and Smartness index*

[5] For the independent variable: SE = 0.058; t = 7.890; p-value = 2.28e-13
[6] For the independent variable: SE = 0.068; t = 10.215; p-value < 2e-16

Finally, to understand how individual components of a smart city are contributing to the number of circular economy initiatives and how different pillars of a circular economy are related to a city's smartness, the spatial distribution of the indices along the two most significant dimensions of principal component analysis (PCA) was analyzed.

To begin with, four specific smart city-related indices (*Internet of Things* index, *ICT* index, *Big Data* index, *Artificial Intelligence* index) and the macro-level *Circularity* index entered the analysis as active variables. PCA generated five dimensions (equal to the number of active variables); however, the first two captured more than 60 percent of the total variance. The PCA graph of variables within the correlation circle is shown in Figure 2.21[7]. By analyzing the contribution of variables to the definition of the plane, one may notice that all of the indices were positively correlated with the first (horizontal) dimension. Hence, the first dimension is primarily defined by the general propensity toward smart and circular economy initiatives. Accordingly, the coordinates of the first dimension of the PCA can be re-interpreted as a more general *Smart Circular City (SCC)* index.

The vertical dimension distinguishes between specific micro-level indices closely related to smart cities (*Artificial Intelligence* index, *Internet of Things* index, and *Big Data* index), negatively correlated with the said dimension, and the macro-level *Circularity* index and micro-level *ICT* index, positively correlated with the said dimension, suggesting that what is essential for the proliferation of circular economy initiatives within a city are not the specific technologies like AI, Big Data or IoT, but the overall presence of a well-developed ICT infrastructure.

According to PCA, cities on the right side of the graph are overall more innovative from the point of view of smart city initiatives. The majority of EU cities, however, still lag in terms of both smartness and circularity initiatives (most cities were clustered slightly to the left of the center of the PCA plane). The distribution of all the urban centers alongside the two most significant dimensions of the PCA factor map is shown in Figure 2.22.

[7] The coordinates of active variables are the squared correlation ratios between each active variable and the two dimensions of the PCA plane; $\cos^2$ denotes the quality of representation of each active variable on the two most significant PCA dimensions.

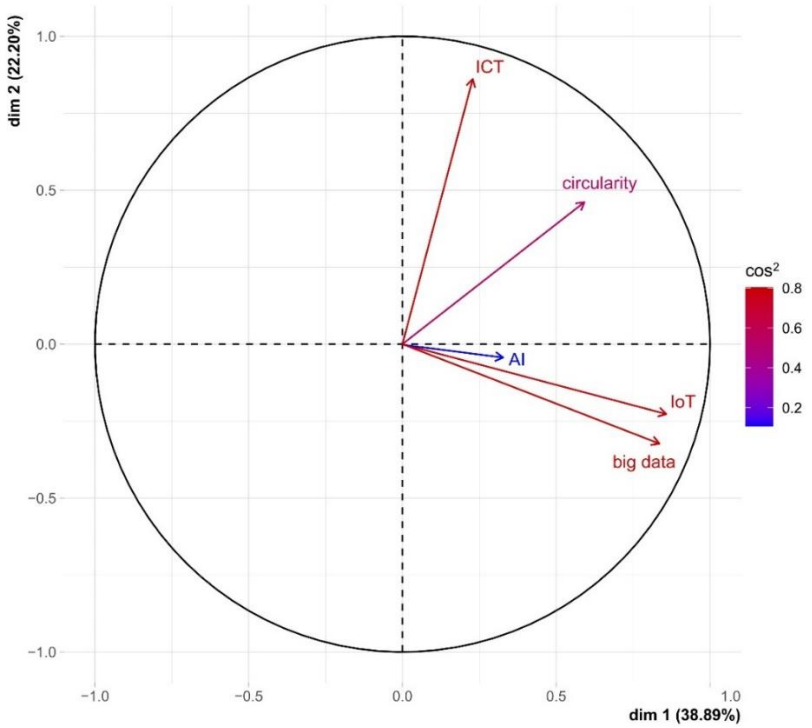


Fig. 2.21 *Squared correlation ratios between individual components of smartness and Circularity index*

Note: cos² denotes the quality of the representation of variables on the plane

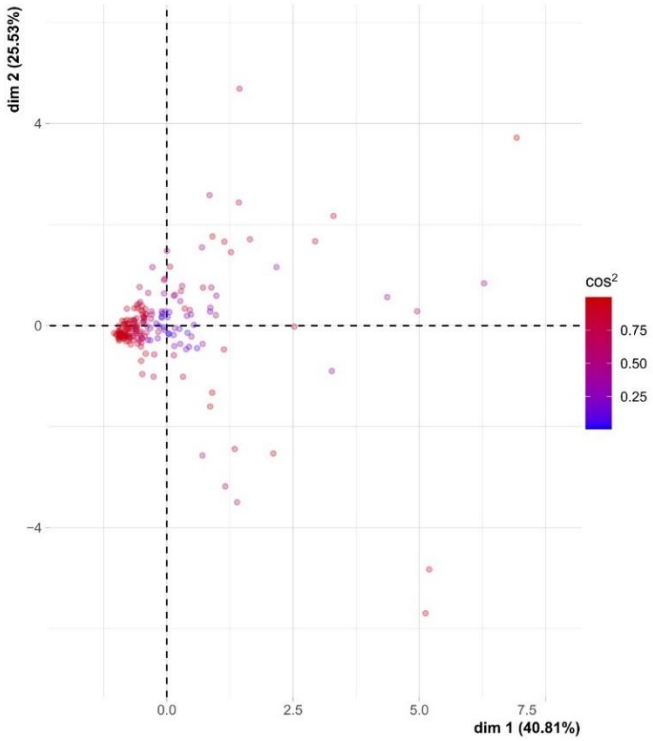


Fig. 2.22 *Relating smartness and circularity. Distribution of individual cities of the dataset along the two most significant dimensions of PCA. Case 1*

Note: cos² denotes the quality of the representation of variables on the plane

As a means of a robustness check, a specular analysis was performed considering three specific micro-level circular economy-related indices (*Waste Management* index, *Recycling* index, *Renewable Energy* index) and the macro-level *Smartness index*. The said indices entered the analysis as active variables. PCA has generated four dimensions, with the first two capturing more than 66 percent of the total variance. The PCA graph of variables inside the correlation circle is shown in Figure 2.23.

Like in the parallel case described above, all the variables were positively correlated with the first (horizontal) dimension. Hence, one may conclude that the first dimension of the PCA unequivocally captures the overall propensity toward both urban circularity and smartness. Again, the coordinates of the first dimension can be readily re-interpreted as the general *Smart Ciruclar City (SCC)* index.

When it comes to the second (vertical) dimension, the *Recycling* index and *Renewable Energy* index were positively correlated, while the macro-level *Smartness* index and *Waste Management* index were negatively correlated with the said dimension. The result suggests that the general propensity of a city toward smartness (including the usage of ICT, AI, IoT, and big data) directly positively impacts its waste management circular initiatives.

Like in the previous case, according to PCA (Figure 2.24), the rightmost cities of the graph are overall more innovative from the point of view of circular economy and smartness initiatives. However, most cities from the dataset are clustered around the origins of axes, suggesting they are doing neither good nor bad in terms of circular economy and smartness initiatives. Some cities, though, do appear to be very innovative in this regard.

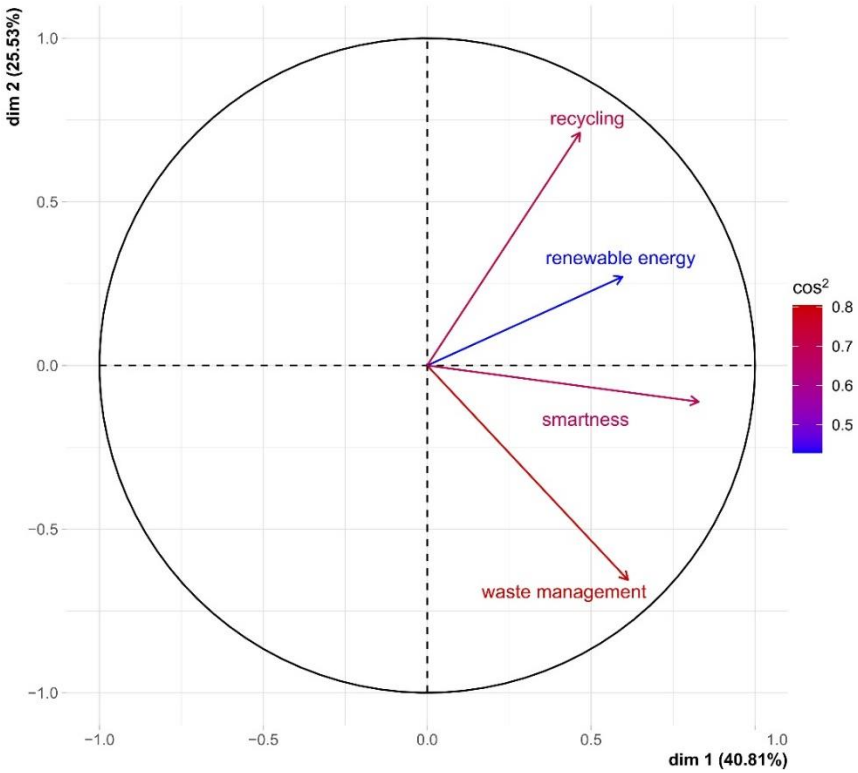


Fig. 2.23 *Squared correlation ratios between individual components of circularity and Smartness index*

Note: cos^2 denotes the quality of the representation of variables on the plane

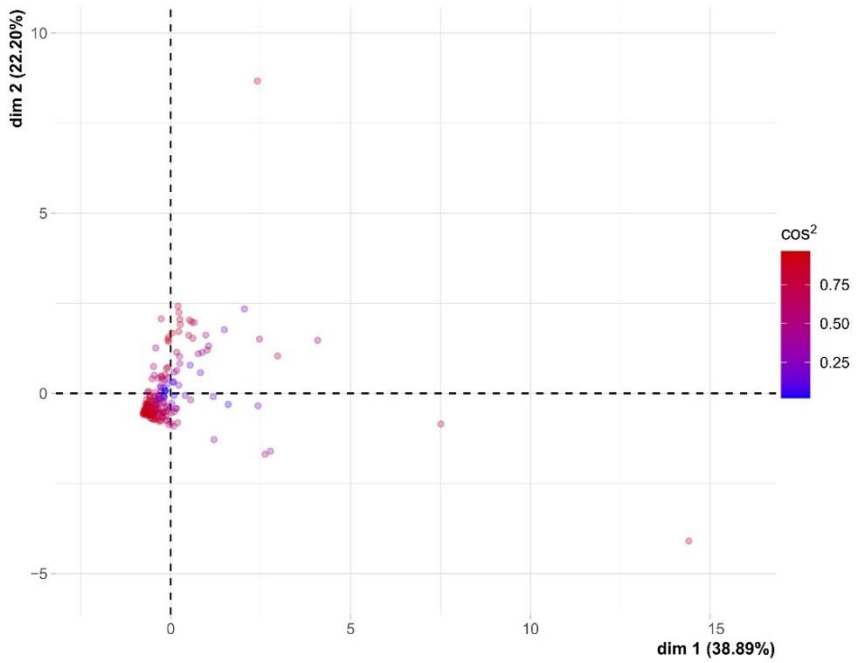


Fig. 2.24 *Relating smartness and circularity. Distribution of individual cities of the dataset along the two most significant dimensions of PCA. Case 2*

Note: cos^2 denotes the quality of the representation of variables on the plane

In order to perform a third robustness check and to obtain a more in-depth understanding of the nested dynamics between micro-level variables, the *Smart Circular City (SCC)* index was further validated by analyzing the relationships between all the specific micro-level indices of *Smartness* (*Big Data, IoT, ICT, AI*) and *Circularity* (*Waste Management, Recycling, Renewable Energy*). All seven variables entered the principal component analysis jointly. In this last case, both macro-level indices (*Circularity* index and *Smartness* index) were excluded from the analysis.

PCA yielded seven uncorrelated dimensions, with the first two accounting for 52.82% of total variance. In particular, like in the previous cases, all the active variables were positively correlated with the first (horizontal) dimension—accounting for 33.4% of total variance. Conceptually speaking, cities scoring high on the first dimension are characterized by both a higher propensity toward smartness and a higher propensity toward circularity. Hence, the first dimension of the PCA can be again interpreted as an ad hoc measure of smart circularity (i.e., *Smart Ciruclar City* index). Again, when looking at the actual distribution of individual cities on the plane, most landed around the origins of the PCA bi-plane. That is, most EU cities with more than one hundred thousand inhabitants cannot be readily considered as being both smart and circular.

The interesting dynamic emerges captured by the second (vertical) dimension. In particular, *Recycling* and *ICT* indices turned out to be closely connected and positively correlated with the said dimension. This further confirms the finding of the first PCA of Study 2 (i.e., Case 1), relating the *Circularity* index and *ICT* index. Accordingly, the two are closely connected, and the facet of circularity closely related to ICT usage is recycling. Similar considerations can be made about the *Waste Management* index and *Smartness* index. As emerged from the second principal component analysis of Study 2, those were the only two that negatively correlated with the second dimension. As the third PCA of this study reveals, the waste management component of circularity is the closest in conceptual terms to a particular component of urban smartness, chiefly artificial intelligence (AI). Indeed, both seem to contribute to the formation of dimensions beyond the first two, as both are only slightly correlated with the two axes of the bi-dimensional PCA plane.

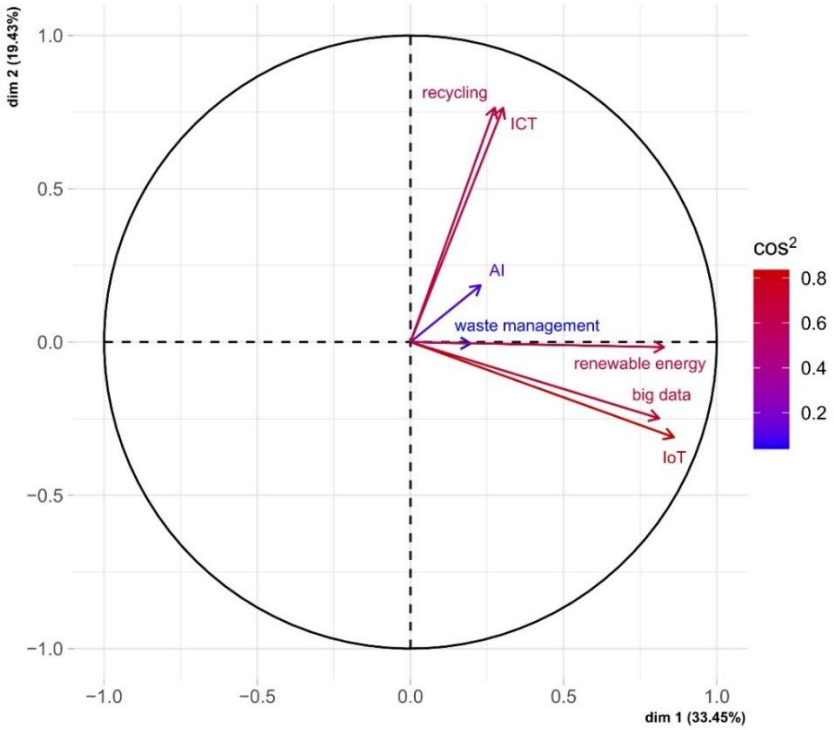


Fig. 2.25 *Squared correlation ratios between individual components of circularity and individual components of smartness*

Note: cos^2 denotes the quality of the representation of variables on the plane

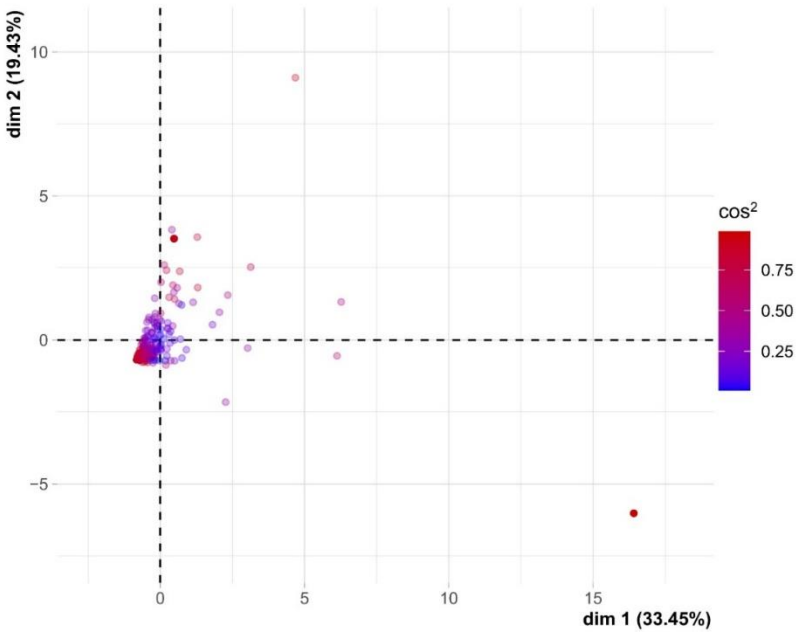


Fig. 2.26 *Relating smartness and circularity. Distribution of individual cities of the dataset along the two most significant dimensions of PCA. Case 3*

Note: cos^2 denotes the quality of the representation of variables on the plane

To complete the PCAs overview, Figures 2.27 – 2.29 report the scree plots for the respective exploratory analyses. In order to verify the overall robustness of the obtained *Smart Circular City* indices, one could expect them to be 1) similarly distributed and 2) highly correlated. Indeed, after standardizing the three indices obtained by means of three PCA cases, the respective distributions appear isomorphic, with a marked asymmetry to the right (Figures 2.30 – 2.32).

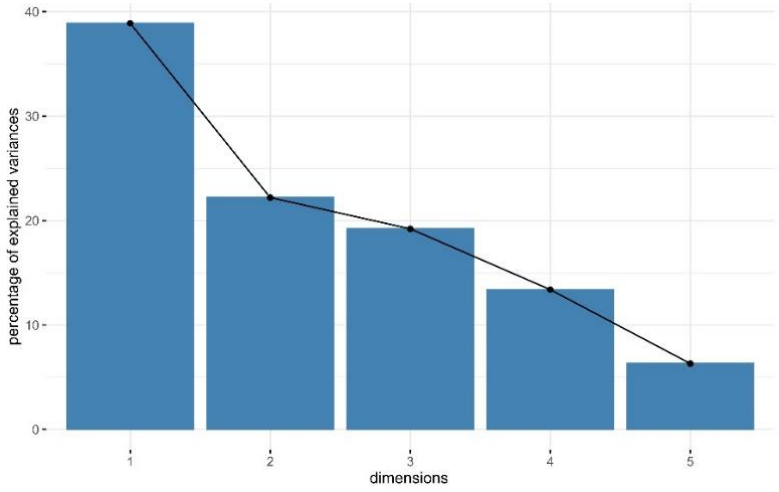


Fig. 2.27 *PCA. Individual components of smartness and Circularity index. Scree plot*

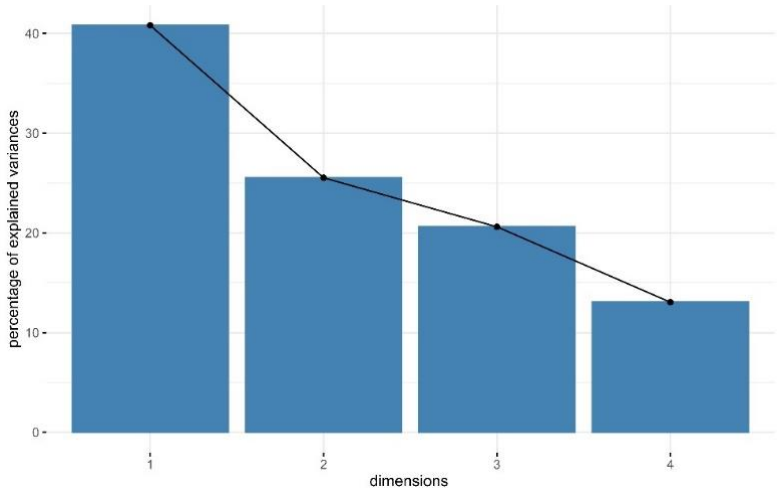


Fig. 2.28 *Individual components of circularity and Smartness index. Scree plot*

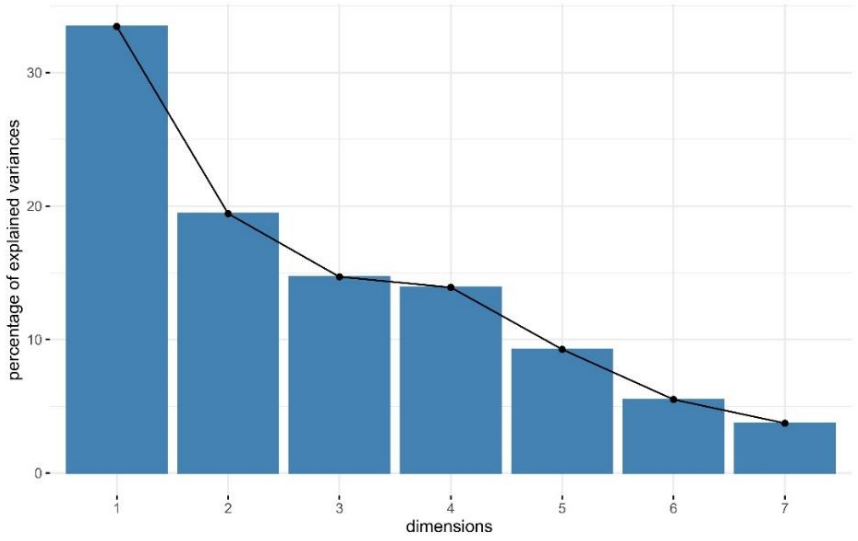


Fig. 2.29 *PCA. Individual components of circularity and smartness. Scree plot*

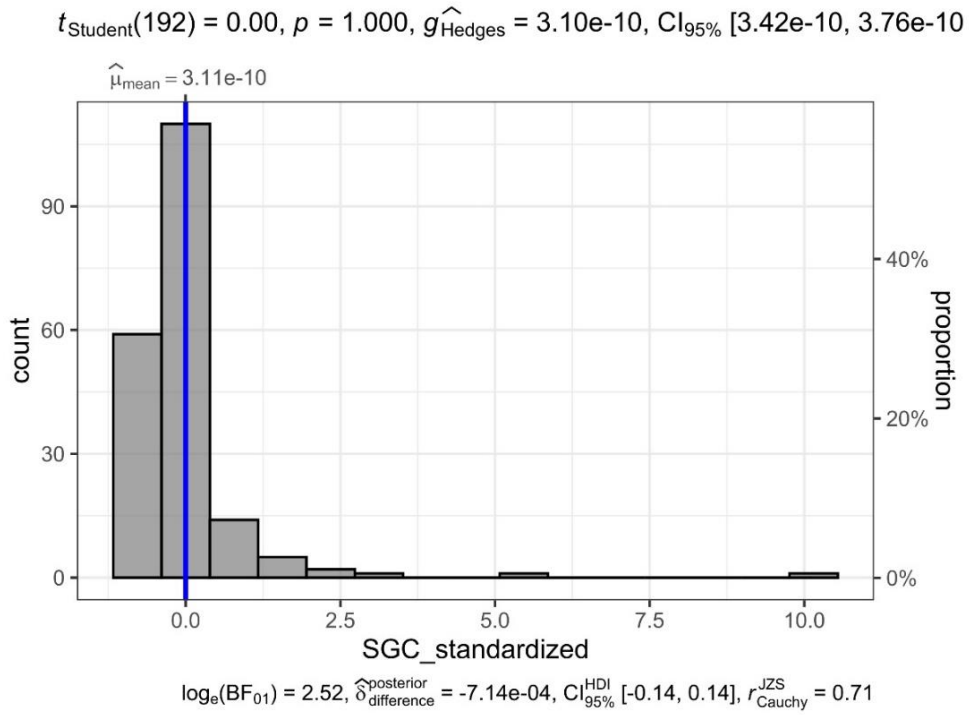


Fig. 2.30 *Smart Circular City index based on individual components of smartness and Circularity index*

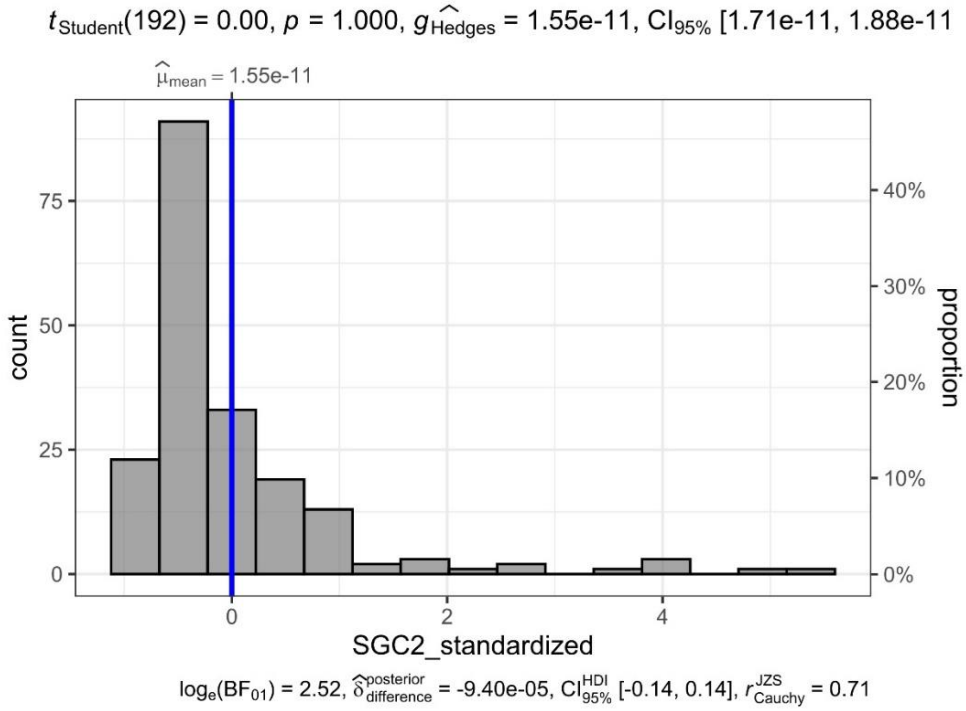


Fig. 2.31 *Smart Circular City index based on individual components of circularity and Smartness index*

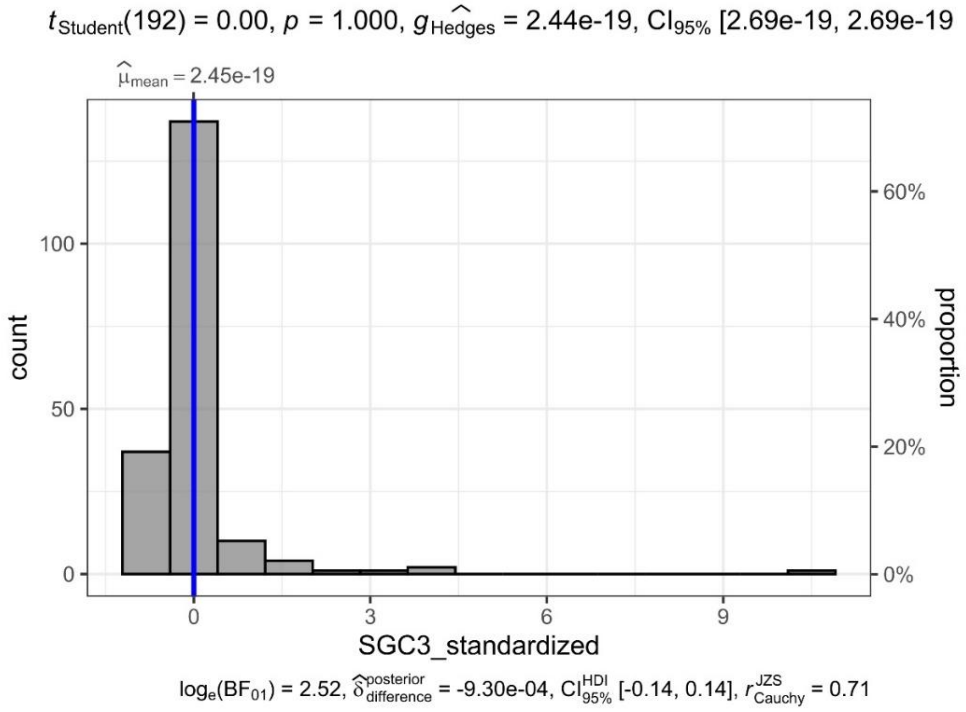


Fig. 2.32 *Smart circular city index based on individual components of circularity and smartness*

The three indices are also highly correlated, as shown in the correlation matrix in Figure 2.33. As seen in the plot, all correlations were statistically significant at $p < 0.001$ level.

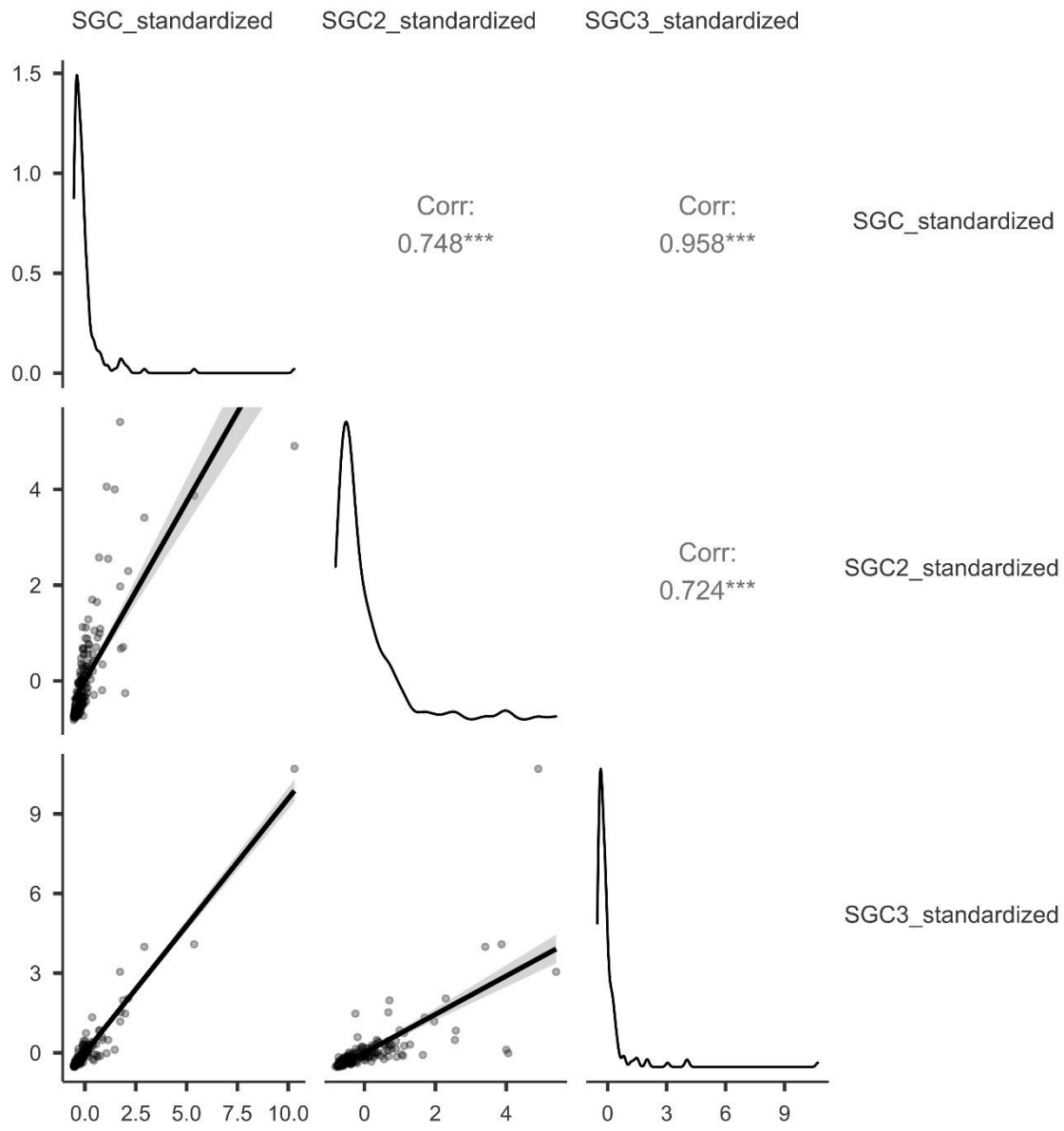


Fig. 2.33 *Correlation plot between the three Smart Circular City (SCC) indices, obtained through PCA by emphasizing different aspects of circularity and smartness*

Note: Distributions are kernel density estimations of the respective histograms in Figures 2.30 – 2.32

An arithmetic average of the three *Smart Circular City* indices was then calculated in order to obtain a unified *Smart Circular City* (*SCC)* index capturing both micro-level and macro-level aspects of urban-related circularity and smartness. According to the resulting index and the respective classification, the top five cities of the EU that scored the highest on the *Smart Circular City* index are Split (Croatia, 8.63), Funchal (Portugal, 4.44), Aalborg (Denmark, 3.44), Oulu (Finland, 3.39), and Thessaloniki (Greece, 2.15). A short empirical investigation of the above cities further confirms the validity and usefulness of the proposed index.

For instance, Split (43.5147° N, 16.4435° E), a Croatian city of around 200,000 inhabitants (the second largest in the country), has scored the highest on the *Smart Circular City* index centered on individual micro-level components of smartness (first PCA case of Study 2), the *Smart Circular City* index emphasizing individual micro-level components of both smartness and greenness (third PCA case of Study 2), and the overall *Smart Circular City* index resulting from the arithmetic average of the three case-specific *SCC* indices. In general, Split is famous for its circular economy research and initiatives, being at the forefront of Croatian advances in the field (Barbir & Dabić, 2024; Lobo et al., 2021). Of recent events, for example, is a Circular Bioeconomy on Aquaculture held in the city on April 18th, 2024 (*Workshop: Circular Bioeconomy in Aquaculture*, 2024). A collaboration between Norwegian and Croatian Universities, research institutes, and private companies, the workshop aims to discuss new possibilities within the circular economy of coastline cities. Moreover, the said initiatives and research trickle down to the (younger) inhabitants of the city, who are evidently more conscientious toward the environment (Hržić et al., 2023). When it comes to smartness, the city of Split is also at the forefront, and according to the European Commission's "Intelligent Cities Challenge" report, it has "started to implement many smart city projects […] improving the quality of life for its citizens. Many of the plans and activities are being realized, including digitalization of energy systems, digitalization of government services, green mobility and enhancing the bicycle network, intelligent transport systems, traffic security video surveillance systems, modernization and management of public lightning system, energy renovation of publicly owned buildings, modernization of the municipal waste management" (*Split | Intelligent Cities Challenge*, 2022). The emphasis, however, is also on the sustainability and circularity initiatives as according to the same report "improving the public green spaces is a project that consists of activities that can also include citizens [of Split] to directly participate in greening and cultivating" (*Split | Intelligent Cities Challenge*, 2022).

A similar case for the empirical validity of the obtained composite *SCC* index and the resulting classification can be made regarding Oulu (65.0121° N, 25.4651° E), a Finnish city of comparable size to Croatian Split (around 200,000 inhabitants). The city has ranked second in the composite *Smart Circular City* index obtained by averaging the three previously PCA-derived indices. However, it ranked first according to the second *Smart Circular City* index obtained through PCA emphasizing circularity micro-level variables. On the one hand, Oulu is a prototypical medium-sized smart city with a dedicated research center centered on the

study of the appropriate smart city design and implementation initiatives (Gil-Castineira et al., 2011). On the other hand, it is deeply involved in regional and state-level circular economy initiatives, integrated in synergetic ways with its smart city projects (Hosseinian et al., 2021; Väisänen, 2020).



Fig. 2.34 *Urban landscapes of two of the EU smart circular cities*

Note: Top—Split, Croatia; bottom—Oulu, Finland. Data openly available on Google Earth

2.4.3 Discussion

Only recently have sustainability issues related to smart cities started acquiring the necessary attention from scholars. From the suggestions to rescale the studies of smart cities from large urban realities to the eco-friendlier smart villages (Visvizi & Lytras, 2018) to the proposals of the bottom-up smart city initiatives "that facilitate participation and collaboration among city

stakeholders" (Graaf & Veeckman, 2015), to the attempts to study the quality of life within smart cities (Alizadeh & Sharifi, 2023) the novel urban literature is rich with sustainability topics of every kind. The application of circular economy principles to smart cities is undoubtfully a part of this bigger trend, as even a brief assessment of the related literature shows (Aceleanu et al., 2019; Petit-Boix & Leipold, 2018; Schipper & Silvius, 2019).

In Study 2, the hypothesized relationships between circular cities and smart cities were investigated, and the empirical validation for the existence of the so-called smart circular cities was provided, intended as cities striving to achieve environmental sustainability goals through circular economy initiatives boosted by conventional smart city technologies.

In particular, for what concerns *HP3* (There is a positive relationship between city circularity and city smartness), the results were confirmed by means of simple linear regression analyses. The medium-to-strong positive linear relationship between smartness and circularity reveals how closely the topics of technology and environmental sustainability are connected, confirming the assertion of Bifulco et al. (2016) about the importance of sustainability for smart cities. Regardless of the conceptual simplicity of the regression analyses, the methodology through which macro-level indices of smartness and circularity and the related micro-level indices operationalizing different components of circular cities and smart cities were derived is essential here. The methodology developed in the present study has led to ranking the biggest cities in the EU according to the number of smart city initiatives and circular economy initiatives. Whether the indices of smartness and circularity perfectly capture the real situation is left to the further analysis of the compatibility between operational definitions of smartness and circularity (as defined by respective indices) and the empirical reality. On the other hand, the indices allowed the ranking of the EU cities in the dataset according to a universal criterion. Thus, the indices were not devised as the most precise or proximal, as what counts here is the ordinal ranking rather than an exact and unequivocal measure. This comes as no surprise, given how heterogeneous the perception of a smart city in the literature is (Yigitcanlar et al., 2018).

According to the results of three principal component analyses, among specific technological components of a smart city, only ICT seems to be closely related to the *Circularity* index. Hence, the smart city constituent that seems to contribute to circularity initiatives the most is the general presence of an ICT infrastructure within the city. As for the contribution of specific components of circularity to a city's smartness, only the *Waste Management* index positively correlates with the *Smartness* index on both dimensions of the respective PCA

plane. In particular, one component of city smartness is of crucial importance here: artificial intelligence. This highlights the critical importance of successful and ethical AI deployment and usage for heterogeneous waste management initiatives in a medium-to-large (European) smart city. The issue will only get more relevant as the EU legislator introduces a first-of-its-kind regulatory mechanism to oversee the development and usage of AI tools within the borders of the Union (*EU AI Act*, 2023).

Concerning the *HP4* (a smart circular city is a distinct category of cities that exhibits the traits of both smart and circular cities), three principle component analyses emphasizing 1) smartness and its constituent components, 2) circularity and its constituent components, and 3) both smartness and circularity and their constituent components, all have pointed out to the presence of the unified dimension capturing what, in essence, can be interpreted as smart circularity. Hence, in all three cases, the respective indices were treated as operationalizations of smart circular cities (i.e., *Smart Circular City* indices). All three indices passed the robustness check as they were highly correlated and presented isomorphic distributions. Hence, the three indices were standardized and arithmetically averaged to obtain the cumulative *SCC* index. The first two cities scoring the highest on the latter were also discussed as empirically valid examples of ideal-type European smart circular cities. As in the case of the *Smart Green City* index of Study 1, however, the obtained *SCC* indices should be treated as idiosyncratically derived from the principal component analyses themselves. Hence, while perfectly valid for capturing the ordinal relationship between the EU cities (i.e., which cities are more smart and circular than the others), those numbers are not pure and relative, like in the case of other indices derived in the study. Hence, unlike in the case of simple circularity of smartness, they say little about the degree to which a given city is of an SCC type. This can be only inferred by comparing *Smart Circular City* indices of different cities jointly.

2.4.4 Conclusions: implications, limitations, and suggestions for further studies

From a managerial point of view, the obtained results imply a set of important implications. Firstly, environmental circularity-related issues should not be neglected during the planning and deployment of smart city initiatives. Those two are, in fact, closely and positively linked. Secondly, while most big European cities appear ready for the implementation of circular economy and smart city initiatives, only a small minority of those scored highly on *Smart Circular City* indices, as the majority are clustered near the origin of the axes of the respective

PCA bi-plots. Besides, by looking at the PCA distributions of individual cities, it becomes clear that smartness topics are addressed more frequently than circularity topics. Hence, an apparent advice to city managers and planners is to consider circular economy initiatives more willingly while planning for city smartness. Not only may it produce benefits of its own, but given the positive relationship between circularity and smartness, there will be indirect positive effects on the latter through the implementation of the former. Thirdly, while planning for both circularity and smartness, city managers should take the synergetic relationships between them into account. For instance, as revealed by the analyses, the presence of a well-developed ICT infrastructure will undoubtedly benefit a city's future circular economy initiatives. Similarly, further development and adoption of AI can only boost successful waste management initiatives.

Given that the dataset of cities was not based on a random selection criterion, there is an obvious limitation to the results of Study 2. Mainly, the above conclusions and suggestions apply to cities in the EU that are medium-to-large (more than one hundred thousand inhabitants) and are already on their way to adopting smartness and circularity initiatives. The generalization of the results is not possible unless the city in question presents similar characteristics of a generic medium-to-large urban center of the European Union.

Regardless of the good face validity of the indices of *Smartness* and *Circularity*, more in-depth statistical validation of both is needed. Further replication studies should also be performed to assess the reliability of indices. The principal component analyses performed herein were an appropriate methodological tool to inductively uncover the latent relationship between the indices and produce the ranking of the EU's smart circular cities. However, to validate the results of Study 2, a more formal and structured analysis of indices' constitutive components is needed. This can be achieved in future studies by applying a more restrictive and robust statistical framework, like, for example, that of the structural equation modeling.

2.5 Study 3: Exploring the relationship between smart green cities and smart circular cities

2.5.1 Methodology

The goal of the third study is to prove the last hypothesis of this chapter, mainly that smart green cities and smart circular cities, as conceptually defined in the Literature Review section and then operationalized in the respective studies (Study 1 and Study 2), are in a strict set

relationship. In particular, that smart greenness is a necessary (but not sufficient) condition for a smart circularity to emerge. Hence, all smart circular cities could be, by definition, considered smart green.

The data for the analyses in this chapter comes from the integration of datasets of Study 1 and Study 2, with the Study 2 dataset being the baseline for the construction of the dataset for Study 3. Therefore, like in Study 2, major European Union cities were considered, this time, only with more than one million inhabitants. Moreover, in relation to the sampled EU cities, the dataset in Study 3 "borrows" some of the indices calculated in Study 1. To understand how individual macro- and micro-level indices of smartness, the reader can reference the two preceding studies of the chapter. The pooling of results with indices derived by different methodologies was deemed necessary in order to avoid problems associated with a common method bias, i.e., systematic errors introduced when the measurement of dependent and independent variables is done relying on identical methods (Podsakoff et al., 2003).

In contrast to the dataset of Study 2, in building the new dataset, the metropolitan area population was considered instead of the urban core population. Hence, all the EU cities with more than one million inhabitants within the metropolitan area region have entered the analysis. In total, thirty-nine such cities were identified within the confines of the EU. For those, the *Smartness* index, *Greenness* index, and *Smart Green City* index were fetched from the results of Study 1. In relation to the results of Study 2, all the micro-level indices of circularity (*Circular Economy* index, *Waste Management* index, *Renewable Energy* index, *Recycling* index) and smartness (*Smart City* index, *AI* index, *ICT* index, *IoT* index, *Big Data* index) were fetched. The overall *Smartness* and *Circularity* indices and the composite (average of the three independently derived *SCC* indices) *Smart Circular City* (*SCC*) index were also included in the new dataset. All the said indices were standardized, i.e., rendered mean-centered and with a standard deviation equal to one.

As the related methodologies applied to derive the abovementioned indices are based on the overall media (Study 1) and academic attention (Study 2) to the topics of city smartness, greenness, and circularity, none of those are completely immune to distorted and inflated results due to the significant "popularity" or the opposite, "unpopularity" of certain cities compared to others. Accordingly, for some cities, the related frequencies in denominators (i.e., total results in terms of Google searches) could have inflated or deflated the respective indices beyond the acceptable threshold. To overcome these negative effects, four outliers were taken out of the new dataset, mainly those cities that scored disproportionately high or low on the

Smart Circular City index and *Smart Green City* index. In total, four cities were excluded from the dataset: Sofia (scoring disproportionally high on smart circularity), Paris (scoring disproportionately low on smart circularity due to the very high denominator), The Hague (scoring disproportionately high on smart circularity), and Porto (scoring disproportionately high on smart greenness). Accordingly, thirty-five cities have composed the dataset of Study 3.

To prove the hypothesized set relationship between the two types of cities (smart green cities and smart circular cities), a new but increasingly popular approach was used: the so-called necessary condition analysis (Dul, 2016). According to the author of the methodology, while "the hypotheses in organizational sciences frequently imply sufficiency," hence, reflecting "X causes Y" logic, the hypotheses of necessity, i.e., "No Y without X," are "rarely formulated and tested in organizational sciences" (Dul, 2016, 2019). Conventional methods, such as ordinary least square regression, estimate the relationships in terms of averages (Dul, 2016). Hence, the results from a conventional maximum likelihood estimation tell how much, on average, one variable is expected to increase, given an average increase in the value of the other variable. A necessary condition analysis (NCA) shifts the focus to the conditions of necessity (so-called critical factors, e.g., the necessity of having a certain level of independent variable to have a certain level of dependent variable) (Hauff et al., 2021).

Instead of considering the regression line, NCA takes into account the "ceiling line" separating the two areas in a bi-plot: the area with observation and the area without observation. The size of empty space above the ceiling line in relation to the total space of the bi-plot represents the degree of "necessity" or "criticality" of the independent variable with respect to the dependent variable (Dul, 2016, 2019). Hence, the larger the empty space, the larger the constraints that the independent variable puts on the dependent variable (Dul et al., 2019).

The dedicated R package provided all the necessary tools for the evaluations, including effect sizes and significance testing (Dul et al., 2021).

2.5.2 Analyses and results

In parallel with the analyses of Study 1 and Study 2, population-related descriptive statistics are first presented, also comprising the four outliers.

As mentioned in the methodology section, all the EU cities with a metropolitan area population of more or equal to one million inhabitants have entered the analysis. Again, like in the case of Study 1 and Study 2, the dataset is based on the updated edition of the free-to-use version of the World Cities Database (*World Cities Database | Simplemaps.Com*, 2020) and the related metropolitan area populations.

The box plot in Figure 2.35 reports the essential descriptive statistics, including the two quartiles, the median, and an arithmetical mean. On average, an EU megapolis has around 2.16 million inhabitants. Only two cities have exceeded the threshold of five million inhabitants: Paris (approaching ten million) and Madrid (around five million). A Kernel density estimation (bandwidth = 0.4487) of the distribution of cities in the dataset according to their population is reported in Figure 2.36. Like in the previous cases, the distribution is clearly asymmetrical and skewed to the right.

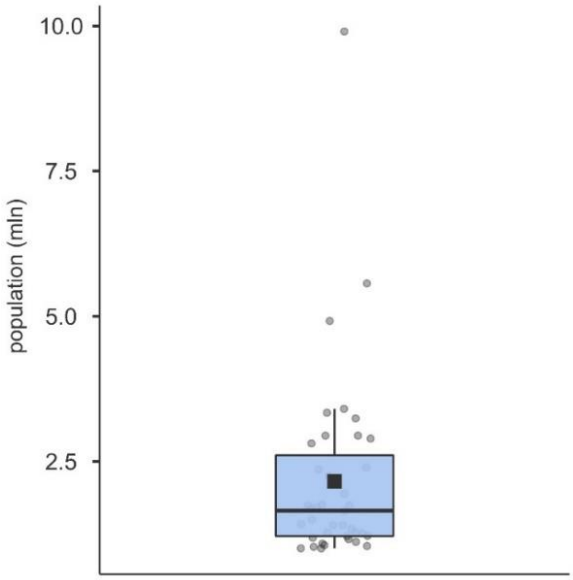


Fig. 2.35 *Relating smart green cities and smart circular cities. A visual summary of the population distribution (in mln)*

Note: dots represent single data points (over one million inhabitants in the EU). The black square represents an arithmetical average

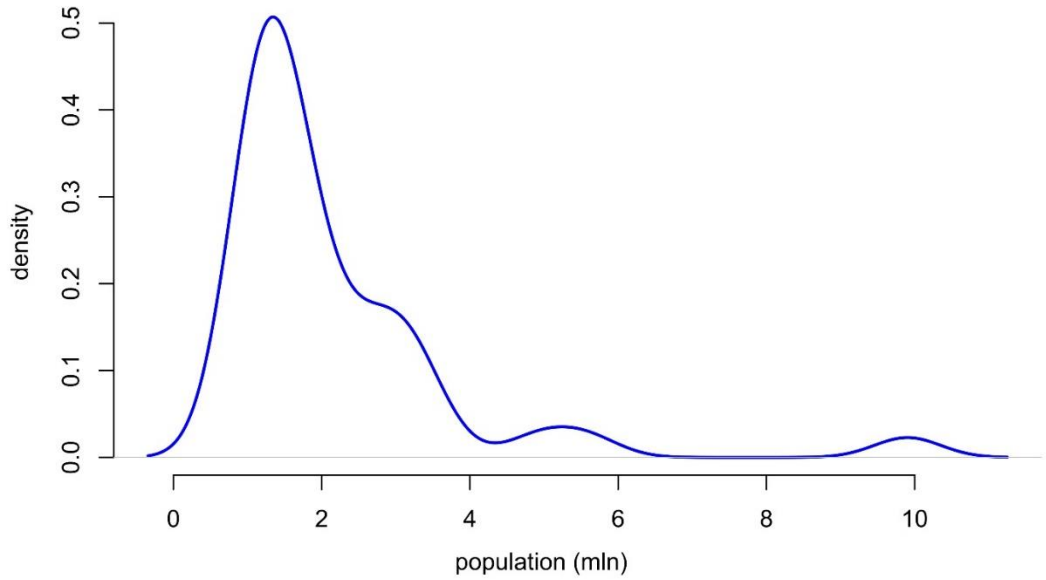


Fig. 2.36 *Relating smart green cities and smart circular cities. Kernel density estimation of the EU cities of the dataset according to their populations*

The bar plot in Figure 2.37 shows the distribution of countries in the dataset according to the number of cities with more than one million inhabitants. As expected, Germany has clear primacy in this regard, with ten cities included, followed by Italy (five cities), France (four cities), and Spain (three cities). Contrary to the case of Study 2, some countries have been excluded from the dataset, as none of their cities satisfied the inclusion criteria of population size. For example, the three Baltic states were excluded from the NCA.

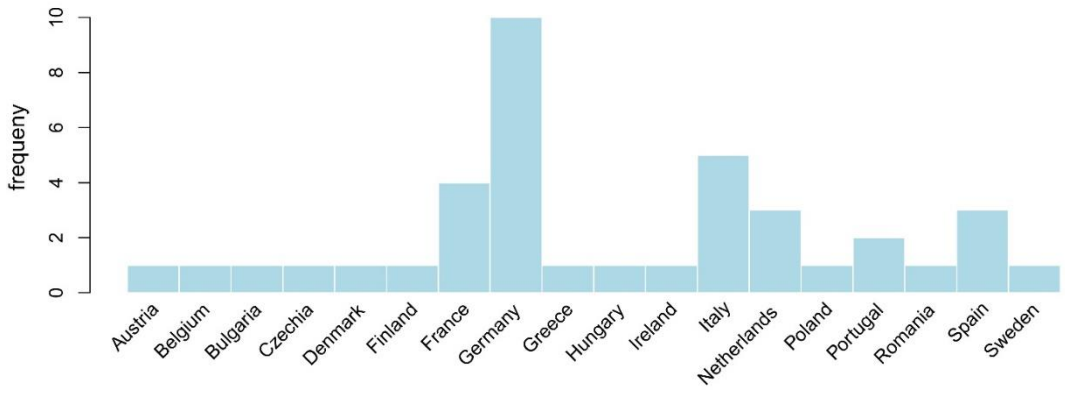


Fig. 2.37 *Relating smart green cities and smart circular cities. Distribution of countries in terms of the number of EU cities with more than one million inhabitants*

As the data regarding the indices come from different datasets with similar but heterogenous methodologies, and in both cases, the *Smartness* index is calculated differently, an additional

robustness check was performed to validate the index empirically. In particular, the *Smartness* index in Study 1 was calculated considering the media and online press attention to the smartness initiatives in the related cities. In Study 2, academic attention was considered instead in terms of the academic publications related to smartness initiatives in said cities (for more details, see the dedicated Methodology sections of Study 1 and Study 2). In essence, for the two indexes, one would expect a certain amount of positive, statistically significant, albeit not perfect, correlation. This is indeed the case according to the scatter plot in Figure 2.38, as the relationship between the two turned out to be positive ($R = 0.305$; p-value < 0.05). In this case, however, given the limited sample size and large standard errors, further validation of the indices is required in future studies and with larger samples.

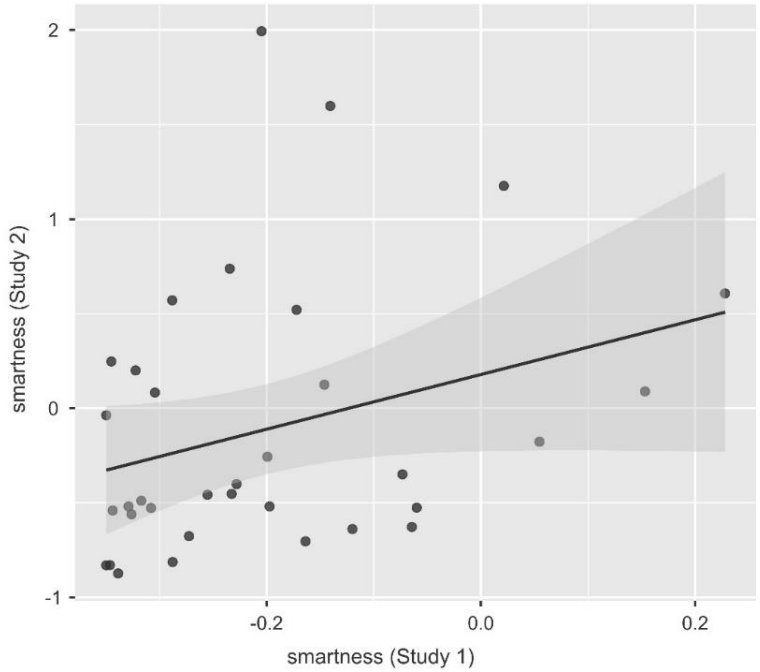


Fig. 2.38 *A positive significant relationship between the two indices of Smartness derived through heterogeneous methodologies*

When it comes to the "necessity" hypothesis regarding smart green cities and smart circular cities, a necessary condition analysis was performed on the two related indices (*Smart Green City* index and *Smart Circular City* index). As a form of bivariate analysis, NCA also works well when the sample size is not overly large. Indeed, contrary to regression analyses requiring large sample sizes to alleviate the problem of big standard errors, NCA can be performed even with a single case (N = 1 denoting the absence/presence of the condition) (Dul et al., 2021).

To perform the NCA, the dataset was imported into RStudio, and the dedicated NCA package was used. *Smart Green City* index entered the analysis as the independent variable, while the averaged *Smart Ciruclar City* index was treated as a dependent variable. In both cases, standardized versions of indices were used. According to the last hypothesis of the chapter, being a smart green city is a necessary condition for being a smart circular city. In this regard, one would expect a significantly large ceiling compared to the overall bi-plot. Indeed, this was also the case, according to the NCA output. As shown in Figure 2.39, overall, a high *Smart Green City* index is a necessary condition for a high *Smart Ciruclar City* index.

Figure 2.39 depicts two types of ceiling lines/envelopes. According to the guidelines of the methodology, the so-called CE-FDH (the red step function) is a suitable ceiling envelope to consider when the two variables are discreet (Dul, 2024). Instead, when the two variables are continuous, CR-FDH (the yellow function) is the appropriate ceiling line. The green line in Figure 39 represents the estimated regression line (R = 0.586, angular coefficient = 1.370, p-value < 0.01). However, as the analysis is centered on the necessity condition, the regression results are not of interest here.

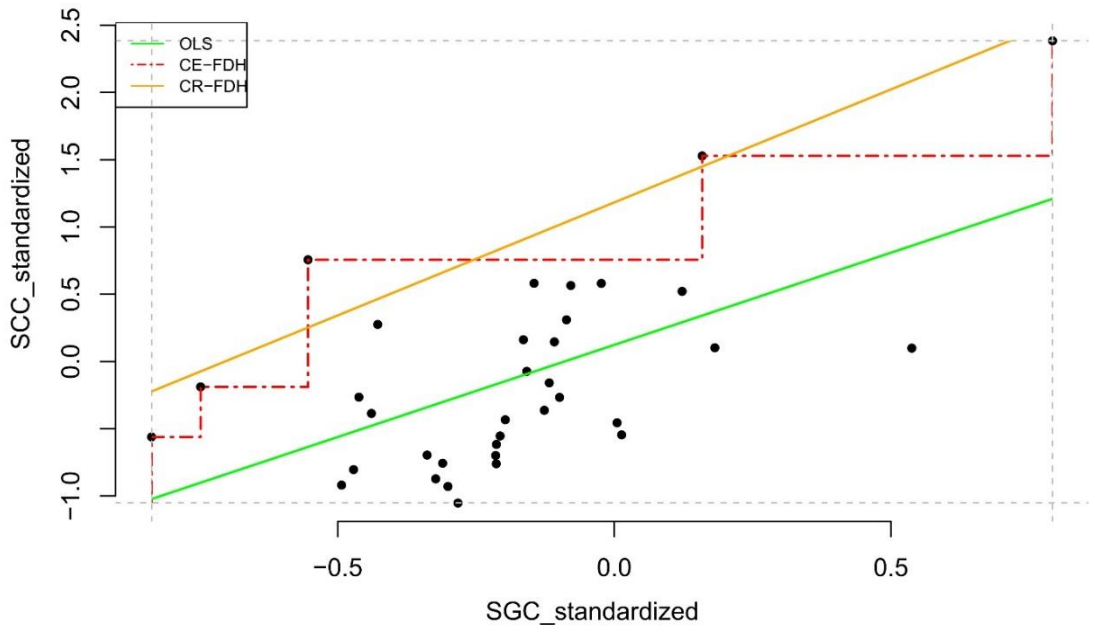


Fig. 2.39 *Relating smart green cities and smart circular cities. Necessary Condition Analysis. Bi-plot*

Central to the interpretation of NCA results is a *d-statistic* (ranging from zero to one) obtained by comparing the (empty) ceiling space to the overall area of the bi-plot. According to Dul (2024), the following criteria are then applied:

- 0 < d < 0.1 small effect
- 0.1 < d < 0.3 medium effect
- 0.3 < d < 0,5 large effect
- 0.5 very large effect

As both dependent and independent variables were continuous, a CR-FDH ceiling line was considered. In the latter case, the *d-statistic* was equal to 0.361, indicating a large effect or, in other words, that scoring high on the *Smart Green City* index is necessary for scoring high on the *Smart Circular City* index. To check the statistical significance of the results, a bootstrapping validation was performed by extracting 500 subsamples and building the distribution of effect samples under the assumption that the independent variable is not a necessary condition for the dependent variable (hence, d = 0). As shown in Figure 2.40, the true effect size (*d-statistic*) is not likely to be large by a mere chance (p-value < 0.01, *c-accuracy* = 95%). Hence, it is reasonable to conclude that, in the conformation of the "necessity" hypothesis, being a smart green city is, indeed, a necessary condition for a smart circular city to emerge.

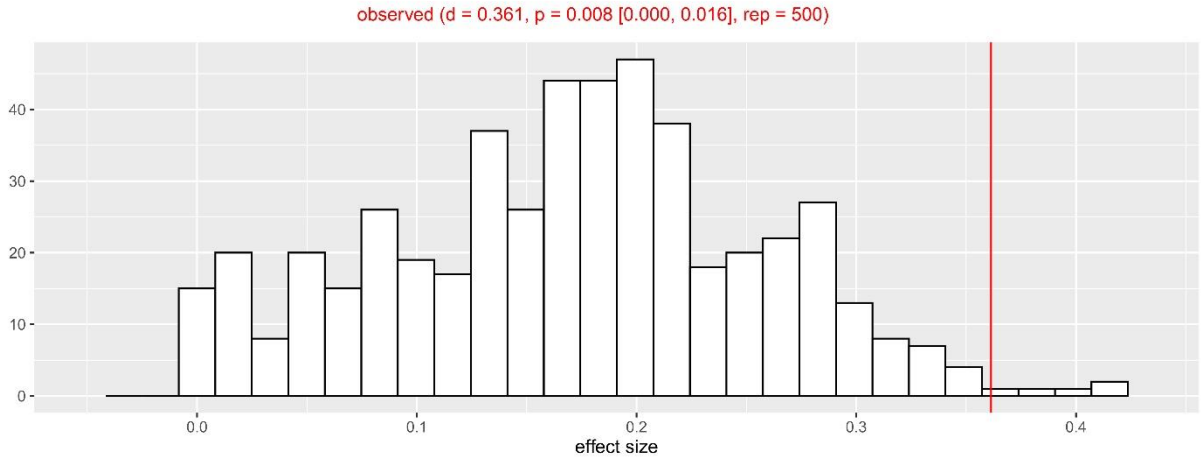


Fig. 2.40 *Relating smart green cities and smart circular cities. NCA results validation. Bootstrapping method*

2.5.3 Discussion

Study 3 results are primarily based on indices obtained in Study 1 and Study 2. In particular, the entirety of cities in the EU, with more than one million inhabitants within their metropolitan areas, was considered (*World Cities Database | Simplemaps.Com*, 2020). From

Study 2, the average *Smart Circular City* index was fetched, capturing the degree to which a city can be considered both circular and smart (in terms of the related initiatives). From Study 1, the *Smart Green City* index was fetched, measuring the degree to which a city can be considered environmentally smart. As both indices derive from heterogeneous albeit similar methodologies, the preoccupations about the potential for common method bias affecting the results are, therefore, minimal (Podsakoff et al., 2003).

In particular, for what concerns *HP3* (being a smart green city is a necessary condition for a smart circular city to emerge), the results were confirmed by means of a necessary condition analysis methodology (Dul, 2016). The obtained effect size was large, and the related bootstrapping has validated its statistical significance. Moreover, the two *Smartness* indices obtained through different methodologies (Study 1 and Study 2) were significantly positively correlated, further validating the respective indices and the related methodologies.

Overall, the results are far from surprising. Environmental concerns are at the heart of the circular economy. It is, after all, a model for production and consumption involving leasing, reusing, recycling, sharing, and fixing existing products as long as possible (Arruda et al., 2021). Conversely, it is hard to envision circular economy initiatives “divorced” from a set of environmental sustainability concerns. The latter, in fact, constitutes its primary rationale (Geissdoerfer et al., 2017). Nothing substantially differs when the same principles are applied in the context of urban development and management. A truly circular city is also a green city. Similarly, a truly smart circular city is, by its primary merit, a smart green (environmental, eco-) city (Petit-Boix & Leipold, 2018). The Study 3 constitutes mere empirical proof of the said relationship. Proof that may seem tautological but is deemed necessary in the context of the development of the broader integrative framework of smart sustainable cities, of which technology-driven circularity is potentially one of the most important constituents.

2.6 Discussion and conclusions

2.6.1 Toward conceptualizing a smart sustainable city based on the ESGE framework

In this chapter, the conceptual distinction between smart cities (more centered on technology and innovation discourses) and green cities (focused on the harmonious integration of urban and natural) was advanced and validated. Moreover, a subset of green cities, the so-called circular cities (i.e., cities that apply principles of circular economy to advance their environmentally sustainable initiatives), was studied in relation to the notion of a smart city.

Accordingly, two types of smart cities were conceptualized and empirically validated in Study 1 and Study 2: smart green cities and smart circular cities. The two, albeit conceptually distinct, appeared to exist in a strict set relationship. Chiefly, smart circular cities are a subset of smart green cities. Hence, in mathematical terms, Study 3 provided empirical evidence that being a smart green city is a necessary but not sufficient condition for being a smart circular city. Inversely, being a smart circular city is a sufficient but not necessary condition for being considered a smart green city. The set relationships between the abovementioned categories of city types are reported in Figure 2.2 in the Literature Review section of the chapter.

One question remains unanswered, however. Mainly, how are all the studied city types related to the concept of smart sustainable cities?

First, the notion of smart, sustainable cities should be considered more intricate than most of the other city concepts discussed above, as, by definition, sustainability is a holistic issue that transcends environmental concerns, on which this chapter mainly focuses. The argument for the need to reconceptualize our understanding of all things urban through the lens of sustainable development was already advanced in the Introduction section. A smart sustainable city (SCC) can now be (re-)conceptualized by buttressing the definition with regards to environmental, social, governance, and economic pillars (ESGE) of sustainable development (Antwi-Afari, Owusu-Manu, Simons, et al., 2021; Macke et al., 2019; Zygiaris, 2013).

In particular, one way to distinguish between heterogeneous definitions of smart cities is to categorize them through the lens of sustainable development based on the three ESG pillars (environmental, social, and governance) (Escrig-Olmedo et al., 2019). The three criteria are primarily used in organizational reports to measure the sustainability of a company's strategies. However, some of the frequently mentioned attributes of a smart city (see Table 2.1) already perfectly fit the ESG framework (for instance, increasing urban transience can be considered an environmental issue) (Isetti et al., 2020). Moreover, some authors distinguish the economy as an independent pillar of sustainability (Armeanu et al., 2018). However, due to the intrinsic economic nature of business organizations, it is not part of the ESG framework. Instead, financial reports frequently report it as an external contingency (Alsayegh et al., 2020). The principal argument of this section of the chapter is that the ESG framework (including the fourth pillar of economic sustainability) can be extrapolated onto the broader urban context. Hence, a novel conceptualization of a smart city based on three pillars of ESG and an additional economic pillar of sustainability (ESGE) can be advanced.

Given the chapter's definition of a smart city (see sub-Section 2.2.1), it becomes evident that smart cities should also aim at sustainable development—something that intrinsically implies going beyond the mere emphasis on novel technology. However, by definition, the sustainability aspect of a city's "smartness" can only be implemented through developing and integrating novel technologies for the greater good of a city's inhabitants. Hence, smart city and sustainability are interconnected in the sense that a non-sustainable city is far from being "smart." On the other hand, the concepts of a smart city and a sustainable city should not be considered synonymous (Ahvenniemi et al., 2017). As highlighted in the study by Ahvenniemi et al. (2017), "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, to achieve sustainability, it is essential to understand the set of existing relationships between individuals and, consequently, the social, economic, environmental, and cultural dimensions of their activities (Bibri & Krogstie, 2017; Martin et al., 2018).

The chapter argues for the proper integration of the four sustainability pillars in smart city design, planning, and development to achieve sustainable urban growth effectively. Accordingly, as already mentioned in the Introduction section, a thriving smart city can also be categorized as a smart environmental (smart eco-) city, a smart social city, a smart governance city, and a smart economic city. In particular, the chapter primarily focused on the environmental pillar of smart sustainable cities. It also discussed possible tensions that may arise while striving to be simultaneously "smart" and "green." On the one hand, it is possible to envision tech-heavy cities completely devoid of environmental sustainability (e.g., something akin to the popular cyberpunk aesthetic in mass culture). On the other hand, not all green (i.e., environmentally sustainable) cities are necessarily smart. Accordingly, the attempt was made to reconcile the two by re-conceptualizing the so-called "smart green cities"—cities in which nature and urban co-exist in perfect harmony (e.g., something akin to the ever-more popular "solarpunk" aesthetic). The latter is the notion equivalent to that of smart environmental and smart eco-cities, and the three terms can be used interchangeably.

Following the chapter's definition of a smart city, major government, economy, living, mobility, and people-related initiatives (Giffinger & Pichler-Milanović, 2007) should be integrated with a technological infrastructure to achieve sustainable development in the environmental, social, governance, and economic areas. Besides, all four subsystems must act organically and synergistically, and there are no clear borders between the areas (De Guimaraes et al., 2020; Hoyt, 2018). Given the environmental and social impact of

contemporary cities, including the exploitation of resources, the production of waste, and the generation of emissions, addressing an evolutionary dynamic co-creation of value based on a long-term approach emphasizing sustainability is essential (Bulkeley & Betsill, 2005). Moreover, among the challenges that cities must face is 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 studies on smart sustainable cities should emphasize the effects and implications of ICT and infrastructures on urban sustainability (Al-Nasrawi et al., 2016; Kramers et al., 2014). This is primarily possible through the development of integrated frameworks to measure the sustainable smartness of cities (Ahvenniemi et al., 2017). One such possible holistic framework was outlined in this section of the chapter and is reported in Figure 2.41. While the chapter has exhaustively focused on the empirical validation of the framework's environmental pillar (i.e., the so-called smart green city), further empirical validations of the other three smart sustainability pillars are expected to follow in future studies on the topics.

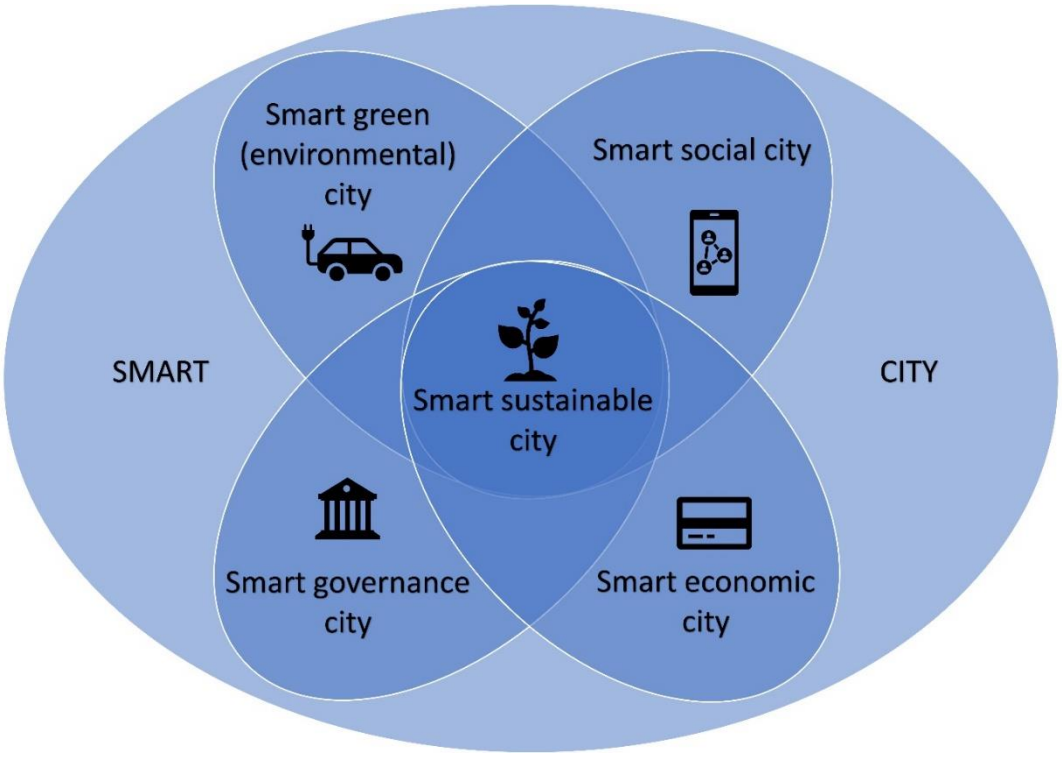


Fig. 2.41 *Smart sustainable city conceptualization*

2.6.2 Overview of the results of Study 1 – 3

The primary goal of this chapter was to outline a holistic framework for understanding smart

sustainable cities based on four pillars of sustainable development as an alternative to the heavy techno-centric smart cities of today and, in accordance with the framework, to investigate and quantitatively validate one of the four said pillars, chiefly, the so-called smart green (or environmental) cities. The latter has been done by 1) conceptualizing the notion of smart green cities in terms of its primary constituents, 2) investigating the relationships between the different constituents (i.e., city smartness, greenness, and circularity) and 3) validating the outlined set relationships between the constituents of smart green cities (as illustrated in Figure 2.2). This has been primarily achieved through three separate quantitative explorative and confirmative studies.

In Study 1, all the world's cities with more than one million inhabitants were included in the analyses. By looking at the attention the related cities generate in online press with respect to their smart and green (environmental) initiatives, indices of *Smartness* and *Greenness* were derived, and the relationships between the indices were explored by means of correlational, principal component, and hierarchical clustering analyses. In Study 2, in a specular manner, indices of *Smartness* and *Circularity* were derived, explored, and validated. The difference here is in the framing. To derive the latter, only medium-to-large EU cities (with more than one hundred thousand inhabitants) were considered. The reason for this conceptual shift is described in detail in the Methodology section of Study 2. As a result of Study 1 and Study 2, two important conceptualizations emerged: smart green cities and smart circular cities. Study 3 investigated the hypothesized set relationship between the two, confirming that (as shown in Figure 2.2) being a smart green city is a necessary condition for becoming a smart circular city.

Below, all the hypotheses of the chapter are again reported, and the related results are summarized.

HP1 There is a positive relationship between city smartness and city greenness.

Hypothesis confirmed. The log-log correlational model (see Figure 2.6) produced an angular coefficient of 0.26. Hence, for a one percent increase in a city's greenness, its *Smartness* index should rise by 0.26 percent. Moreover, when the respective indices were transformed into categorical variables (with four categories each, denoting, respectively, the degree of smartness and greenness of a city), a statistically significant association between the two categorical indices was detected. Specifically, "very smart" cities were likely to be also "very

green."

An interesting observation can additionally be made with respect to city size (the metropolitan area population). Both linear regressions and association Chi-Square tests confirmed a positive relationship between a city's population and its smartness. On the contrary, the relationship was negative regarding a city's population and its greenness. Hence, there is a nested conflicting dynamic working in favor of smartness and to the detriment of greenness (i.e., sustainable environmental concerns) that increases with population growth.

HP2 A smart green city is a distinct category of cities that exhibits the traits of both green and smart cities.

Hypothesis confirmed. Principal component analysis of the two indices of *Smartness* and *Greenness* together with a variable denoting metropolitan area population size has confirmed the existence of the so-called smart green cities that were entirely captured by the first dimension of the PCA. The results were then robustly confirmed by the agglomerative hierarchical clustering. In particular, the fourth cluster was composed of cities that could be readily conceptualized as real-life examples of smart green cities. However, the numerosity of the cluster suggests that those cities are still relatively few, and more can be done to push other cities to strive toward a smart green city status. The standardized coordinates of the first PCA component were then treated as an idiosyncratically derived *Smart Green City* (*SGC*) index.

Like in the case of conventional smart cities and conventional green cities, a significant linear relation between a *Smart Green City* index and a city's population was detected. In particular, the relationship was negative, suggesting that agglomeration economies that benefit smart city initiatives are not enough to surpass the negative ecological contributions that excessive population growth entails for a city's greenness. Hence, ideally, a smart green city should not surpass more than five million inhabitants in order to maintain its SGC status.

HP3 There is a positive relationship between city circularity and city smartness.

Hypothesis confirmed. The log-log correlational model (see Figure 2.20) produced an angular coefficient of 0.68. According to the "elasticity" interpretation of log-log models, for a one percent increase in a city's *Smartness*, its *Circularity* index should rise by 0.68 percent. Indeed, the correlation turned out to be even stronger than in the case of smartness and

greenness, suggesting a more close relationship between technology and circular production practices. This should not come as a surprise, as greenness does not always involve industrial practices but also refers to things that are not tangent to city smartness (such as the embeddedness of a city in a beautiful natural landscape or an abundance of green areas within a city).

HP4 A smart circular city is a distinct category of cities that exhibits the traits of both smart and circular cities.

Hypothesis confirmed. Three cases of principal component analyses, each focusing on various aspects of smartness and circularity, have independently confirmed the existence of the so-called smart circular cities (SCC), i.e., cities that score high on both smartness and circularity. A unified *Smart Circular City (SCC)* index was obtained by averaging the three abovementioned indices.

Again, according to the results of three PCAs, among specific technological components of a smart city, only ICT was closely related to the *Circularity* index. Hence, the smart city practice that contributes the most to circularity initiatives is the robust presence of an advanced ICT infrastructure within the city. As for the contribution of specific components of circularity to a city's smartness, only the *Waste Management* index positively correlates with the *Smartness* index on both dimensions of the respective PCA plane. In particular, as revealed by the third PCA, AI is the smart city constituent that contributes the most to effective waste management initiatives.

HP5 Being a smart green city is a necessary condition for a smart circular city to emerge.

Hypothesis confirmed. The results were derived by means of a necessary condition analysis (NCA). The obtained effect size was large, and the bootstrapping testing has validated its statistical significance. Indeed, it is hard to envision circular economy initiatives that are not connected in some form or another to a set of larger environmental sustainability concerns at the heart of smart green city metaphor. Hence, according to the results of the NCA, a truly circular city is also a green city. Similarly, a truly smart circular city is, by the merits of mere transitivity, a smart green city.

2.6.3 Conclusions, implications, and suggestion for future research

When it comes to the conclusions related to the results of the individual studies, the reader can reference the respective sections at the end of Study 1, Study 2, and Study 3. However, a few broader and more conceptual considerations are worthy of mention in the current sub-section.

To begin with, the role of awareness should be emphasized, both in academia and among urban planners and managers. Specifically, urban scholars and practitioners should internalize that urban smartness does not necessarily entail sustainability. As the analyses in this chapter show, some cities can be smart but not green, and, on the contrary, some can be green but not smart. Conversely, many authors implicitly incorporate sustainability into their definitions of smart cities (see Table 2.1). While it is generally true that the new technology implemented in such cities is, on average, greener and less negatively impactful on the environment, one can still envision scenarios of tech-heavy cities "suffocated" by their technological ambition. The framework proposed herein is the first one in urban management literature to explicitly emphasize the ambiguous role of a city's size in relation to greenness and smartness.

However, in the long run, all smart cities are necessarily sustainable. In fact, both environmental 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, one may think of a city as being environmentally sustainable without relying on a substantial ICT infrastructure. To overcome the issue and to shift the focus toward the more prominent problems within state of the art, some authors recommend starting to use the term smart sustainable city more often (Ahvenniemi et al., 2017). The term elevates both smartness and sustainability on the same conceptual level, making them equally important for the researchers. Too often indeed, the previous research efforts overlooked 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 reveal (see the related bibliometric evaluation in Chapter 1), the more "thrilling" technological aspects were investigated more frequently. However, those treatments lacked cohesion and were largely disconnected (Virtanen et al., 2020). Hence, this chapter's main goal was to integrate heterogeneous conceptualizations of smart cities into a cohesive and well-defined framework of smart sustainable cities that transcends mere techno-centric smart city narratives. Here, the emphasis was placed on environmental sustainability and the related concepts of smart green city and smart circular city. Further empirical validation of the three remaining pillars of smart urban sustainability is expected to be performed in future studies on the topic.

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3 THEORETICAL AND EMPIRICAL VALIDATION OF THE QUANTUM CITY CONCEPT

3.1 Introduction

3.1.1 An outline of the chapter

At this point, an important consideration should be made regarding the role of technology in smart sustainable cities. Most smart city research implicitly assumes the conventional nature of technologies used in urban contexts. In particular, it is assumed that all the constituent components of smart cities, be it AI, Internet of Things, big data, or blockchain, are based on the typical Von Neumann computer architectures (Allam & Newman, 2023). This implies that the devices used in smart cities are all engineered in a particular way by 1) separating memory and calculation, 2) distinguishing input and output mechanisms, and 3) integrating a control unit to oversee overall calculations and storage processes (Martinez & Sprecher, 2020). While, as of now, it may remain true, the recent academic progress and first prototypes in the paradigms of computing as diverse as quantum computing (Das & Das, 2023) and neuromorphic computing (Fayyazi et al., 2018) transcend the conventional Von Neumann architectures by offering drastically new ways of structuring digital systems (Kimovski et al., 2023). Accordingly, any holistic attempt to outline the conceptual framework of smart sustainable cities is incomplete without incorporating considerations of the role of non-conventional computer architectures if used therein.

In this chapter, the potentially disruptive role of quantum technologies in smart cities is assessed. While other types of non-conventional computing paradigms may also be interesting in their relation to smart cities, as of now, the cumulative research-based evidence is sufficient only for quantum technologies to be discussed and incorporated into the larger integrative framework (Arida, 2002). In particular, the chapter advances the notion of a quantum city (QC) and discusses its integration with conventional smart city components.

In particular, Section 2 is largely theoretical, and its goals are two-fold: to review the major city-related conceptualization and narratives of the past (so-called Newtonian metaphors), showing how their attempts toward simplification and isolation of causal links could be detrimental to urban practice and offering an alternative point of view (the so-called urban quantum metaphor), the one that actively encourages to embrace complexity as the fundamental ontological property of a city. Section 3 consists of an in-depth, mixed-methods systematic review of urban quantum technologies. The review is done in an attempt to outline

the concept of a quantum city, a reification of the urban quantum metaphor through the introduction of quantum technologies in future cities. Finally, Section 4 of the chapter looks at the potential synergies between quantum technologies and conventional smart city technologies. This is again achieved through a combination of quantitative and qualitative methodologies.

It is also important to specify in advance that, contrary to the previous chapter, the analyses of this chapter are exploratory, mostly given the state of the research and the actual development of current-day quantum technologies.

3.1.2 Tracing the development of Newtonian urban metaphors

The ever-increasing quantity of information, including information generated by novel ICT and IoT implementations, the differentiation of the ways of interfacing with the technology, and the disruptive innovations associated with the processing of large amounts of data have led to a proliferation of socio-technical variables contributing to the complexity of the contemporary socio-technical systems, be it public organizations, public institution, cities, or entire states (Cooke, 2024). Consequently, accurate societal and environmental responses to looming environmental and other anthropogenic crises, as well as related predictions, have become nearly impossible to compute with a reliable degree of certainty (Ellis, 2023; Larsson, 2018). As complex systems composed of heterogeneous social, technological, and ecological variables, contemporary cities are one of the primary catalyzers of this unpredictability (Arida, 1998, 2002, 2008b).

The last century saw the emergence of numerous city metaphors directed at advancing concrete solutions for diverse urban-related problems (Arida, 2002). All of those, however, treat the issue of complexity as epiphenomenal, i.e., as the bi-product of transversal vertical and horizontal relations woven into urban development (Macionis & Parrillo, 2010). To bypass the issue of uncertainty and complexity of urban-related decisions, most of the existing metaphors and models rely on simplifications and the reduction and isolation of variables, which are treated as mere proximal representations of complex urban sociotechnical realities (Barile & Saviano, 2010). The latter undoubtedly risks becoming a grave crime of omission.

Two classes of urban metaphors may be distinguished in this regard: intuitive Newtonian metaphors emphasizing cause and effect and eliminating most causative variables and Quantum metaphors, for which the complexity and uncertainty should not be swept under the

proverbial “rug” but are constituent parts of their ontology (Arida, 2002). For the former, parsimony is typically considered merit rather than a problem. For the latter, simplified approaches are to be avoided at all costs, especially as societies become complex and the diversity related to growing functional differentiation precludes the exact prediction and calculation of decision-making outcomes (Barile & Saviano, 2010).

Newtonian urban metaphors have dominated academia during the past century. With their emphasis on linearity, predictability, control, standardization, and modularity of industrial processes, concepts as diverse as Archigram’s Walking City (Archigram (Group), 1999), Soleri's (1999) archologies, and Lynchian City-as-a-Machine (Lynch, 1984) have captured minds and hearts of urban scholar, managers, and planers for more than a hundred years. Yet, stretched to its limits, at the turn of the new millennium, the mechanistic approaches gave way to more sophisticated conceptualizations of a city (Arida, 2002), such as the City-as-Organism metaphor grounded in notions of general system theory (Broto et al., 2012). The latter became popular, both as a response to the simplistic mechanical approaches of previous decades and as a helpful abstraction offering novel insights into urban theorizing (Broto et al., 2012; Kennedy et al., 2011). The City-as-Organism, though, was still the logical continuation of the City-as-a-Machine and, as such, just another spin at the plethora of Newtonian city approaches (Arida, 1998). Hence, no true paradigm shift took place. Indeed, the underlying core logic of the two approaches is rooted in Newtonian determinism.

Eventually, though, even the founders of original metaphorizations grew weary of the limitations of their deterministic concepts and models. For instance, toward the end of his life, Lynch rejected the City-as-a-Machine model and, more so, the City-as-Organism, emphasizing the failure of the two metaphors to address the increasingly complex problems of contemporary urban life (Lynch, 1990). Consequently, novel approaches were advanced in opposition to prior cybernetic ones.

3.1.3 When Newtonian metaphors fail: a comparative case study

This chapter takes a critical stance toward the so-called Newtonian urban metaphors. As mentioned above, in contrast to the Quantum metaphor, those endorse simplification, simple cause-and-effect relationships, and the emphasis on a few key variables. The proper critique of Newtonian urban conceptualizations should uncover flaws in the related theories and shed light on the epistemological and ontological fallacies enshrined in the metaphor. This, in turn,

might contribute to the emergence of novel urban models and alternative ways of thinking. A good way to start is to look at real-life examples of how urban management and planning that rely on the simplifications of urban reality can lead to undesirable outcomes in terms of how cities are built, planned, and managed.

An excellent example of a failed attempt to apply overly simplified reasoning to urban management is a typical Soviet city. Even though these cities were built with a focus on livability and efficiency, the lack of diversity and utopian undertones quickly compromised the said goals (Morton & Stuart, 2017). For instance, Magnitogorsk (53.3927° N, 59.0623° E), an industrial city in Chelyabinsk, Russia—founded in 1931 as a part of Stalin's attempt to industrialize the Union —was planned according to the so-called linear urban design, with rows of identically looking superblocks built parallelly to the factory, with a greenbelt separating the factory and the living space. In essence, Magnitogorsk's planners looked for ways to align urban living and production activities in order to minimize the required commute time (Ispulova et al., 2017). Like most post-Soviet mono-industry closed cities, Magnitogorsk now faces increasing urban degradation, decay, and pollution-related problems (Koshkina et al., 2016), highlighting the difficulties in transitioning from a communist utopia to new economic and social realities, hampered recently by the Russian aggression in Ukraine, and the related sanctions imposed on Russia by the EU and the US.

Ulaanbaatar (47.9221° N, 106.9155° E) is an even more dire example of how a simplified view of urban management and planning, or, in all likelihood, its absence, can lead to disastrous environmental consequences and the degradation of a city grid. The urban anarchism and pollution of Ulaanbaatar result mainly from a nomadic tradition that allows the disposition of yurts (portable traditional Mongolian dwellings covered in skins or felt) anywhere within the city limits, excluding the central areas where it is explicitly prohibited (Altangerel, 2020). This, in turn, has led to the uncontrolled sprawl of shantytowns around the city core (the so-called ger districts). When it comes to environmental degradation, this is particularly problematic in winter when the residents of yurts start using coal for heating. As Ulaanbaatar's location in a valley surrounded by high mountains impedes proper air circulation within city limits, the level of pollution in the city is one of the highest in the world during winter (Guttikunda, 2008).

On the other end of the ideological spectrum, the city of Los Angeles (34.0549° N, 118.2426° W) represents a typical postmodern late-stage capitalist city with a history of four distinct phases of land-use laws (Whittemore, 2012). Today, the city is one of the most sprawled in

the US. This is mainly due to overconfidence in the idealistic notion that the free-market economy can solve all urban problems and will always lead to the best consequences in terms of urban (self-)management (Eidlin, 2005). As a result, Los Angeles has seen an increase in wasteful and chaotic land consumption, long commute times, traffic and road congestion, and unsustainable vehicle-based suburban lifestyle (Dear & Flusty, 1997).

The final example of failing Newtonian urban conceptualization is Songdo (37.3861° N, 126.6389° E), a smart city in South Korea, a smart city that was designed and built as a greenfield development on reclaimed land (Yigitcanlar et al., 2019). The project heavily relies on high-tech implementations guided by sustainability goals; hence, it is, in essence, a smart sustainable city. For example, thanks to a well-designed public transportation system, Songdo has become a car-free urban region with little to no registered levels of pollution (Shwayri, 2013). Moreover, by recruiting biotech enterprises, city administrators have managed to transform Songdo into one of the world's most important bio hubs (Jeong et al., 2023). Yet, despite the best intentions of its planners and managers, a simplified view of the importance of technology and the resulting technological implementations in the city has failed to attract even half of the projected population. The over-emphasis on the technological dimension and the disregard for the importance of social interactions, spontaneity, and serendipity (something at the center of the social pillar of smart sustainable cities) have resulted in a "Chornobyl-like ghost town" experience, with inhabitants perceiving the city as soulless and cold (Yigitcanlar et al., 2019).



Fig. 3.1 *Examples of failing Newtonian urban conceptualizations*

Note: from top left, clockwise: Magnitogorsk and its linear urban design, sprawling Los Angeles, New Songdo City, one of Ulaanbaatar's gars. Data openly available on Google Earth

3.1.4 A summary of the most important Newtonian urban metaphors and their critiques

As can be seen from the comparative case study above, overconfidence in simple, mono-dimensional urban perspectives and models (defined here as Newtonian approaches) can be detrimental to cities in the long run. To sum up, most of the important conventional urban metaphors and conceptualizations are outlined in Table 3.1. Suffice it to say, some of those models are mere theoretical tools for simplifying particularized urban dynamics; some, however, have been applied to plan and manage cities in real life, often with questionable

results, like in the case of Songdo (Koshkina et al., 2016) or Magnitogorsk (Koshkina et al., 2016).

Perspective	Newtonian metaphors, approaches, models, and conceptualizations	Authors	Definitions	Critiques
Economic geography theories of urban systems	Central place theory	(Christaller, 1933)	An economic-mathematical model devised in order to represent how, through demand for space and in the function of the distance, the pattern of settlements develops.	Models consider individuals (and cities) as entirely rational decision-makers operating in abstract environments of simple geometric properties (like a grid of hexagons on the bi-dimensional plane). Models preserve the illusion of urban science that is value-free and positivist while, at the same time, legitimizing existing practices of capitalist exploitation. Models do not focus on a moral basis of decision-making, hence emphasizing formal rationality over the substantive one (in a strictly Weberian sense).
	Network model of urban settlement	(Camagni & Capello, 2004)	A model that describes urban systems by means of network analysis and graph theory. It represents urban settlements as nodes and then proceeds to elaborate on the nature of the edges that connect them.	
	Diffusion theory	(Bylund, 1960)	A theory that describes how urban settlements grow over territory following the initial phase of colonization.	
Ecological models of urban morphology	Concentric-zone model	(Park & Burgess, 2019)	A model that describes the development of a city's morphology by emphasizing the role of radial urban expansion that starts from a city core.	

	Urban sector model	(Hoyt, 1939)	A model that describes how heterogeneous land uses emerge around a city center and, as a city expands, how those develop outward into a specific sector.	Models do not consider equality and fair distribution of resources in society. Models ignore the significance of technological, cultural, historical, and institutional factors. Models do not consider diversity in preferences and social values Models and theories are mere mathematical simplifications and relate mainly to the context of the US.
	Multiple-nuclei model	(Harris & Ullman, 1945)	A model that describes a combination of regulatory factors determining the integration of multiple distinct urban nuclei into a single urban entity.	
Variations on classical ecological models	Mann's model of a typical medium-sized British city	(Mann, 1965)	It combines the models of Burgess and Hoyt while also factoring in a climate variable, in particular, by presuming a predominant wind direction from the west to the east in the Northern hemisphere.	

	Modified Mann's model	(Kearsley, 1983)	A variation on Mann's model, it also factors in heterogenous urban-related factors, such as the extent of government participation in urban development, decentralization of economic activity in the UK, gentrification, ghettoization, suburbanization, and the clearance of slums.	
	Twenty-first-century city	(White, 1987)	A modification of the Burgess model, it also incorporates contemporary urban-related trends such as the dominance of cars, the decrease in family size, the deindustrialization of the urban economy, and others.	
Political economy perspective	Circulation of capital	(Harvey, 1975)	The model describes the mechanism of circuitous competition for which capital constructs a material physical base suitable for its self-replication.	Models disregard cultural diversity. Models are overly abstract and "academic." Models are too conservative for what concerns the potential for social change. Models over-emphasize the role of material base and the adverse effects of the market.
	Informationalism	(Castells, 1991)	A model that incorporates a deep understanding of the structural dynamics of urban economies integrated into the information network society.	

Sustainable development perspective	Sustainable city	(Saccaro Del Buffa & Lewis, 1989)	An idealistic vision of a city that prioritizes the demands of the current generation without jeopardizing the capacity of future generations to address their own needs and wants.	Models do not adequately answer the question of whether existing cities can become self-regulating and environmentally sustainable. Creating universal recipes for sustainable urban development is a challenging task, mainly due to the differentiation of cities in terms of size, economic, political, and social factors, population growth rates, as well as heterogeneous geographical, cultural, and ecological contexts. Inconsistencies exist between sustainability goals and further economic growth.
	Urban metabolism perspective	(Stren et al., 1992)	A theory that emphasizes the role of the resources' flow through a city. It is mainly focused on the origins and the destination of urban waste.	
	Green city	(Howard, 1898)	An idealistic vision of a city harmoniously integrated into a surrounding natural environment.	
	Circular city	(Williams, 2021)	An urban metaphor that emphasizes how a city seeks to retain the value of materials, components, and products within its boundaries by relying on renewable energy sources and closed-loop production and consumption systems to minimize waste and pollution and maximize the social and economic benefits of the circular economy.	

	Eco-city	(Roseland, 1997)	An urban metaphor that has its roots in the concept of a green city. It describes a compact, multifunctional, high-density, human-oriented, connected (through an efficient, sustainable transportation system) city.	
	Dispersed city	(Burton, 1963)	An idealistic vision of a city that is totally dispersed and decentralized as an alternative to large and compact cities.	
	Car-free city or zero-carbon city	(Crawford, 2000; Topp & Pharoah, 1994)	An idealistic vision of a city that emphasizes the optimal planning of the efficient public transportation system providing the fastest services for most urban-related trips.	
High-tech perspective	Compact city or 15-minute city	(Breheny, 1995)	A model that describes a high-density compact urban living. It is mainly associated with the proliferation of high-rise residential buildings and the related vicinity of all urban amenities.	The concept of a cohesive metropolitan area as a unified economic, cultural, environmental, and social entity undercuts diversity as well as cultural, historical, and aesthetic qualities.
	Regional city	(Lynch, 1981)	A model that describes a city composed of a succession of distinct medium-size urban centers surrounded by big open areas and efficiently connected by major	

			transportation hubs	
	Network city	(Craven & Wellman, 1973)	A city that consists of a complex network of so-called “corridor cities” for which geographical and communication linkages create competitive advantages over conventional monocentric cities.	
Futuristic perspective	Smart city	(Hall et al., 2000)	A popular perspective that depicts a city in which digital technologies are integrated into all aspects of urban life, including transportation, energy management, healthcare, and education, to improve inhabitants’ quality of life, promote economic growth, and increase long-term urban sustainability.	Real-life cities are more than a collection of cyber-flows and integrated technologies. A complete urban experience includes emotions, scent, sight, scent, sound, and serendipitous human interactions.
	Informational city	(Castells, 1991)	A perspective that emphasizes the sociological elimination of space and time boundaries, bringing society to an ultimate degree of urban decentralization, eventually leading to the inevitable termination of the concept of the city as a	

			physically manifested space.	
	Virtual city	(Bianco et al., 2017)	An expansion of the informational city metaphor. For cyber-utopians, it entails a futuristic urban environment free of the limits of place-bound communication.	

Table 3.1 *Newtonian city conceptualizations and the related criticisms*

As a response to shortcomings and critiques of Newtonian city metaphors, in the following section of the chapter, a quantum city metaphor is introduced and theoretically developed. As an alternative to Newtonian conceptualizations emphasizing simplistic, reductionist approaches, the quantum metaphor emphasizes the role complexity rather than proposing simple ad-hoc "one size fits all" urban solutions. Accordingly, three theoretical postulates on which the quantum metaphor builds are presented and briefly discussed in the context of social sciences and city management: relativity, uncertainty, and duality. These are primarily based on the considerations stemming from quantum theory and are potentially of high value for a better understanding of contemporary cities' complexity. Then, in the remaining part of the chapter, a more empirically grounded conceptualization of a quantum city based on the adoption and exploitation of quantum technologies in urban contexts is outlined. Accordingly, through a systematic review of related academic literature, a functional technology-based definition of a quantum city (QC) is given, and two classes of quantum technologies for cities of the future are discussed: quantum communication and quantum computing.

3.2 Study 1: Developing theoretical framework of the quantum city concept

In 1905, Albert Einstein established his revolutionary theory of relativity, using the concept of spacetime to explain gravity. Soon after, the quantum theory developed as the standard formulation for atomic physics (Arida, 2002; Griffiths & Schroeter, 2018). Empirically grounded in "hard" science, quantum theory also provides a rich metaphorical basis for social sciences. The metaphorical approach is relatively unproblematic since a metaphor does not pre-require experimental proof for its validity; however, a metaphor needs to be validated by its relevance and usefulness—in other words, its adaptation and scalability (Cornelissen, 2005).

Quantum social science is a developing interdisciplinary perspective that is attempting to bridge the plethora of "soft" sciences and quantum physics. Indeed, a simple "in-title" search on Scopus for "quantum theory" resulted in 4062 academic documents (as of February 2022). Among these, seven percent belonged to either the "social science" or "humanities" category (Figure 3.2), showcasing a degree of interconnectedness between the so-called "soft" sciences and quantum theory concepts.

Although there is no consensus on what constitutes the optimal approach toward introducing quantum theory in social sciences (de Freitas & Sinclair, 2018), a common understanding is that, while social sciences have long modeled themselves on a traditional Newtonian understanding of cause and effect, it can (and should) now be enriched with quantum-related ideas and logic (de Freitas & Sinclair, 2018). Reducing social phenomena to a set of micro-interactions—which roughly approximate the core of quantum metaphorizing—seems inapplicable to studying macroscopic elements of reality. However, interpretations of macro-level phenomena through the lens of quantum metaphor have sometimes led to successful explanations of social behaviors (Haven & Khrennikov, 2013).

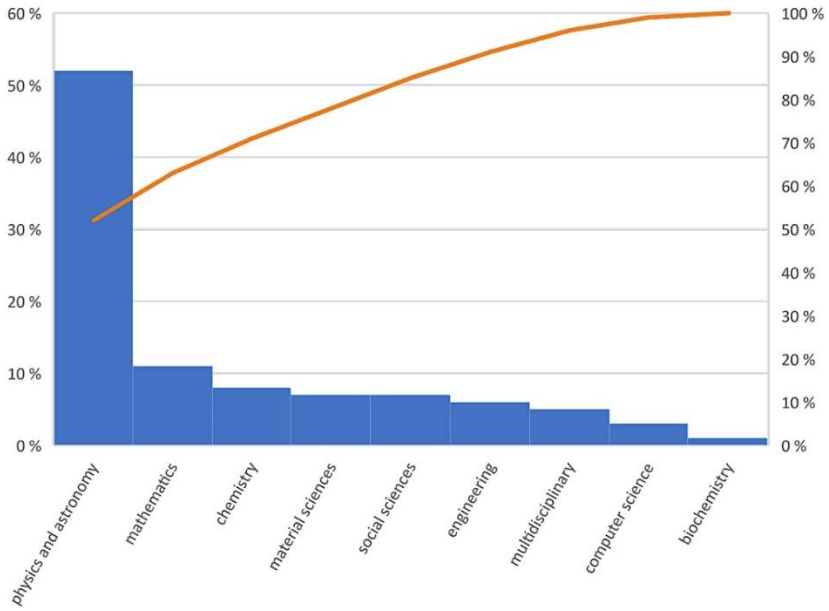


Fig. 3.2 *Pareto chart. Distribution of quantum theory-related academic documents by subject area on Scopus*

The first significant attempt at bringing concepts from quantum physics to social settings is attributed to Zohar and Marshall (1990). In their book, The Quantum Society, the authors claim that the mind and social life are both "macroscopic quantum mechanical phenomena." A more pragmatic middle-range view is also necessary regardless of the variety of theoretical approaches to the holistic quantum understanding of social science. For example, the application of quantum principles to social science concepts has been possible in the areas of politics, diplomacy, and international relations (Derian, 2011; Lewis, 1983), social systems (Arfi & Kessler, 2018; Fuller, 2018; Katzenstein, 2018; Wendt, 2015), game theory (Flitney & Abbott, 2002), decision theory (Yukalov & Sornette, 2009), finance (Lee, 2020; Schaden, 2002), and economics (Alaminos et al., 2022; Orrell, 2018). From the perspective of this chapter, unpredictability, uncertainty, and complexity—all defining features of a contemporary city—are central to the quantum metaphor (Singh & Singh, 2016). Hence, a complex urban system is likewise a perfect candidate to be analyzed through metaphoric quantum reasoning (Arida, 2002).

3.2.1 Relativity and complexity

Although *civitas*, the etymological origin of the term *city*, points to the formalized contract or even a simple collective will of a community to coexist in one location (Rippon, 2018), the contemporary city is not easy to define solely in geometric or social terms. The proper

definition, which considers the ever-increasing complexity of contemporary cities, requires an n-dimensional approach (Ramaprasad et al., 2017).

Spacetime, in physics, is a mathematical construct combining three spatial dimensions and one temporal into a four-dimensional manifold (Griffiths & Schroeter, 2018; Nielsen & Chuang, 2010). Until the beginning of the past century, scholars considered the Universe's three-dimensional spatial representation independent of one-dimensional time. Consequently, Albert Einstein's theory of relativity assisted in developing the concept of spacetime (Griffiths & Schroeter, 2018). Analogously, building upon general relativity and quantum theory principles, Arida argues for a novel conceptual construct of the "society-space-time" (SST) continuum of urban life (Arida, 1998, 2002).

With the advent of the new millennium, scholars are predicting radical changes in increasingly numerous aspects of social life due to the advances in technological development (Kaplan, 2015; Maynard, 2015; Philbeck & Davis, 2018). These aspects cover a vast range of activities in cultural, educational, entertainment, transportation, communication, marketing, production, and other fields. Buttressing Arida's (1998) conceptualization, technology can be considered an additional dimension of urban complexity, and thus, the concept of the "society-technology-space-time" (STST) continuum can be introduced.

By analogy with quantum field theory (Griffiths & Schroeter, 2018)—in which spacetime is the stage where the "dance of the quanta" occurs—the complexity of a city is reified in the interference patterns of STST continuum dimensions. Considering a city as a holistic multi-dimensional unity instead of a complex system and its subsystems (although a more challenging task) could potentially lead to a better understanding of the structuration dynamics of urban reality. In short, it means that, for the complete assessment of any urban phenomenon, we should consider its relationship with the city as a whole rather than its selective aspects.

Urbanists and city managers face increasingly complex problems, undermining their expertise and pushing them toward more comprehensive multidisciplinary collaborations (Arida, 2008a, 2008b). For urban planning, design, and management to fulfill the requirements of a virtuous interdisciplinary endeavor, they should be thought of—and taught—as one of many constituent parts of a multi-faceted discipline. A plethora of seemingly independent subject areas will play equally crucial roles in the study and structuration of quantum cities. According to Arida (2008a, 2008b)., landscape architecture, communication, transport engineering, but also the economy, sociology, behavioral studies, psychology, art, and

humanities—are some of the disciplines that together will shape the urban-related research of the future.

Although multidisciplinarity is inherent in studying all things urban, classical Newtonian approaches to urbanism and city management always sacrifice one set of variables to highlight the importance of others (see the "Criticisms" column of Table 3.1). By fully embracing complexity, qauantum city's planning, design, and management promise to transform the interactions of a multiplicity of urban variables into a higher quality of life without compromising variety and diversity.

3.2.2 Uncertainty and complexity

The principle of uncertainty, also known as Heisenberg's uncertainty principle (or the indeterminacy principle) Heisenberg and Pauli (1930), posits that it is impossible, even in theory, to measure any given particle's position and velocity simultaneously. Indeed, the concepts of precise position and velocity have no manifest meaning in physical reality. In this regard, quantum theory portrays a world composed of infinitely small chunks of possibilities and tendencies—not physical certainties. Likewise, the uncertainty emerging from the twenty-first-century functional differentiation and integration of urban phenomena complexifies reality beyond the explanative limits of prior Newtonian urban perspectives (Table 3.1). This consideration makes the analogy with quantum theory and, therefore, the corollary metaphor of the quantum city a viable alternative to simple traditional urban-related postulates and models.

While early approaches toward urbanism reduce a city to a predictable machine-like entity, often entrenched with fantasies of order and omnipotence, a quantum city metaphor emphasizes things and events that are, by definition, uncertain and yet "not there" (Arida, 1998) and to which no complete probability distribution can be assigned. This rejection of maximizing approaches toward urban phenomena, however, implies that there is always a better solution, no matter how complex and uncertain. Consequently, the quantum mindset intrinsically promotes all forms of sustainable urban development (Rees, 1997).

3.2.3 Duality/parallelism and complexity

Quantum physics treats electrons not only as particles (for which, according to the principle of uncertainty, both momentum and position cannot be established simultaneously) but also as

waves—interpreted as such in probabilistic terms (Griffiths & Schroeter, 2018). The stochastic "waves" are thought to exist as "waves" before the observation. However, after the observation, they are identified as "particles" (Griffiths & Schroeter, 2018). Among others, "many-worlds interpretation" by Everett (1957) posits the enthralling view of "parallel worlds"—as countless as the possibilities of looking at an electron. In brief, when an observer detects an electron at point A of a wave, the world in which the electron is positioned at this point is reified. Accordingly, in addition to this world, there exist several other "parallel worlds"—those in which the same electron is detected at points B, C, or D, and so on (Griffiths & Schroeter, 2018; Machida & Namiki, 1997).

A metaphorical conceptualization of a quantum city emerges by close analogy with the "many-worlds" interpretation in quantum physics, implying the existence of parallel "urban realities"—as many as there are ways of "looking" at a city. In other words, the "present location" and "the flow" (i.e., the developmental dynamics) of city constituents are, in effect, forever uncertain (Arida, 2002). Moreover, their systemic states (Barile & Saviano, 2010) are akin to probabilistic "waves"—that is, on the move—until the moment of observation.

This "wave-particle" view intrinsic to a quantum city metaphor gives rise to sets of dualistic concepts such as "liquefaction of urban society" vs. "sedentary urban society" (Bauman, 2013), "parallel habitat" vs. "UN-Habitat" and "urban governance in fluidity" vs. "urban governance in solidity." Embracing the duality-driven complexity in quantum cities allows opposing sides of different spectrums (ideological, political, economic, cultural) to coexist without neglecting either one of them. Therefore, the idea of dual urban realities incorporates a vast number of social theories, including deterritorialization/reterritorialization (Elden, 2006), globalization (Ritzer & Stepnisky, 2021), liquidized publicness (Splichal, 2018), global entrepreneurship (Pacione, 2009; Ritzer & Stepnisky, 2021), surveillance society (Lyon, 2010), philosophy of difference and fluidity (Bauman, 2013), the quantum self (Zohar, 1995; Zohar & Marshall, 1990), and many others. At this point, particular emphasis should be placed on the semantics of the word "duality." A "duality" could be perceived as a synonym for "dualism." In reality, unlike in the case of dualism, the two elements of duality are interdependent and no longer wholly distinct or opposed, even though they are conceptually separated. In this regard, the notion aligns with that of a Hegelian dialectic.

Quantum parallelism also highlights the effect of the observer on the phenomena. For example, the worldviews of city inhabitants and other city stakeholders have always influenced urban spaces (Giddens, 2005; Ritzer & Stepnisky, 2021). Before the scientific

revolution, those worldviews resulted from a set of archaic beliefs still echoing in some contemporary non-Western civilizations (Arida, 2002).

Finally, a quantum city itself can be considered an alternative viewpoint that, by emphasizing the "many-worlds" quantum interpretation, goes beyond the twentieth-century conventional Newtonian city metaphors. Machida and Namiki (1997) conclude that the "transition from Newtonian mechanics to quantum mechanics is apt to give one the feeling that all conventional things were denied and everything new emerged." Hence, the transition could be incorrectly thought of as a paradigm change. Nevertheless, Sumio Wada (1988), a well-known author of quantum physics texts, argues that "the transition should be seen as paradigm deepening rather than a so-called paradigm shift."

For Roger G. Newton (1997), the crux of the quantum worldview is that the "reality portrayed in classical mechanics falls short of perfection, and, at the same time, a world depicted in quantum mechanics fails to reveal the holistic picture." Nevertheless, there is no harm in considering the approximative Newtonian calculations as appropriate whenever applicable. By analogy, even under today's expanding globalization and computerization, different Newtonian urban paradigms may still constitute a good approximation of reality. In other words, in the case of cities, continuing to apply Newtonian models to describe urban dynamics at a lower level of complexity is inevitable. Thus, prior results of urban theorizing are never rejected or questioned in the attempt to envision a viable quantum city. They could, however, be effectively subsumed within the "quantum city" concept. Therefore, the two approaches can be understood as dualistic on the STST continuum.

Figure 3.3 shows an overview of the three theoretical principles of quantum urban metaphorizing. To sum up, a quantum view of a city necessarily presumes a more nuanced and holistic take compared to traditional Newtonian conceptualizations. More so, it transcends a conventional cybernetic view of the system composed of sub-systems (Barile & Saviano, 2010). Instead, an urban quantum metaphor emphasizes the utility of looking at a city as an infinitely complex set of dialectical dualities existing on the space, time, social, and technological continua, with no possibility of optimal solutions but an unlimited sustainability-driven impetus for which complexity and uncertainty should be actively embraced rather than discouraged. This, in turn, requires an active effort to cultivate a complexity-oriented mindset in the general population, as well as other city-related stakeholders (Arida, 2002, 2008a).

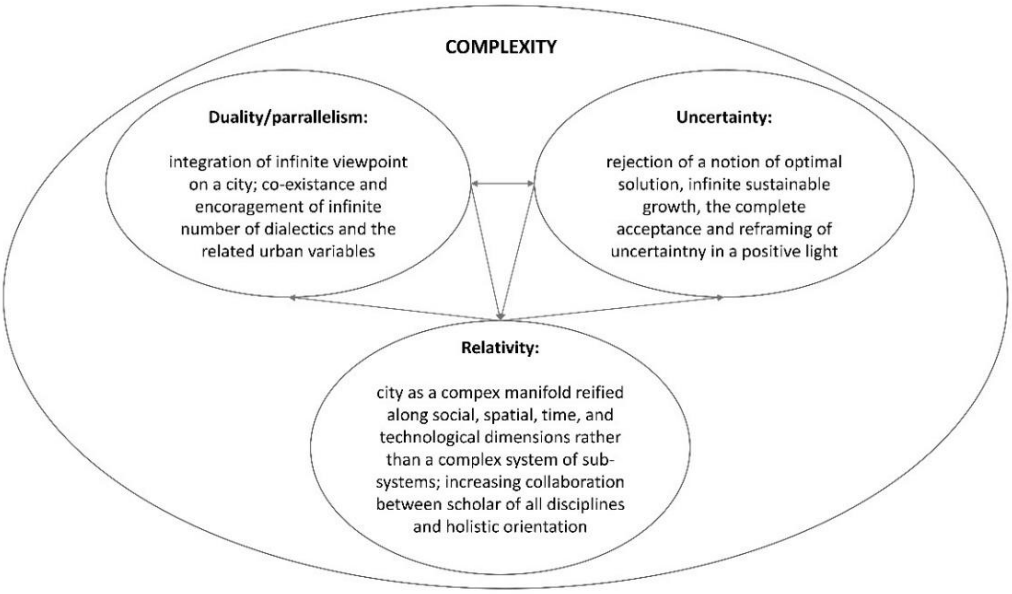


Fig. 3.3 *Urban quantum metaphor and its principles*

3.3 Study 2: A systematic literature review of urban quantum technologies

3.3.1 Outlining the technology-based approach to quantum cities

In the previous section, the urban quantum paradigm was outlined as a novel metaphorical basis for studying increasingly complex urban phenomena. According to the quantum metaphor, the quantum city concept relies on a set of fundamental principles—"borrowed" from quantum physics—that allow for a more accurate and holistic understanding of all things urban.

From a practical point of view, a quantum city can be considered a prospective research area shaped by the development of quantum technologies (QTs). Hence, it represents a natural continuation of a smart city and its related concepts (Aumasson, 2017). The goal of this section of the chapter is to individuate and assess the potential that quantum technologies hold in terms of their contribution to the reification of quantum cities, based, in particular, on the implications and considerations of urban quantum metaphorizing, as described above. Indeed, the introduction of urban quantum technologies itself can be considered alongside the "technology" dimension of the STST continuum, as previously theorized (Arida, 2002).

For the vision of a quantum city to be fully realized, the broader public must willingly adopt quantum technologies and understand the risks and benefits they may bring to daily life as quantum technologies become a part of everyday existence, including in healthcare, environment, economy, communication, and others (Aumasson, 2017; Gisin et al., 2004; Gow

et al., 2018; Joint Research Centre (European Commission) et al., 2018). Due to the complexities of quantum mechanics, the notion of a quantum city could be challenging to communicate to the public properly. However, with the increasing academic interest in quantum technologies as well as their impact on the future, it is essential to engage urban stakeholders with reasonable explanations, examples, and metaphors. Only the proper educational approach toward quantum technologies can positively shape the public's perception of complex quantum urban reality (Arida, 1998, 2002, 2008a).

As previously mentioned, a metaphorical view of a quantum city fully embarrasses complexity in order to extract the most accurate and compelling conclusions and evidence, hence boosting the welfare of the inhabitants of the city through an ever-increasing quality of decision-making. However, this idealistic approach toward complexity may not justify the expenditure of currently available resources. With the massive leap in computational power that quantum technologies promise, the theoretical possibility of the inclusion of an exponentially higher number of variables in urban-related decision-making is a feasible future reality.

Quantum technologies could potentially fix the problems intrinsic to Newtonian cities (see Table 3.1) in several ways:

- when addressing a problem, QTs could accommodate exponentially more variables. In the case of cities, quantum AI, for example, can be introduced in decision-making processes in order to take into account multiple social and cultural, economic and financial, environmental, and technical factors to provide the highest degree of variety and diversity while serving the needs of all urban stakeholders (Khan & Robles-Kelly, 2020);
- in digital-heavy settings such as smart cities, quantum technologies have the capability to enable the storage of large amounts of data and consequently prevent errors caused by data sieving (Dowling & Milburn, 2002);
- using quantum technologies makes it possible to estimate solutions with increasingly high precision. Accordingly, having more exact predictions and estimates of decisions undertaken in urban management and planning, which are particularly susceptible to uncertainty, may be highly beneficial (Kim et al., 2021; Proctor et al., 2022);
- quantum technologies can sustain complicated communication networks. This feature may contribute to creating highly integrated smart sustainable cities where various technological, antrhopic, and environmental parties are comprehensively linked and operate harmoniously (Bassoli et al., 2021);

- one of the obstacles to promoting complexity-embracing paradigms in cities (such as a quantum city paradigm) is the security issues caused by complex systems. Quantum cryptography and quantum secure communication systems provide the most advanced safety and security algorithms for information protection (Kumari et al., 2021; Portmann & Renner, 2022; X. Zhang et al., 2015).

3.3.2 Research goals and methods

Acin et al. (2018) distinguish four types of quantum technologies:

- quantum communication, in which entangled particles (typically photons) are exploited to send and receive data in a demonstrably safe manner;
- quantum simulation, in which well-controlled quantum systems replicate the conduct of other, less precise quantum systems;
- quantum computation, which uses the concepts of quantum physics to accelerate complex calculations significantly;
- quantum sensing and metrology, in which higher sensitivity of quantum systems to outside disturbances is used to increase the quality of measurements of specific physical quantities.

A thorough assessment of both academic and "grey" literature on the topic revealed that no prior in-depth systematic evaluation had been conducted on the potential contribution of quantum technologies to urban planning, design, and management. Accordingly, the systematic literature review was structured considering two explorative research questions:

RQ1 Which types of quantum technologies are most likely to contribute the most to the urban planning, design, and management of quantum cities?

RQ2 What are the main contributions of identified types of quantum technologies to quantum cities?

A systematic literature review has been chosen as the most appropriate methodological tool to address the above research questions. A systematic review was preferred over other types of review for two reasons (Grant & Booth, 2009; Snyder, 2019): 1) quantum technologies are still not part of everyday life; therefore, the literature on the topic is not abundant; 2) this, in turn, perfectly fits the scope of a typical systematic review, which is typically defined as appropriately small (Xiao & Watson, 2019).

As the literature on urban-related quantum technologies is scarce, the systematic literature

review allows for assessing the role of quantum technologies in all kinds of social contexts potentially related to urban planning, design, and management. Several scholars have advanced the topic of the societal contribution of quantum technologies with the same broad scope in mind (de Wolf, 2017; Wendt, 2015; Zohar & Marshall, 1990)(de Wolf, 2017; Wendt, 2015; Zohar & Marshall, 1993). Nevertheless, none approached the subject by emphasizing the urban domain.

Figure 3.4 shows the four steps followed for the systematic review purposes. The first three are described in the following sub-section. The two subsequent sub-sections report the results of the quantitative content analysis of included scholarly records and qualitative thematic synthesis of the most relevant types of quantum technologies in urban-related contexts.

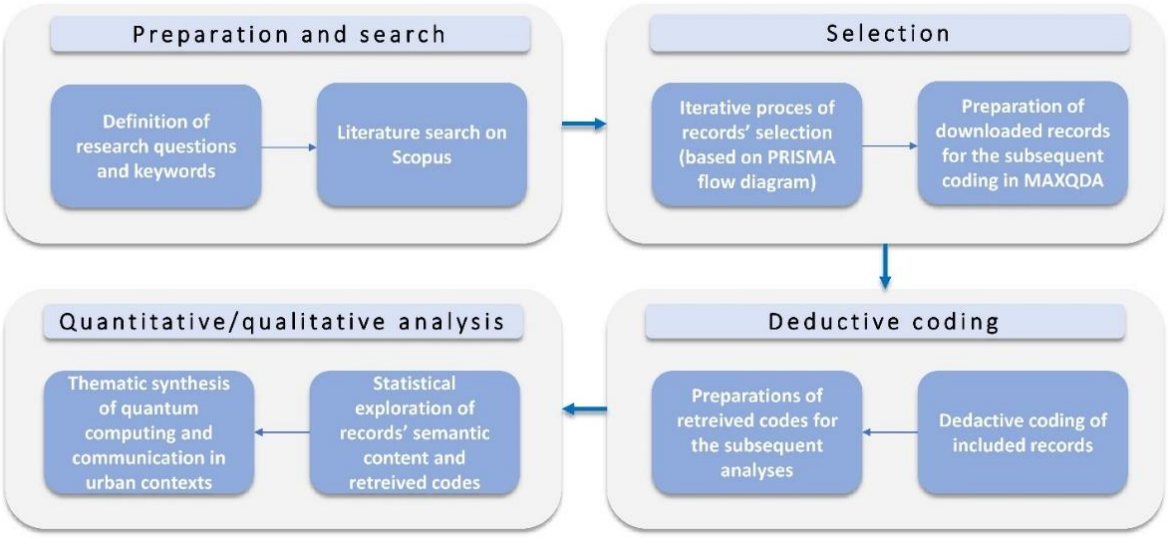


Fig. 3.4 *Systematic literature review of urban-related quantum technologies. Research protocol and process flow*

3.3.3 Preparation, search, and selection

A typical mistake in performing a systematic review is choosing an overly broad research question (Xiao & Watson, 2019). Indeed, some form of semi-structured or scoping literature review appeared, at first, better suited for the functional mapping of such a heterogeneous research area of inquiry (Munn et al., 2018; Snyder, 2019). However, although the initial plethora of research methods and methodologies within reviewed papers on quantum technologies was vast, a systematic literature review was, in the end, considered the most appropriate for the scope of the chapter. In fact, regardless of such methodological diversity, the two research questions are well-defined and sufficiently specific. Moreover, the selection

process did not produce the amount of literature that was unsurmountable to diligently review and code (Snyder, 2019).

According to the suggestion of Xiao and Watson (2019), the review protocol was developed and validated before the initial literature search (Figure 3.4). The review protocol strictly followed the current Preferred Reporting Items for Systematic Review (PRISMA 2020) guidelines (Page et al., 2021), comprising the definition of research questions, criteria for selecting and including records, and other essential systematic review elements as reported in the PRISMA checklist.

The Scopus academic search engine and database was the sole source for the literature search (currently containing more than eighty-seven million academic records). No backward or forward searches were included in the protocol. Therefore, only keyword-based searches were performed. The choice of the Scopus academic search engine is not accidental but based on the suggestion of Gusenbauer and Haddaway (2020). According to the authors, Scopus constitutes a suitable primary search engine for systematic reviews in the field of social sciences (Gusenbauer & Haddaway, 2020).

The deductive coding approach was preferred for data analysis. Therefore, coding categories were defined beforehand based on the four types of quantum technologies as identified by Acin et al. (2018). The related search terms were also based on the same taxonomy. Accordingly, five separate searches on Scopus were performed ("quantum communication," "quantum simulation," "quantum computation," "quantum sensing," and "quantum metrology"). The search was performed using the "in-title" specifier and restricting the results to the domains of "Social Sciences," "Decision Sciences," "Business, Management and Accounting," "Economics, Econometrics, and Finance." No restrictions were put on the types of records, allowing for the "grey" literature to be included in the review. The broader criteria for articles' inclusion allowed for assessing the vastest amount of "soft science"-related literature on quantum computing in different contexts. However, only city-related papers (although with the broadest criteria for consideration) were selected during the identification, screening, and inclusion of scholarly documents.

PRISMA 2020 guidelines were strictly followed for the stages of identification, screening, eligibility assessment, and inclusion of records in the review (Page et al., 2021). Figure 3.5 shows the PRISMA 2020-based chart of the four selection stages. Initial title screenings allowed to restrict the number of documents to 58 for quantum communication, 122 for quantum computing, 5 for quantum simulation, and 11 for quantum metrology and sensing.

As a following step, all the available scholarly documents were downloaded, and a more detailed abstract screening was performed, reducing the total number of records to 141. Additional screening of the records' content also followed. In the process of deductive coding (McKibben et al., 2020), 20 records were excluded due to the mismatch of their content with the research questions, and the total number of records included for the final analysis was reduced to 80, with one paper assessed twice, separately for quantum computing and quantum communication domains.

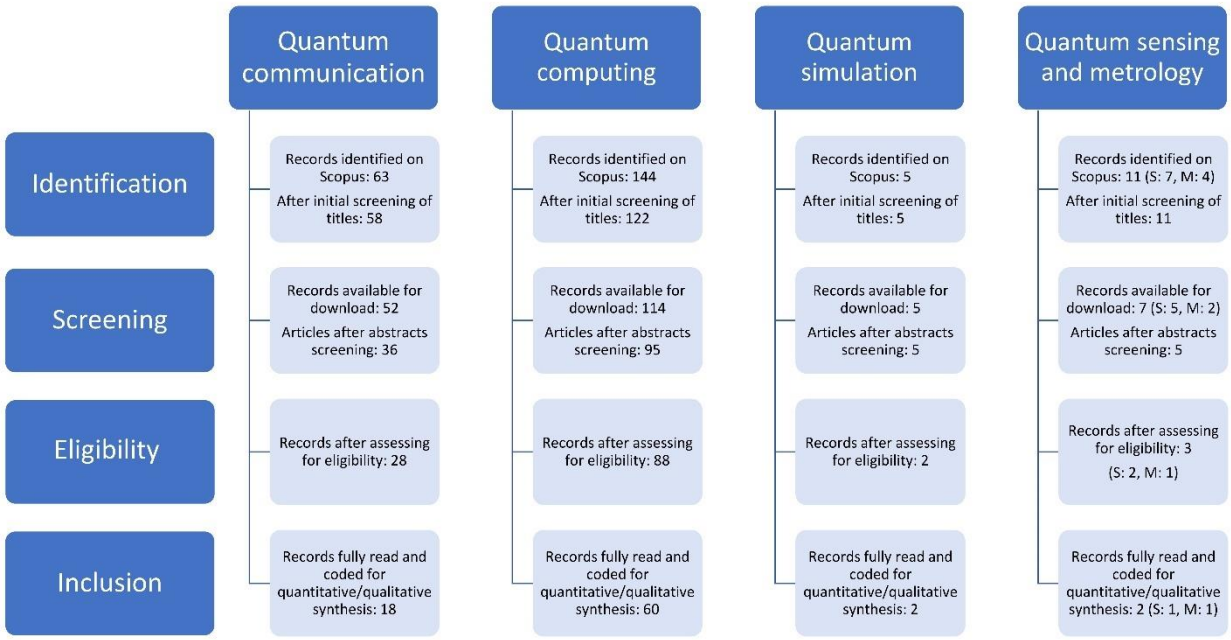


Fig. 3.5 *Systematic literature review of urban-related quantum technologies. Criteria of identification and selection of scholarly documents*

3.3.4 Quantitative content analysis of scholarly records

Quantitative content analysis was chosen as the primary analytical tool for assessing the included records. Content analysis can be automated or non-automated (Bryman, 2016; Stemler, 2015). In this case, the former was chosen, given the homogenous nature of the units of analysis (text-based records). Figure 3.6 shows the breakdown of identified records by year. As is evident from observing the distribution, there has been an increase in interest in the topic of quantum technologies within the social sciences in the last three years (the last identified year was 2021, as, at the time of the initial search, the year 2022 was still ongoing). It is, however, unclear how much of the increase is attributed to exogenous factors, such as

academic inflation and the dynamics related to the recent COVID-19 pandemic (Yi & McMurtrey, 2013).

A qualitative data analysis software, MAXQDA (release 22.0.0), was used to calculate the absolute frequency of all words and word combinations across 80 assessed records. The English language lemmatization was applied to control for different spellings and inflected forms. The first 100 most frequent nouns, verbs, adjectives, and their combinations that are related to different facets of quantum technologies were selected. Figure 3.7 shows the respective word cloud with the size of keywords linearly proportional to their overall frequency in texts.

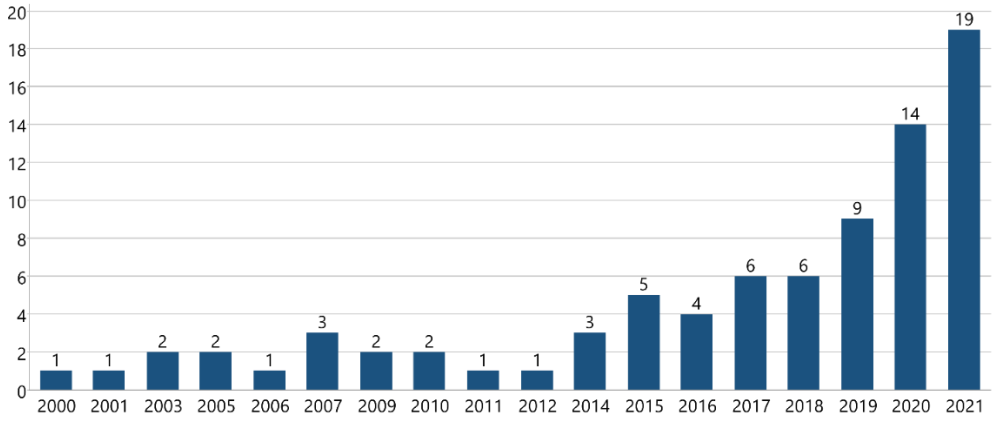


Fig. 3.6 *Systematic literature review of urban-related quantum technologies. Distribution of included records by year*

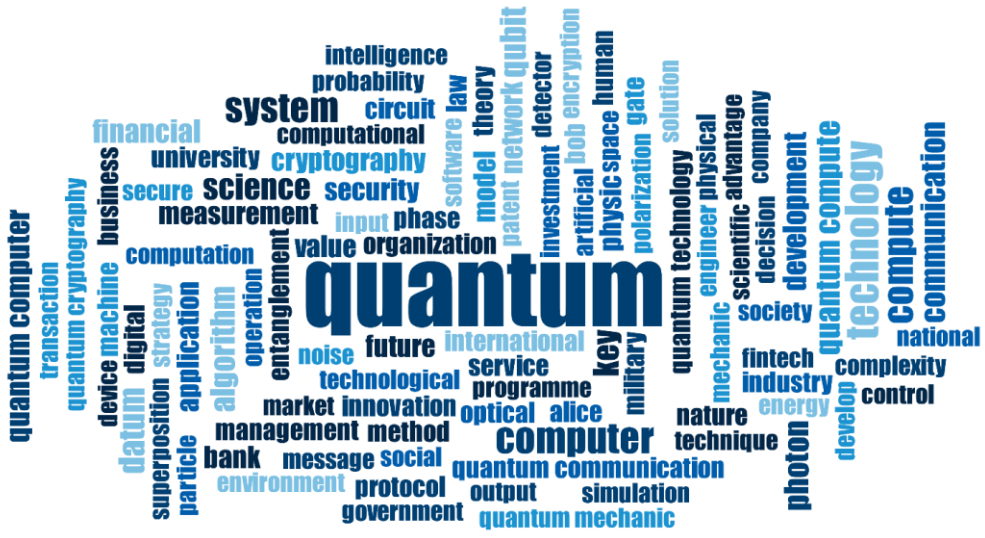


Fig. 3.7 *The most frequent quantum technologies-related words and word combinations*

However, besides giving an approximate "bird's-view" of the thematic depth of the retrieved records, the simple analysis of frequencies is inadequate for a proper understanding of relatedness between different topics within the reviewed literature. Accordingly, a more in-depth latent semantic analysis (LSA) of retrieved records was performed, including the bottom-up construction of semantic space based on the frequencies of the related keywords. LSA is one the most famous and validated natural language processing techniques based on applying singular value decomposition techniques (PCA or similar dimensionality reduction techniques) to a matrix relating the most frequently used words and documents of a specific textual corpus. LSA is based on the distributional hypothesis, assuming that words that are similar in meaning (i.e., have high semantic similarity) occur in semantically similar documents (Evangelopoulos, 2013).

For each record, absolute frequencies were then transformed into relative to make the comparison between included documents possible. The following calculation was applied:

$$rel.frequency_k^i = \frac{abs.frequency_k^i}{\sum_{j=1}^{100} abs.frequency_j^i}$$

where *i* denotes a unit of analysis (one of 80 records), *k* and *j* denote a generic keyword or keyword combination (one of 100).

The data was then exported into RStudio (version 1.4.1717), the variance was scaled to one, and and a principal component analysis (PCA) was applied to the dataset. The 100 most frequent meaningful words and word combinations entered the analysis as active variables (in terms of their absolute frequencies across 80 records). As no a priori hypotheses were made about the potential relationship between various QT-related topics, PCA was preferred to exploratory factor analysis, which typically has more stringent underlying assumptions (Bartholomew et al., 2008)

In total, 81 uncorrelated dimensions were obtained from 100 active variables. According to LSA scholars (Shermis & Burstein, 2003), while around 300 dimensions are optimal for the analysis of moderate-size document collection (hundreds of thousands of documents), for a smaller-size textual corpus, like in the current case, around fifty dimensions are more than sufficient.

The high ratio between the first PCA dimensions (0.81) indicates that the original keywords were already largely uncorrelated across the included records. However, the first two dimensions stood out, accounting for approximately 20% of the total variance. Only those two two most significant dimensions were considered for further exploratory analysis, as

contributions of the remaining dimensions to the total variance were individually insignificant and, thus, uninterpretable.

Figure 3.8 shows the variables that contributed the most to the creation of the PCA plane (cos^2 denotes the quality of representation of variables on the two dimensions). Based on the analysis of contributing variables and their distribution on the PCA plane, three clusters of records were identified. In particular, records in the northeastern part of the plane tended to be business, governance, and management-oriented (hence the dominance of keywords such as *market, decision, society, innovation, government,* and *management*). Records in the southern part of the plane (both south-eastern and south-western) were mostly related to computational and theoretical aspects of quantum technologies (*probability, quantum, computer, quantum computing,* and others). Records in the north-western part of the plane were closer to the topic of quantum communication (*quantum cryptography, protocol, security, communication,* and others).

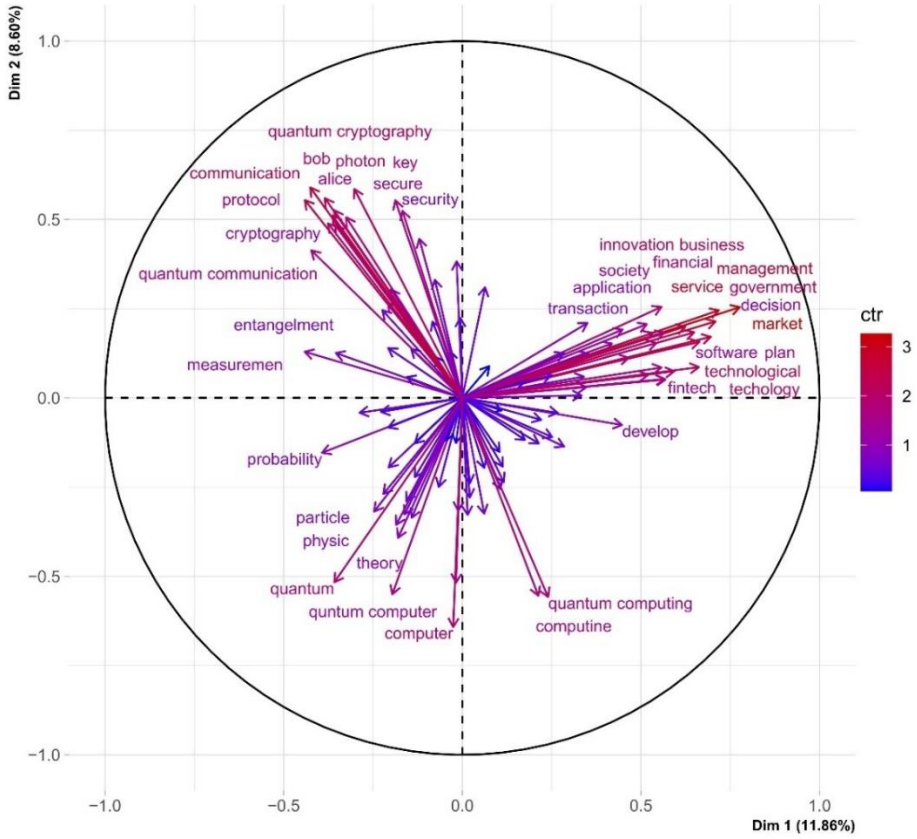


Fig. 3.8 *Systematic literature review of urban-related quantum technologies. Distribution of active variables on the two most significant PCA dimensions*

Note: ctr (similar to cos^2) measures the contribution of single variables to the construction of the dimensions

While conceptually separate, the business/governance cluster slightly correlated with the quantum communication cluster (vertical axis) and the quantum computing cluster (horizontal axis). Interestingly, quantum simulation, sensing, and metrology have not emerged as separate categories, unlike in the general taxonomy of Acin et al. (2018). Therefore, those are considered not immediately applicable in urban planning, design, and management contexts. Consequently, according to the LSA results, only quantum computing and quantum communication are the two macro-categories of quantum technologies (Acin et al., 2018) that appear closely related to the theoretical notion of quantum cities.

To further confirm the results of latent semantic analysis, agglomerative hierarchical clustering was performed based on the obtained PCA dimensions. The five most contributing PCA dimensions have entered the clustering. The Euclidean distance was used to measure the similarity between pairs of records. Ward's method was preferred as a measure of closeness between the groups to ensure the partitioning with small within-class variability and high between-class variability.

Figure 3.9 shows the respective cluster dendrogram projected on the first two dimensions of the PCA factor map. Single points denote individual observations (i.e., analyzed scholarly records). The partitioning of documents into three distinct clusters was deemed optimal by the R package (*Factoshiny*). In particular, the related function first built a hierarchical tree. Then, the sum of the within-cluster inertia was calculated for each partition. The suggested partition was the one with the higher relative loss of inertia [i.e., (i(clusters n+1)/i(cluster n))]. As a result, additional inertia gains from considering four or more clusters were deemed unjustified, given relatively small inertia gains.

Confirming the interpretation of latent semantic analysis results), Cluster 1 (Figure 3.10) is characterized by high values for variables like *photon, communication, protocol, quantum communication, detector, optical, polarization,* and *quantum cryptography* (variables are sorted from the most contributing to the least contributing; p-value < 0.05). Cluster 2 (Figure 3.10) is characterized by high values for variables like *computer, quantum computer, compute, computation, algorithm, quantum computing, quantum, computational, theory,* and *superposition* (again, sorted from the most contributing to the least, p-value < 0.05). Finally, Cluster 3 (Figure 3.10) is characterized by high values for variables like *technological, investment, technology, market, innovation, national, industry, business, society,* and *service* (sorted from the most contributing to the least, p-value < 0.05).

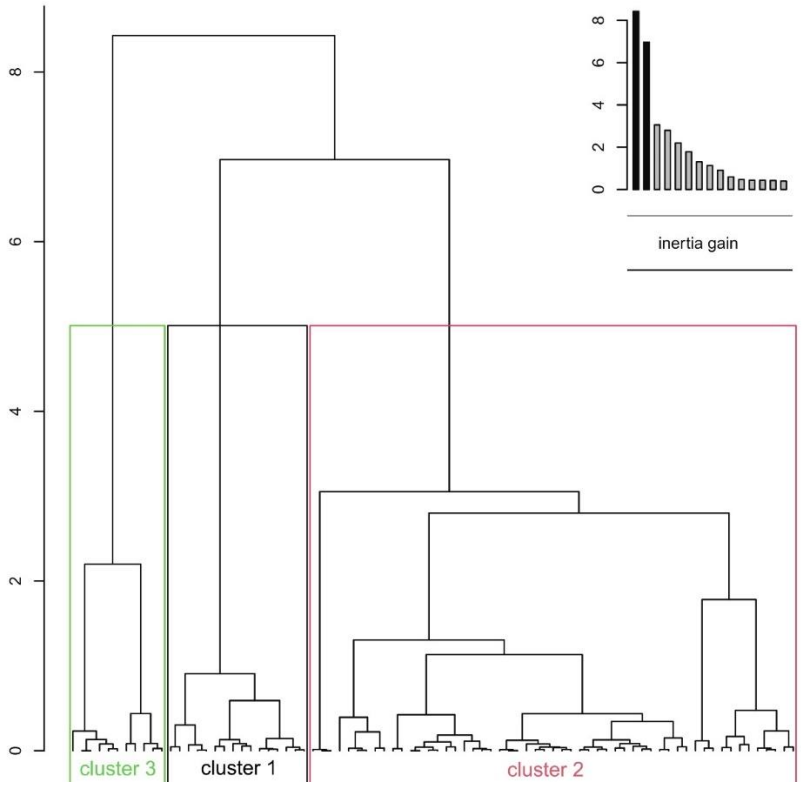


Fig. 3.9 *Systematic literature review of urban-related quantum technologies. Agglomerative hierarchical clustering. Dendrogram*

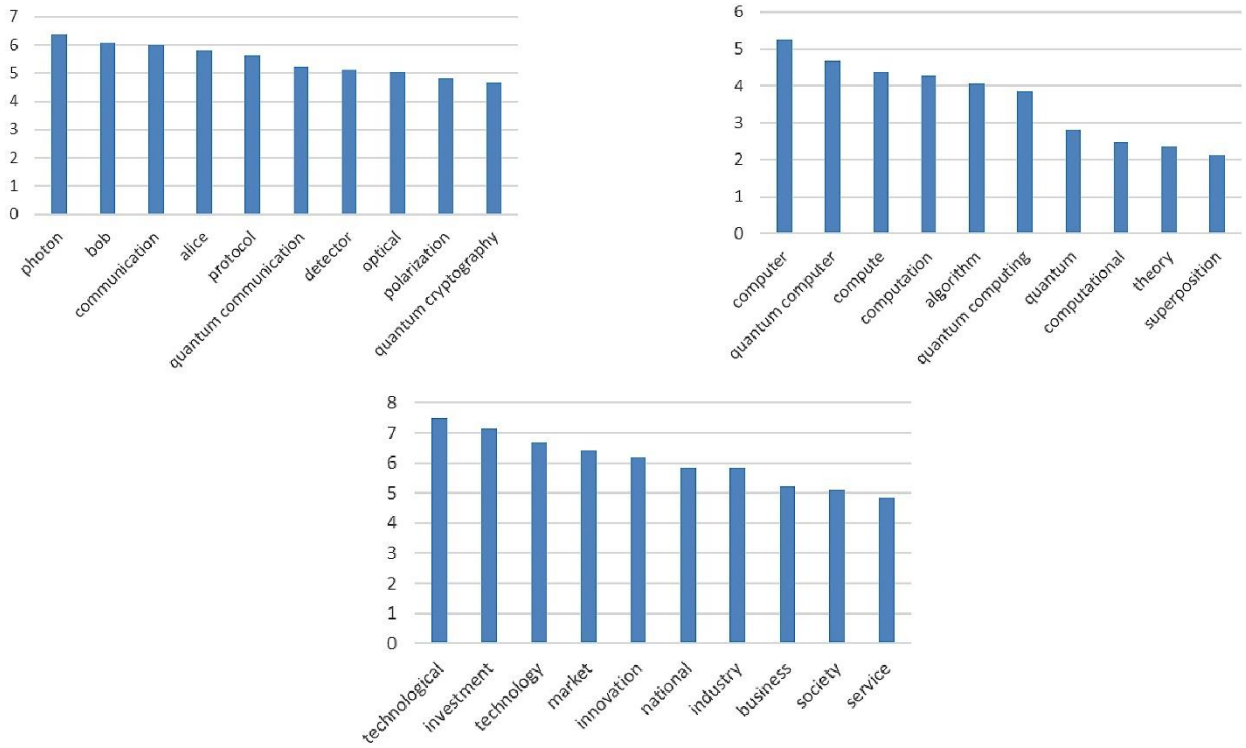


Fig. 3.10 *Systematic literature review of urban-related quantum technologies. Most significant (p-value less or equal to 0.05) variables in each cluster*

Note: top left—Cluster 1; top right—Cluster 2; down—Cluster 3

To conclude, according to the overall results of quantitative content analysis, three classes of scholarly records can be identified when it comes to quantum technologies in social sciences, with a particular emphasis on urban management, planning, design, and studies. The first two are centered on specific quantum implementations in urban-related contexts. Based on the taxonomy of Acin et al. (2018), quantum computing (Cluster 2) and quantum communication (Cluster 1) appear to be the only types of quantum technologies currently investigated by social scientists, including their prospective usage in quantum cities. Records in Cluster 3 primarily focus on more traditional managerial themes and topics, only loosely related to quantum technologies. Due to the low numerosity of Cluster 3, its peripheral position on the PCA factor map, and its overall irrelevance in light of the section's two research questions, only the first two clusters were qualitatively assessed.

3.3.5 Thematic analysis of scholarly records

In this sub-section of the chapter, the qualitative thematic analysis of the 80 retrieved scholarly records on quantum technologies within the context of urban-related social science is presented. The analysis was performed using qualitative data analysis software (MAXQDA), and the deductive coding approach was used (Fereday & Muir-Cochrane, 2006). In particular, the two higher-level code categories, *quantum communication*, and *quantum computing* were decided in advance and constituted the starting point for the successive development and grounded theory-like analysis of the lower-level codes system (Bryman, 2016). The main findings regarding the two categories of quantum technology potential usage in cities are presented in the form of a narrative review (Greenhalgh et al., 2016) in the two following sub-sections.

3.3.5.1 Quantum communication in quantum cities

Within the urban context, quantum communication deals with securely transmitting and exchanging quantum information between distant city network nodes connected via quantum channels. Accordingly, the communication between the channels occurs by exchanging qubits (Z. Liu et al., 2020; Sauge et al., 2007). A crucial technological aspect of quantum cities centers on implementing more complex networks and urban quantum communication protocols. An urban quantum network should be planned and projected, allowing for the extension to more complex situations with a higher of sources and nodes and across superior

distances (Z. Liu et al., 2020; Sauge et al., 2007).

The quantum states teleportation is a fascinating concept in quantum physics, constituting a promising application of quantum entanglement. In other words, quantum teleportation exhibits what Albert Einstein termed "spooky action at a distance […] for quantum entanglement" (Lele, 2021). Quantum teleportation's goal is to transmit a random quantum state to a distant location (e.g., between different nodes in distinct parts of a city or different cities) without sending the actual physical particles that carry the state. In Newtonian physics, this is an impossible achievement. Quantum physics, conversely, provides a viable solution (Aspelmeyer et al., 2005; Chehimi & Saad, 2021).

By the end of 2019, physicists were, for the first time, able to showcase quantum teleportation among two computer chips, passing the information between them not by electronic connections but through quantum entanglement (Lele, 2021). The effect of quantum teleportation in connecting different nodes of an urban system can be groundbreaking. This technology can also enrich extant smart-city-related technologies such as IoT, smart grids, and machine-to-machine communication, which, in turn, can also affect urban transportation systems and consumption patterns (Hamdoun & Sagheer, 2020).

Quantum internet (QI) is one of the likely outcomes of a well-developed quantum teleportation technology. QI can be described as a quantum techno-system in which sensors, computers, and networks exchange data in a substantially different way, with sensing, communication, and computing working together as a unit. Once the quantum internet becomes a viable reality, its speed could become so astonishing that "physically distant clocks could be synchronized about a thousand times more precisely than the best atomic clocks available today" (Lele, 2021). Such computational advantages can result in better control of complex city systems. For example, the transportation system can considerably improve efficiency if detailed on-line traffic and vehicular data collection, transmission, and analysis are made possible (Joseph et al., 2006).

Conversely, inter-city quantum networks might consist of distant network nodes composed of physical qubits that are quantumly entangled despite the significant physical separation. This physical distribution of entanglement is essential for instantiating a working quantum internet, employed for more efficient transportation management and quantumly enhanced IoT and blockchain (Lele, 2021). As a result, urban managers and planners should be open and ready to upgrade the existing communication platforms in cities to adopt the first viable quantum communication implementations.

One of the most crucial and vulnerable aspects of quantum communication for cities is security. The human will for secret communication is at least as old as writing, going back to the dawn of human civilization. Therefore, methods of secret communication were developed by many ancient societies (Aspelmeyer et al., 2005). For closely related reasons, information security in the urban environment is a crucial goal for most city managers and planners (Malluh et al., 2014).

Due to quantum-based Shor's algorithm implementations (Monz et al., 2016), many classical cryptosystems can be, in theory, broken by quantum computers. Accordingly, some conventional secret communication protocols are no longer secure, motivating researchers to develop different secure crypto-systems (Tsai et al., 2005). Indeed, when a quantum computer with powerful parallel computation capabilities is used for a quantum decrypt, only several minutes are sufficient to decrypt the file that otherwise may need years to be cracked by the most advanced conventional computer; hence, there is no meaningful ciphertext in a quantum computer world (Lele, 2021; Wei & Zhang, 2019). As loci of communication, cities are among the most vulnerable targets of attacks by quantum computers.

A secure communication protocol permits the sender (in cryptography, commonly referred to as "Alice") and the receiver (commonly referred to as "Bob") to exchange messages in a trustable and secure manner without the risk of being decrypted by a potential eavesdropper ("Eve"). Two requirements must be satisfied for the communication protocol to be considered secure. The secret messages must first be read out in their original form by the legitimate receiver after successful transmission. Moreover, even if an eavesdropper has complete control of the channel, the encrypted message should provide no information to her (Tsai et al., 2005).

Charles Bennett and Gilles Brassard introduced the concept of quantum cryptography in 1984 (Bennett & Brassard, 1985). They theorized an algorithm (known as BB86) in which data transmission depends on quantum particles—typically photons (Bennett & Brassard, 1985). Quantum cryptography mainly relies on Heisenberg's principle of uncertainty, stating that when a quantum state is measured, its disturbance causes imperfect information about the entire system. Consequently, eavesdropping on a quantum communication channel alarms its legal users. This feature represents the primary benefit of effective quantum cryptography (Aspelmeyer et al., 2005; Malluh et al., 2014).

A fundamental requirement for developing quantum communication networks in cities is the ability to "exploit and combine widely different technologies in a modular and reliable way"

(Carvacho et al., 2021). In other words, quantum communication brings about high-quality long-distance quantum channels, supporting the increasing complexity of city environments (Aspelmeyer et al., 2005; Chen et al., 2010; Lele, 2021; Resch et al., 2005). Consequently, urban quantum communication can be successfully used in shopping systems (Chou et al., 2014), 6G networks (Chehimi & Saad, 2021), local and online games (Klauck et al., 2007), IoT, blockchain (Al-Mohammed & Yaacoub, 2021), financial modeling, traffic optimization, weather forecasting, AI, solar capture, and medicine (Nema & Nene, 2020).

Today, one of the most promising quantum communication techniques is quantum key distribution (QKD). QKD enables two legitimate remote users (e.g., users in various parts of a city or users in different cities) to establish a shared secret key through the photons' transmission. The key is later used to encrypt/decrypt secret messages (Chou et al., 2014; Piacentini et al., 2015). As such, QKD can serve as a functional building block for highly secure city networks (Chou et al., 2014). For example, it provides a way for two different devices within the city to agree on a shared random sequence of (conventional) bits, with a very low probability that intrusive devices (known as eavesdroppers) will accomplish a successful inference of the values of those bits. The obtained sequences may then function as secret keys for encoding/decoding messages between the sender and receiver (Aspelmeyer et al., 2005).

While quantum cryptography implies using quantum phenomena as the basis of its security strategy, post-quantum cryptography (also known as quantum-proof, quantum-resistant, or quantum-safe cryptography) denotes the class of cryptographic algorithms (typically, public-key algorithms) that are protected against a potential attack by a quantum computer (Lele, 2021). Post-quantum cryptography is primarily concerned with getting ready for the era of quantum vulnerability by keeping the existing algorithms and standards updated in light of quantum city development. In an urban context, efficient post-quantum cryptography should resist quantum computer attacks against a city's communication systems while simultaneously providing features as diverse as variability, unforgeability, identifiability, and confidentiality (F. Zhang et al., 2020).

Even though the future of quantum cryptography is still uncertain, it is already attracting attention (and monetary resources) from different urban entities. On the experimental side, however, much progress is still expected (Aspelmeyer et al., 2005).

3.3.5.2 Quantum computing in quantum cities

Quantum computers are the next-generation technology that may significantly change our cities' industrial, academic, economic, and social landscapes. Indeed, scholars argue that quantum computers will play a crucial role in smart city-related technologies such as blockchain, IoT, Big Data, ICT, and AI (Inglesant et al., 2021; Meng, 2020; Ten Holter et al., 2023; Uhlig et al., 2019).

The notion of quantum computing was first popularized by Richard Feynman nearly 40 years ago (Salehi et al., 2022). Nowadays, quantum computing is an innovative, ground-breaking field of inquiry at the crossroads between computer science, mathematics, and quantum physics (Elhaddad & Mohammed, 2016; Trabesinger, 2017). Quantum computing development relies on the principles of quantum theory and its fundamental phenomena (i.e., entanglement and superposition) for advanced computational processes. In other words, quantum computing represents the extension of conventional computing to elaborate quantum information through quantum means (Taha, 2016).

In conventional computing, information is stored in bits—either one or zero—one bit at a time (Amiri, 2003). As such, it entirely relies on the rules of Boolean algebra. Conversely, quantum computing is based on quantum bits (qubits). Contrary to traditional bits, a single qubit may represent a one, zero, and a mixed state in which it is both zero and one, called quantum superposition (Sotelo, 2019, 2021); in other words, a quantum computer works in a probabilistic rather than deterministic manner (Cuffaro, 2018; Elhaddad & Mohammed, 2016).

According to DeBenedictis (2020), quantum computation can potentially encode one billion operations at a time. Consequently, the main advantage of quantum computers is their ability to solve computationally complex problems, which nowadays require excessive temporal, technical, and economic resources (Mosteanu & Faccia, 2021). Moreover, memory in quantum computers is exponentially larger, and the simultaneous processing of a substantial quantity of inputs is possible. Thus, quantum computers are superior to conventional computers in several ways (Raisinghani, 2001). However, this does not mean that quantum architectures will entirely replace von Neumann architectures; instead, quantum computers can potentially assist traditional ones in specific tasks (Yetis & Karakoes, 2021). This, indeed, is in line with the theorized quantum urban metaphor and the related duality principle: the metaphor itself is not devised as a replacement but rather as a complement and something that subsumes traditional Newtonian city conceptualizations.

One of the fields in which quantum computing may substantially assist conventional computers is artificial intelligence. The relationship, though, is dual. The main contributions of AI to quantum computing include the automation of computing systems and the reduction of human intervention (Bhatia et al., 2020). Furthermore, quantum algorithms and artificial intelligence detain the reciprocal reinforcement potential: quantum algorithms can improve unsupervised machine learning, while the latter can be used for quantum state tomography of deeply entangled states with over a hundred quantum bits (Palmieri et al., 2020; Torlai et al., 2018).

The speeding-up of current machine learning methods through quantum computing has significant potential for solving complex urban problems (Casati, 2020; Jhanwar & Nene, 2021). Some cities are already pursuing strategies for successfully exploiting quantum computing technologies, announcing massive investments to ensure global competitiveness. Conversely, as of 2020, more than one hundred firms were already focused on quantum computing development (Casati, 2020). However, some of the scientific community continues to be skeptical of the possibilities of quantum computing. Many feel that quantum computing still has a long way to go before being widely embraced (Gutierrez-Salcedo et al., 2018; Paraoanu, 2011). A distinction should always be made between the theoretical and practical possibility of building a quantum device. On the practical side, efforts to advance quantum computing have been slowed down by multiple challenges, such as enabling precise individual control of qubits, quantum algorithm implementation, and environmental noise (Elhaddad & Mohammed, 2016)(Elhaddad & Mohammed, 2016).

According to the analyzed scholarly records, some of the most important potential usages of quantum computing include smart factory optimization, 5G and 6G communications, power grid management, drug discovery (Gutierrez-Salcedo et al., 2018), cryptography, integer factorization, database search improvement (Kumar Sharma & Ghunawat, 2019; Kumari et al., 2021), blockchain, banking (Aderman, 2019; Sazonova & Krendelev, 2018), finance and business (Chambers-Jones, 2021), economics (Alaminos et al., 2022), simulation and modeling (Inglesant et al., 2021; Weder et al., 2020), weather forecasting, market prediction (Shubham et al., 2019), disease prediction (Swarna et al., 2021), strategic management (Casati, 2020), AI, big data (Singh & Singh, 2016), education (Gioda et al., 2021; Uhlig et al., 2019), law (Atik & Jeutner, 2021; Majot & Yampolskiy, 2015), aircraft's production (Muller & Vuik, 2017), military (Lele, 2021), IoT (Bhatia et al., 2020), and art (Heaney, 2019).

At least three different views of quantum computing are identifiable in the analyzed literature.

According to the first, we are simply on the verge of an era of super-powerful computing. Scholars adhering to the second vision seek to evaluate the short-term practical implications of QC. According to the third vision, the topic of quantum supremacy is more relevant than the potential benefits of developing proper quantum computing. The quantum supremacy issue denotes the increasing potential for technical problems within the quantum domain (Inglesant et al., 2021). According to scholars, potentially destructive outcomes of quantum computing cannot be easily verified and controlled, especially in the initial development stages. Nevertheless, it may be more challenging to change the developmental trajectory later on once the outcomes of quantum computing are more evident (Sotelo, 2021).

On the negative side, one of the most relevant risks of quantum computing development is the danger of "breaking the internet," making vulnerable the dominant forms of data encryption, for example, substantially speeding up Shor's algorithm to break public-key cryptography schemes (Inglesant et al., 2021; Zhang et al., 2020).

Cryptographic vulnerabilities can affect security in cities' financial and other confidential entities (Covers & Doeland, 2020). Conversely, cryptography is one of the fields in which the use of quantum computing is much anticipated (Mogos, 2009; Shubham et al., 2019). For the emergence of large-scale quantum computers to occur, researchers must first render cryptographic infrastructures protected against quantum attacks (Mitchell, 2020; Mosca, 2018). The adverse effects of quantum computing on security systems in cities increase the need for decisive regulations that promote the responsible use of quantum computers to "help alleviate some of the security issues posed by outdated cryptographic systems in a post-quantum environment" (Majot & Yampolskiy, 2015).

Finally, an additional negative consequence of quantum computers' usage in urban settings is the likely increase in inequality caused by an absence of knowledge or financial resources to acquire the new technology (de Wolf, 2017). Therefore, openness and accessibility are the best ways to guarantee that quantum computers' beneficial influence surpasses their negative impact: relevant scientific knowledge should be made publicly available and actively promoted, and quantum computers' unprecedented computational capacity should be made available via the cloud (de Wolf, 2017). Moreover, to reinforce the positive impacts of quantum computing in cities, the crucial step is to ensure that urbanities start thinking in new ways compatible with quantum theory and related technologies and metaphors. It does not mean people should start to think in a manner isomorphic to a quantum computer, but rather that they need to understand what a quantum computer can and cannot do and make sense of

the purpose of its outputs. It can be achieved through education and the gamification of education around the novel quantum paradigm (DeBenedictis, 2020; Gordon & Gordon, 2012; Mykhailova & Svore, 2020; Uhlig et al., 2019).

If quantum computing reaches the stage of widespread practical implementation, a series of radical social challenges will inadvertently follow (Aderman, 2019). For this reason alone, urban decision-makers should be ready to strategize quantum computing introduction as a lever for growth and the reduction of barriers to adopting related novel technologies (Bhasin & Tripathi, 2023). Presently, the race is on to build the first effective quantum computer as it has been initially envisioned by scholars (Lele, 2021). For now, only simple quantum computers have been built, and most agree that an advanced, fully-performant quantum computer is still in its nascent phases of development (Prince, 2014). Indeed, far from undermining the models of complexity theory, quantum computing currently serves to help us conceptualize complexity as a potential rather than a threat (Cuffaro, 2018).

3.4 Study 3: Investigating the potential relationship between urban quantum technologies and conventional smart city technologies

3.4.1 On prediction and semantics: methodological considerations

In this section, the potential for the relationship between conventional smart city technologies and urban-related quantum technologies is assessed. The phrase “the potential for” is central here. Indeed, the existing relationship between the two would be impossible to assess, as 1) full-fledged smart cities are still not that many, and their classifications are vague (Yigitcanlar et al., 2019), and 2) quantum technologies are still largely theoretical possibilities rather than working prototypes ready to be commercialized (Cuffaro, 2018). Hence, given the state of technological development, only the potentiality of the relationships can be adequately assessed rather than their actuality. This is achieved here by looking at the semantic (and the underlying thematic) relatedness of literature on quantum technologies in social sciences (hence, considering the eighty papers identified in the previous section) with heterogeneous facets of conventional smart city technologies identified through means of a scoping review.

The method might seem far from the orthodox, but the recent increase in the popularity and the capabilities of large language models (LLMs) is a testament to the usefulness and value of natural language analysis models in academia and education (Kasneci et al., 2023; Y. Liu et al., 2023). The research on generating predictions relying on semantics alone is, however,

much older than the recent popularity of LLMs and goes all the way back to the conceptualizations and validation of latent semantic analysis as a class of methods "for extracting and representing the contextual-usage meaning of words by statistical computations applied to a large corpus of text" (Landauer et al., 1998). In this regard, Toubia et al. (2021), by representing texts as a sequence of points in latent high-dimensional space, showed that the semantics and their structural organizations within texts predict the success of those texts (e.g., novels, TV shows, and academic papers). In a similar way, Arnulf et al. (2014) showed that it is possible to predict the survey responses in social research with great accuracy by merely considering the semantic structure of survey items.

This section's analyses are in line with the outlined research school of thought; hence, the potential for the relationship between conventional smart city technologies and quantum technologies is assessed here by analyzing dominant semantic pathways and their connections within the high-dimension semantic space constructed bottom-up by looking at the frequencies of the most common related keywords in the literature on quantum technologies in social sciences.

The keywords denoting quantum technologies, chiefly quantum communication and quantum computing, were derived as a part of the qualitative analysis of the previous section. Concerning the other group of keywords, in this section, a taxonomy of conventional smart city solutions is first derived based on the scoping review and the semantic analysis of 567 abstracts of articles on the technological aspects of (conventional) smart cities. Then, the taxonomy serves as a basis for the derivation of the related conventional smart city technology keywords. Consequently, the semantic relationships between eighty articles on quantum technologies according to the frequency of selected keywords are investigated. Although strictly exploratory, the study of semantic relationships can be indicative of current and prospective academic interests within the research field (Arnulf, 2020; Arnulf et al., 2014). Finally, a methodological triangulation of quantitative results is performed through a qualitative thematic analysis of potential uses of quantum technologies within the identified domains of conventional smart city implementations.

3.4.2 Classifying smart city technologies

Before analyzing the contributions of the two classes of quantum technologies (quantum communication and quantum computing) to conventional smart city technologies, i.e., those

based on Von Neumann computer architecture, a less abstract definition of a smart city needed to be derived. To recapitulate, in Chapter 2, a conceptual definition of a smart city was provided based on the analysis and synthesis of the existing definitions. In particular, a smart city was defined as *an organic urban system that integrates data, resources, policies, and people through technological means to achieve aware, sustainable development.* While the conceptual definition remains valid, for the purpose of semantic exploration of smart city-related keywords, an empirical particularization of the said definition is still necessary.

One way to define a smart city in more practical terms is by elaborating a thorough taxonomy of technologies used therein (Javed et al., 2022). Contrary to relying on the existing classification, as was done in the case of quantum technologies (Acin et al., 2018), the taxonomy of smart city solutions was derived based on the automated content analysis of the abstracts of academic literature on the topic.

A scoping review methodology was used to identify the related academic documents. According to (Munn et al., 2018), a scoping review is an appropriate tool for determining the coverage of a body of literature on a topic. It also highlights the emerging evidence when specific research questions remain unclear (Munn et al., 2018). It is critical to emphasize that while relying on the principles and methods of a systematic literature review, the objectives and goals of the scoping reviews are fundamentally different (Mak & Thomas, 2022) and are more aligned with the goals of knowledge synthesis and gap-spotting.

The keywords “smart city” and “technology” (linked by the AND operator) were used on Scopus to search and retrieve all academic records with the two keywords in their titles. Moreover, no restrictions were imposed on the academic field or type of publication. As a result, 567 smart city-related academic articles were identified (as of January 9, 2022). The articles were then downloaded, and 576 abstracts were processed using qualitative data analysis software (MAXQDA, release 22.0.1). The English language lemmatization was applied to control for different spellings and inflected forms (for example, *city* and *cities* were counted as one token), and then the absolute frequency of all semantically distinct words and word combinations in the abstracts was calculated. Finally, the frequency table was manually assessed, and the most frequent words and word combinations related to conventional smart city technologies were selected. In total, forty smart city-related keywords were identified (Figure 3.11).

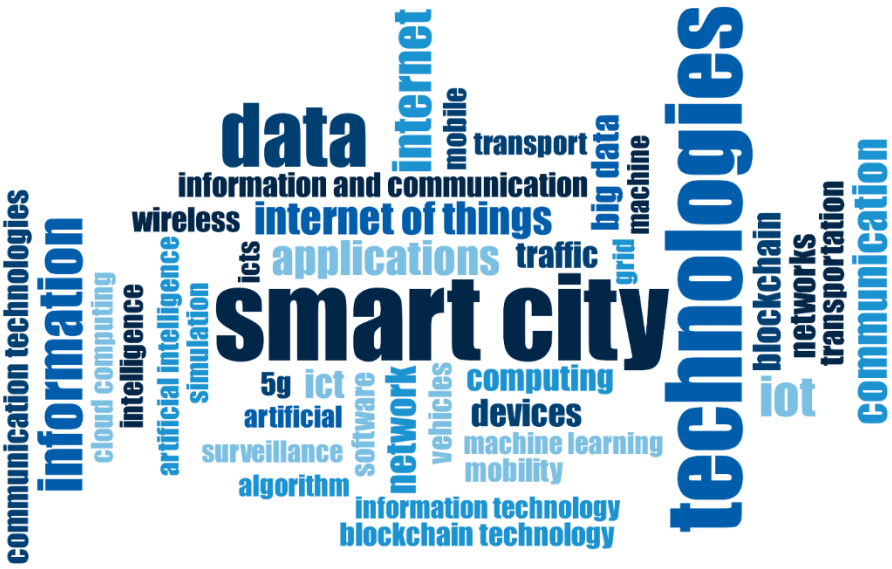


Fig. 3.11 *Most frequent words and word combinations related to smart city technologies*

Next, with the help of MAXQDA, the authors' usage of those words and word combinations in the respective abstracts was individually assessed. An inductive coding (Chandra & Shang, 2019) approach was used to derive the taxonomic representation of the conventional smart city technology types. As a result, seven major categories of conventional smart city technologies were identified: *artificial intelligence* (*AI*), *the Internet of Things* (*IoT*), the more general category *of information and communication technologies* (*ICTs*), *big data*, *blockchain*, *cloud computing*, and *smart transportation technologies*.

3.4.3 Quantum technologies for smart cities: an exploration of semantic relatedness

To study the potential connections between the two types of urban quantum technologies (quantum communication and quantum computing) and the seven common types of smart city solutions (as determined in the previous sub-section), the eighty papers on quantum technologies retrieved in the process of systematic literature review of Study 2 were analyzed. Accordingly, the semantic relatedness of the quantum technology social science literature was analyzed according to the three categories of keywords (quantum communication keywords, quantum computing keywords, and smart city keywords). When it comes to the quantum technology-related keywords, those were derived in the process of qualitative thematic analysis of Study 2 as lower-level coding categories derived in the iterative inductive manner through an open coding approach akin to a grounded theory methodology (Chandra & Shang, 2019) by fully reading coding and re-coding the eighty identified articles.

For the purpose of this chapter, the additional automated qualitative assessment was again performed in MAXQDA (release 22.0.1). Through the available automatic coding tools provided by the software, all sentences containing the seven categories of smart city technologies (*artificial intelligence* (*AI*), *Internet of Things* (*IoT*), *information and communication technologies* (*ICTs*), *big data*, *blockchain*, *cloud computing*, *smart transportation technologies*), twelve quantum communication-related keywords, and nine quantum computing-related keywords were counted and automatically coded.

Figure 3.12 shows the hierarchical code structure resulting from the automatic coding. The numbers denote the absolute frequencies of codes across eighty articles. In all cases, the lemmatized variations of keywords were considered (e.g., "ai" and "artificial intelligence," "computer" and "computers" were treated and counted as identical semantic tokens).

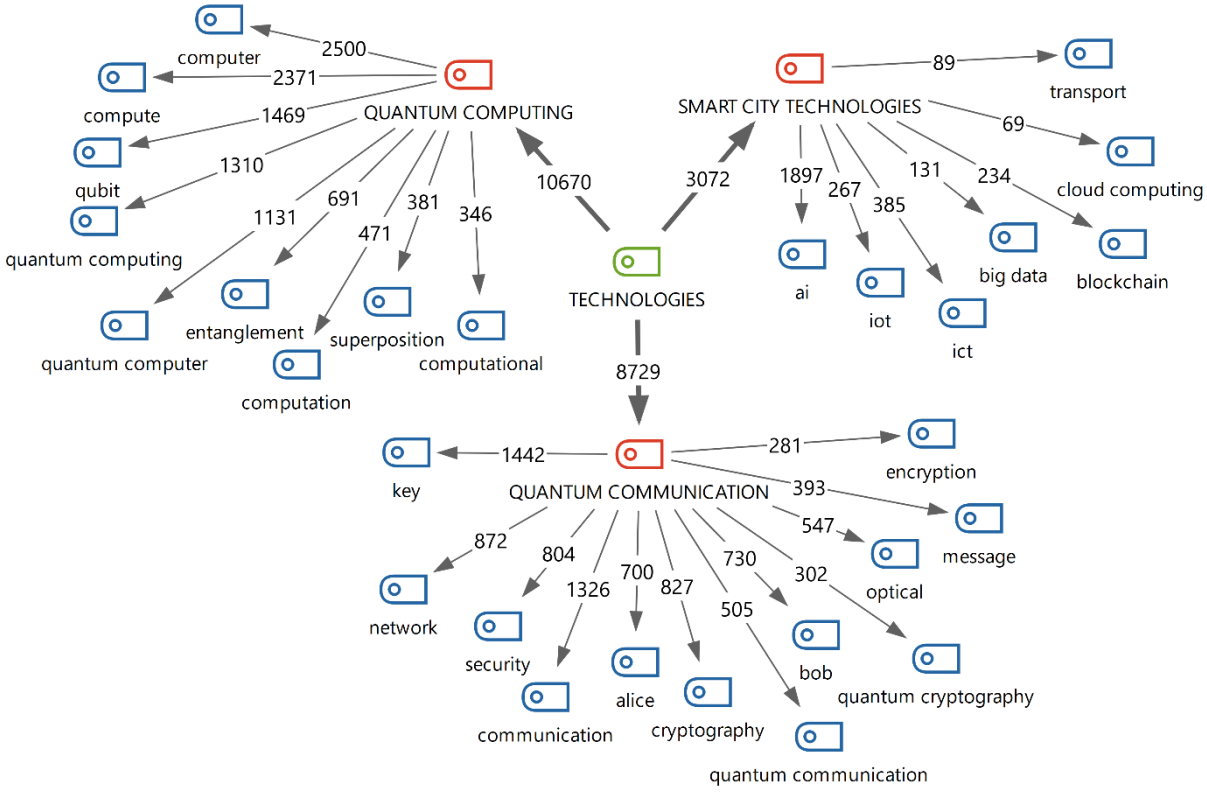


Fig. 3.12 *Conventional and quantum urban technologies. Qualitative codes' structure*

The absolute frequencies of twenty-eight lower-level codes were then transformed into relative frequencies to account for the different lengths of the articles. The following formula was applied for the transformation:

$$rel.frequency_k^i = \frac{abs.frequency_k^i}{\sum_{j=1}^{28} abs.frequency_j^i}$$

In the formula, *i* denotes the unit of analysis (one of eighty retrieved articles); *k* and *j* denote a keyword (one of twenty-eight lower-level categories in Figure 3.12).

In line with latent semantic analysis (LSA) methodology, the resulting keywords were then treated as variables, and the single documents (articles) as independent observations (Evangelopoulos, 2013; Landauer et al., 1998). The dataset was then imported into RStudio (version 1.4.1717), and a dimensional reduction was performed (principal component analysis) to build a related semantic space. Twenty-eight lower-level codes (Figure 3.12) yielded an equal number of uncorrelated dimensions, suggesting a high degree of heterogeneity and semantic diversity within the retrieved articles. In line with the suggestions of LSA scholars (Shermis & Burstein, 2003), the number of resulting dimensions is adequate considering the smaller textual corpus (only 80 documents).

The first two dimensions stood out, accounting for approximately 31% of the total inertia, which, in turn, indicated the presence of certain thematic commonalities and clusters of shared meanings within the analyzed literature. As the remaining principal components did not noticeably contribute to the overall variability, only the first two PCA dimensions were analyzed in-depth. Figure 3.13 shows the contribution of active variables to the creation of axes. The cos^2 indicator measures the quality of the representation of active variables on the axes.

As shown in Figure 3.13, according to the disposition of keywords on the factor map, the horizontal dimension distinguishes between two classes of articles—on quantum computing to the left (mostly QC categories) and quantum communication to the right (mostly QCM categories). Additionally, the vertical axis captures the relevance of seven types of conventional smart city technologies (SCT categories) in those articles. In particular, quantum communication and quantum computing-related articles in the northern part of the plane are more likely to mention conventional smart city technologies than articles in the southern part of the plane. Thus, hypothetically, four clusters of urban-related articles on quantum technologies can be distinguished. These are articles on quantum computing or quantum communication with an emphasis on conventional smart city technologies and articles on quantum computing or quantum communication without an emphasis on conventional smart city technologies.

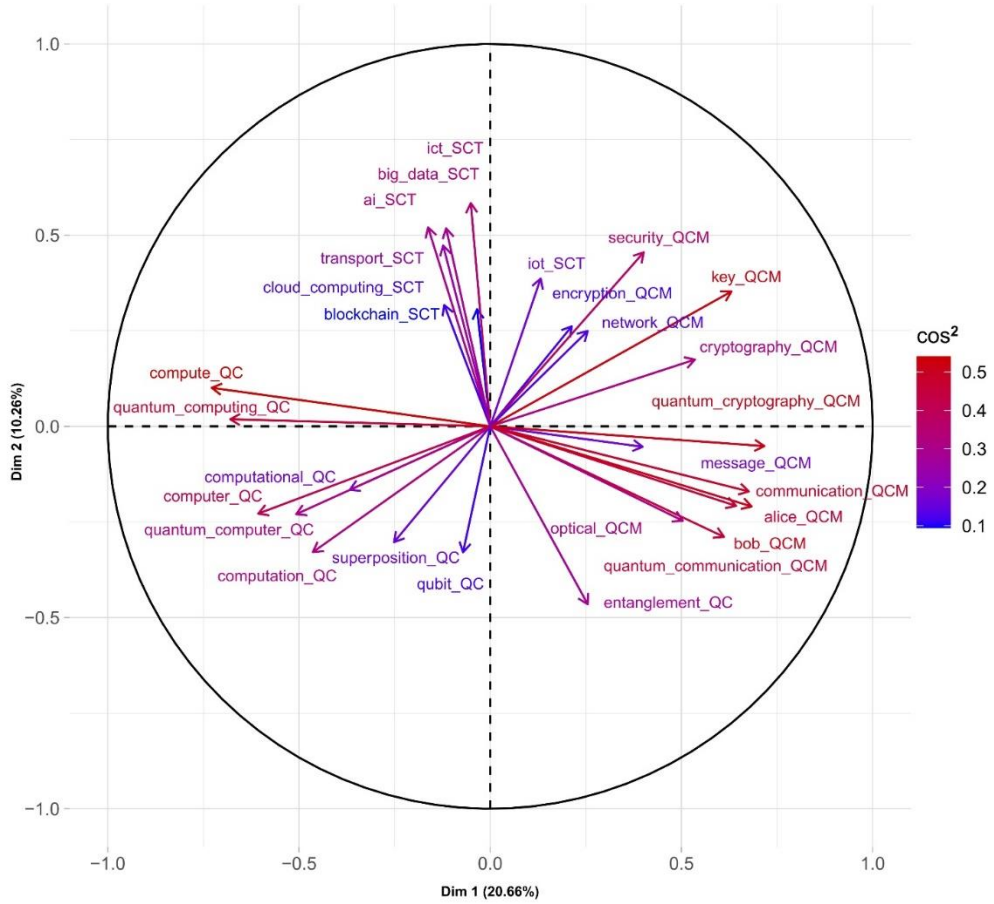


Fig. 3.13 *PCA. Relationships between quantum communication (QCM), quantum computing (QC), and conventional smart city technologies' (SCT) keywords*

As for relationships between quantum communication, quantum computing, and conventional smart city technologies, little can be inferred from the results of the principal component analysis. Indeed, as seen in Figure 3.13, the quantum communication, quantum computing, and conventional smart city technologies variables are mainly orthogonal to one another. However, a careful observation reveals that articles on quantum communication are slightly more likely to mention the topic of IoT. At the same time, the remaining conventional smart city technologies-related keywords are more likely to appear in articles on quantum computing (according to their position on the horizontal dimension).

To understand the relationships better, an agglomerative hierarchical clustering was performed based on the resulting PCA dimensions. The Euclidean distance was calculated to measure the similarity between pairs of records. Ward's method was used as a measure of closeness between the groups to ensure the partitioning with small within-class variability and high between-class variability.

Figure 3.14 shows the hierarchical tree projected on the PCA factor map. Because inertia gains from considering five clusters or more were relatively small, the *Factoshiny* package considered the partitioning of articles into four clusters as optimal. In particular, at first, a hierarchical tree was built. Then, the sum of the within-cluster inertia was calculated for each of the partitions. The suggested partition was the one with the higher relative loss of inertia [i.e., (i(clusters n+1)/i(cluster n))]. As a result, additional inertia gains from considering five clusters or clusters were deemed inappropriate considering the relatively small variability conservation gains.

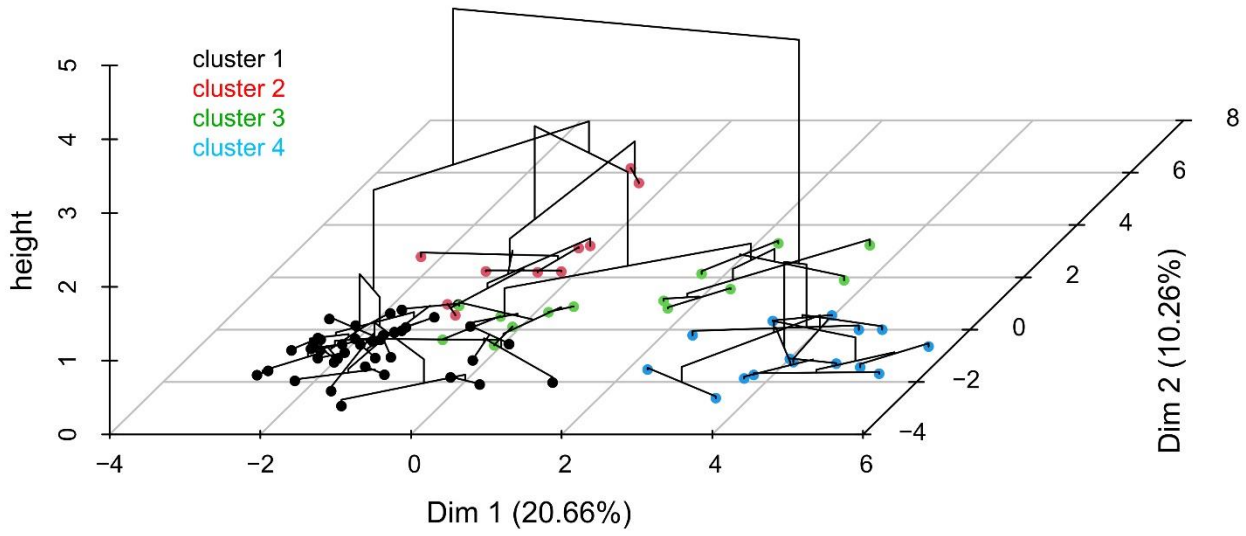


Fig. 3.14 *Quantum technologies for smart cities. Cluster analysis. The hierarchical tree projected on the PCA factor map*

Figure 3.15 shows all the most significant semantic categories that (positively and significantly, p-value < 0.05) contributed to the definition of the four clusters. The analysis of the semantic contributions of variables to the composition of related clusters partially confirmed the interpretation of LSA results. In particular, Clusters 1 and 4 reflect the categorization of articles according to their relatedness to the quantum computing (all contributing variables are QC variables) or quantum communication (QCM variables dominate) categories. One exception is the presence of *entanglement* quantum computing-related keywords among the quantum communication-related keywords in Cluster 4.

Conversely, Cluster 2 contains articles that primarily deal with conventional smart city technologies but also mention quantum technologies (all three classes of variables are present, but conventional smart city technologies-related variables dominate). In particular, network

and security topics (keywords: *network*, *security*) of the quantum communication domain and the general preoccupations with quantum computation (*compute* keyword) of the quantum computing domains are the closest topics when it comes to their discussion in relation to conventional smart city technologies. Regarding all the variables contributing to the definition of Cluster 2, AI appears to be the most discussed topic in the literature pertaining to said cluster. Other conventional smart city technologies often mentioned in quantum technology literature include (in order of importance) ICT, big data, cloud computing, blockchain, and smart transportation.

Conversely, Cluster 3 appears more balanced in terms of its composition, emphasizing both quantum communication and quantum computing topics. Moreover, conventional smart city technologies are also mentioned, albeit only to a limited extent (only the *blockchain* variable), indicating the relevance of both types of quantum technologies when it comes to their integration with conventional blockchain technologies.

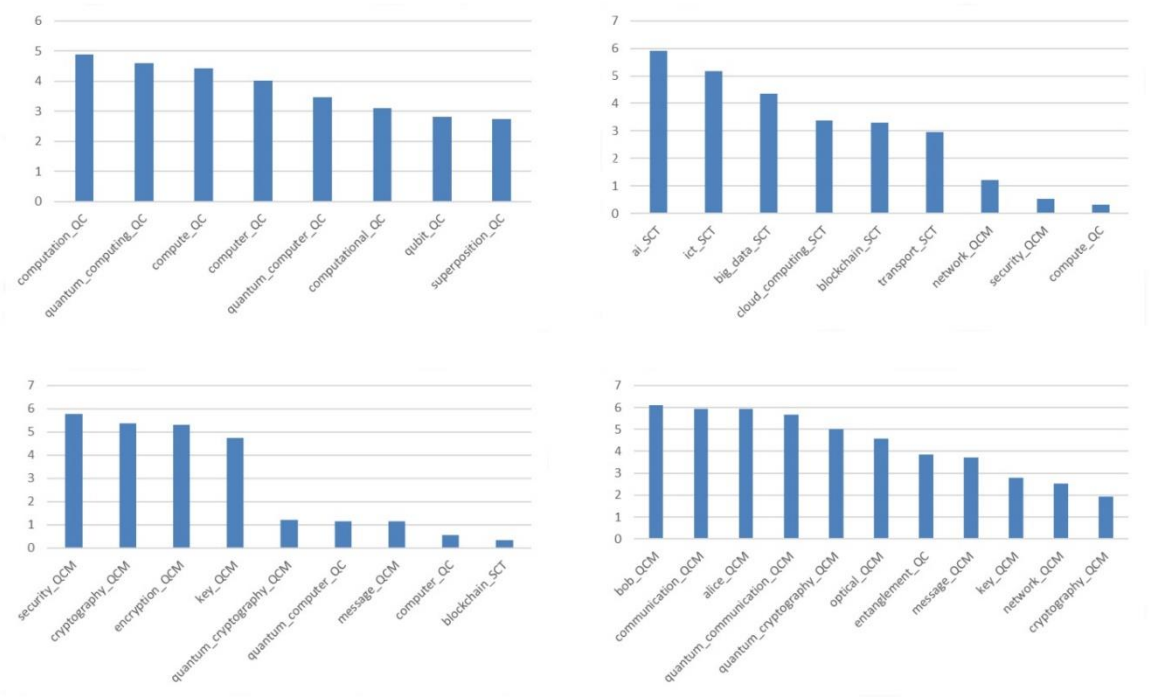


Fig. 3.15 *Quantum technologies for smart cities Most significant (p-value < 0.05) positive contributions to each cluster*

Note: top left—Cluster 1; top right—Cluster 2; down-left—Cluster 3; down-right—Cluster 4

Overall, only Cluster 2 and Cluster 3 appear to be relevant when it comes to the topic of the

integration of the two types of quantum technologies and seven types of conventional smart city technologies. While not as numerous as the other two clusters (see Figure 3.14), their emergence does suggest that the potential of the integration is present, and the said technological integration is likely to emerge in the form of quantum cities, intended—in practical terms—as a subset of smart cities in which conventional smart city solutions are integrated and enhanced by both quantum computing and quantum communication.

3.4.4 The relationship between quantum technologies and conventional smart city technologies: a qualitative thematic analysis

The findings of the quantitative analyses are integrated here with a qualitative thematic analysis of the scholarly documents contained in Cluster 2 and Cluster 3. As seen in the previous section, these are the two clusters of quantum technology-centered papers for which the topic of conventional smart city technology is also semantically relevant. However, to understand the ways in which the two categories of quantum technologies can contribute to conventional smart city technologies, a more in-depth qualitative assessment was deemed necessary. Hence, by means of deductive coding (McKibben et al., 2020), in line with the defined categories (Figure 3.12), a qualitative thematic analysis was performed in the qualitative data analysis software (MAXQDA).

Similarly to the previous section's qualitative exploration, the results of the analysis are presented here in the form of a narrative review (Bassani et al., 2023; Greenhalgh et al., 2016). In particular, each identified category of conventional smart city technologies is described in related sub-sections in terms of their potential synergies with both types of quantum technologies (quantum computing and quantum communication). Given the otological difficulties in separating the big data and cloud computing-related themes and topics on mere qualitative bases, both categories are summarized in a single sub-section. The remaining five conventional smart city technologies are addressed individually in the dedicated sub-sections.

3.4.4.1 Blockchain and quantum technologies

Due to post-quantum vulnerability, future smart cities face substantial security and integrity challenges. As a consequence, communication between various infrastructural components of a city requires more robust security measures. In this regard, blockchain technology can be a

means to manage different smart city components more securely and efficiently (Bagloee et al., 2021).

In a smart city, data can be safely exchanged via blockchain technology, ensuring network security and privacy for services such as the smart grid, transportation, and healthcare. Additionally, blockchain can promote transparency, freedom, democracy, decentralization, privacy, and security (Kumari et al., 2021; Vivekanadam, 2020; Xie et al., 2019). However, conventional blockchain technologies face critical limitations. Today, digital signatures based on asymmetric cryptographic mechanisms are commonly used to validate transaction authenticity in blockchain systems (Vivekanadam, 2020; Xie et al., 2019). On the other hand, quantum computing attacks pose a threat to modern-day cryptography algorithms. This constitutes a significant barrier to the novel secure blockchain-based smart city technologies (Kumari et al., 2021). The threat of post-quantum vulnerability calls for greater integration of blockchain and quantum technologies (Kumari et al., 2021).

According to the results of agglomerative hierarchical clustering, the topic of blockchain relates to both quantum computing and quantum communication. However, according to the qualitative assessment of the documents, its connection to the former is stronger. Indeed, quantum computing could be fundamental for the next generation of blockchain technology since it can provide significantly faster computations. For example, traditional protocols cannot address blockchain mining efficiently. Therefore, each block on a blockchain has a finite transaction capacity that must be extended (Kumari et al., 2021). Conversely, novel quantum techniques can safeguard a blockchain against quantum computing attacks while ensuring more efficient mining to secure and verify blockchain transactions (Chen et al., 2010; Moorman & Stricklen, 2020; Vivekanadam, 2020; Zhu et al., 2019).

To sum up, the synergy between blockchain and post-quantum cryptography can ensure the preservation of privacy and security in digitally vulnerable smart cities while, at the same time, offering faster computation and assisting decision-makers by providing authentic and valid information for more informed decisions (Abd El-Latif et al., 2018; Allam & Dhunny, 2019; Azzaoui & Park, 2020; Chiang et al., 2020; Guo et al., 2021; Gupta et al., 2021; Kumari et al., 2021; McKee et al., 2017; Toapanta et al., 2020; Xie et al., 2019; Zhu et al., 2019).

3.4.4.2 Internet of Things and quantum technologies

The IoT can increase the connectivity of various smart city components (i.e., water meters,

environmental sensors, lighting rods, smart energy networks, smart homes, and vehicles) (Ghorpade et al., 2021; Ghosh et al., 2019). IoT solutions can also be applied in a variety of smaller-scale settings: industry can use IoT devices to increase efficiency; agriculture can use IoT devices to reduce pesticide use while increasing crop yield; healthcare can use IoT devices to assist doctors and nurses in responding more quickly and efficiently to patients; IoT devices can provide key insights on how to develop sustainable solutions for waste management (Garcia-Morchon et al., 2015; Ghorpade et al., 2021; Ghosh et al., 2019; Imran et al., 2020).

The connected devices gather real-time information and communicate it to the cloud to simultaneously store and analyze different data streams. These processes may involve privacy-related and security-sensitive information (Garcia-Morchon et al., 2015). Accordingly, protecting the entire network from malicious events is one of the salient issues associated with successful IoT implementation. Thus, well-integrated security features are necessary for providing optimal IoT functionality (Garcia-Morchon et al., 2015; Ghosh et al., 2019; Routray et al., 2017).

Post-quantum cryptography and, in particular, lattice-based cryptographic algorithms have been proposed as viable approaches to post-quantum security (Garcia-Morchon et al., 2015; Imran et al., 2020; Kumari et al., 2021; Nieto-Chaupis, 2018; Ning & Liu, 2015; Routray et al., 2017; Zhu et al., 2019). Quantum communication technology can ensure a safer and more efficient IoT by increasing the efficiency of sensor networks, improving communication security, and ensuring greater data processing capacity. For example, Quantum Photonic Computer can provide a set of countermeasures to IoT 5G network abuse (Kaatuzian, 2020). Due to its environmentally friendly characteristics, Quantum Photonic Computer may also serve as a viable basis for future 6G networks in smart cities (Kaatuzian, 2020). Additionally, an IoT chip with a quantum number generator can produce non-deterministic real random numbers to increase IoT networks' protection (Kaatuzian, 2020; Ning & Liu, 2015; Ramachandran, 2018).

3.4.4.3 ICT and quantum technologies

When it comes to ICT infrastructure optimization, a city can only be considered partially smart with 5G. Alternatively, 6G constitutes a comprehensive, integrated approach to creating a genuinely "smart" city (Kaatuzian, 2020). Moreover, enhancing urban network

infrastructure combined with cloud and edge computing can enable the further integration of novel services such as the Internet of Things, augmented and virtual reality, multimedia interactive gaming, and unmanned mobility (Manzalini, 2020; Tariq et al., 2020).

Quantum communication can positively contribute to the two key characteristics of 6G: higher data rates and increased security measures (Tariq et al., 2020). As in the case of the IoT, post-quantum cryptography is relevant for 5G networks, 6G networks, and beyond due to the non-negligible possibility of a quantum attack. Quantum encryption and the related encryption algorithms can ensure the secure transfer of information within and between ICT networks (Kaatuzian, 2020; Tariq et al., 2020).

To conclude, integrating quantum communication technologies with conventional ICTs can improve the connectivity between users and devices in a smart city. Moreover, communication costs can be reduced as new communication technologies are implemented, and innovative encryption technologies, such as quantum encryption, can ensure the secure transmission of information (Liang et al., 2018; Toapanta et al., 2020).

3.4.4.4 Big data, cloud computing, and quantum technologies

In smart cities, big data services provided by public and private cloud computing platforms can offer real-time insights into large-scale processes in different urban subsystems (Allam & Dhunny, 2019). Smart city constituents such as the government, residents, businesses, health services, buildings, transportation, and traffic control centers generate a substantial amount of data (Lim et al., 2018; Moustafa, 2020). Part of these data may be open-source and free to use (Criado & Gil-Garcia, 2019; Iavich et al., 2021; Toapanta et al., 2020). In this case, however, maximum security is needed to maintain the system's integrity. As a consequence, smart cities may require quantum-assisted security and protection to safeguard the whole cloud from quantum vulnerability (Abd El-Latif et al., 2018; Chiang et al., 2020; Jabbar et al., 2020; Qian et al., 2021).

As the volumes of data grow, smart cities need to deploy advanced analytical software and hardware solutions to extract value from the data. Accordingly, quantum computing can help overcome data collection, analysis, error detection, and resource management limits through quantum-based algorithms and hardware infrastructures for more efficient data storage and processing (AlSuwaidan, 2021; Balicki, 2022; Balicki et al., 2019; Juma, 2020).

3.4.4.5 Artificial intelligence and quantum technologies

The successful integration of artificial intelligence is essential to several smart city-enabling technologies (Luckey et al., 2021; Mukherjee & Mandal, 2020; Zubov, 2015). According to the agglomerative hierarchical clustering, artificial intelligence is the most discussed conventional smart city technology in relation to the topic of quantum computing and quantum communication.

Concerning quantum computing, complex, intelligent systems relying on the integration of data mining, big data analysis, cloud computing, and post-quantum network security techniques can be implemented with greater ease thanks to advanced quantum computing systems (Balicki et al., 2019; Lindgren, 2020; Mukherjee & Mandal, 2020). Moreover, a framework that comprises all smart city technologies and services can be based on quantum deep learning techniques (Mukherjee & Mandal, 2020).

Conversely, quantum communication can be used in conjunction with artificial intelligence to enable services such as ultra-large-scale networks for connected AI agents. Machine learning can also enhance quantum protocols such as entanglement purification, quantum teleportation, and quantum repeaters (Wallnofer et al., 2020). This is particularly relevant in developing long-distance communication schemes since it allows using machine learning in designing and implementing future quantum networks (Baonan et al., 2019; Manzalini, 2020; Wallnofer et al., 2020).

3.4.4.6 Smart transportation and quantum technologies

Integrated quantum technologies can increase the scheduling efficiency of urban traffic flow. Indeed, a quantum network model can predict and simulate the passage times of vehicles queuing at intersections (Otto, 2013; Santos, 2021). Quantum communication between vehicles can enhance data transmission rates (Santos, 2021). Additionally, incorporating artificial intelligence and the Internet of Things into vehicles can improve the communication system’s efficiency. Likewise, post-quantum cryptography can be critical in developing more secure automated smart city transportation systems (Lv et al., 2021; Otto, 2013).

Accurate traffic flow predictions are essential for efficient smart city management. The advancement in AI technology enables real-time traffic flow forecasting, allowing regulators to intervene early to avoid or alleviate congestion (Otto, 2013; Santos, 2021). In this regard, quantum computers can increase the efficiency of future AI-based systems and, consequently,

improve traffic flow prediction outcomes (Mukherjee & Mandal, 2020).

Finally, an efficient bike-sharing system provides a viable alternative to automated mobility. Short-distance cycling helps alleviate traffic congestion (Harikrishnakumar et al., 2021). Moreover, it reduces carbon emissions and the overpopulation risk (Harikrishnakumar et al., 2021). An effective bike-sharing system requires rebalancing analysis, which includes the transfer of bikes between different bike stations to ensure that supply meets anticipated demand—this could be effectively achieved by employing the higher computational power of quantum computing (Harikrishnakumar et al., 2021; J. Liu et al., 2022; Manna et al., 2021; Manzalini, 2020; Santos, 2021; F. Zhang et al., 2020).

3.5 *Discussion and practical implications*

Traditional Newtonian conceptualizations of cities, characteristic of twentieth-century urban theorizing, are increasingly incapable of dealing with the complexity, uncertainty, and high of contemporary cities (Arida, 2002, 2008a; Macionis & Parrillo, 2010). The new millennium calls for novel city metaphors as grand functionalist narratives of the past increasingly lose their explanative relevance (Lynch, 1990).

After briefly tracing the history of urban metaphorizing over the past one hundred years, from City-as-Machine (Archigram (Group), 1999) to the open system notion of City-as-Organism (Broto et al., 2012), in this chapter, an original way to conceptualize contemporary cities was introduced, the so-called quantum metaphor and the related notion of quantum-cities. This novel urban metaphor relies on fundamental notions of quantum mechanics and represents a particular instance of a larger attempt to extrapolate concepts of quantum physics to the realm of social sciences as an alternative to more straightforward Newtonian principles of cause and effect that are still cardinal therein (Wendt, 2015; Zohar, 1995; Zohar & Marshall, 1990).

Contrary to previous approaches, a quantum city metaphor treats complexity and uncertainty as endogenous and, therefore, desired and sought for rather than “avoid at all costs” epiphenomena (Arida, 2002). In other words, uncertainty and complexity are welcomed rather than avoided. Indeed, those two constitute the basis of the theoretical underpinning of the quantum metaphor. Quantum cities of the future, which, after all, can be envisioned as a particular instance of smart cities, should be able to manage massive amounts of data efficiently and effortlessly while keeping all the potential risks under control. The latter can be achieved through an effective paradigm shift, not only in terms of concrete technological

implementations (e.g., quantum computing and quantum communication) but also in the light of novel and interesting theoretical conceptualizations.

3.5.1 Evidence from a systematic review of quantum technologies for cities

Concerning the systematic review of quantum technologies for cities, as shown by principal component analysis and agglomerative hierarchical clustering, quantum communication and quantum computing dominate the landscape in the context of social sciences, including urban-related literature. On the other hand, quantum simulation, quantum sensing, and metrology are mostly technical fields within the realm of quantum computing and, thus, are uncorrelated to topics of urban planning, management, and design (Degen et al., 2017; Huang et al., 2020; Offert, 2015; Piacentini et al., 2015; Simon et al., 2017).

There are three significant practical implications of the systematic literature review. First, quantum communication and quantum computing are potentially the most promising quantum technologies for city planning, design, and management. Hence, investing in quantum communication and computing can grant urban managers, administrators, and legislators a substantial first-mover advantage in terms of urban efficiency and attractiveness for hi-tech and other types of investors.

Second, quantum technologies rely on more abstract and counterintuitive principles, typical of quantum mechanics. Embracing the technologies for everyday usage, even on the city level, requires city administrators, managers, and planners to effectively communicate the advantages and disadvantages of novel quantum technologies and the basic principles of their functioning, which, in turn, calls for increasing people's "quantum literacy," analogous to the advent of conventional computers and their subsequent diffusion from universities to business and then, for private usage. In a context in which events cannot be predicted with accuracy anymore (Arida, 2002), a novel form of education and training should orient new generations to apprehend the world in dualistic terms, proper of quantum metaphor, rather than as a collection of isolated, albeit interconnected phenomena.

Third, on the more abstract level, the quantum city concept relies on quantum metaphorizing. Furthermore, besides technology-related knowledge, a change in conventional views on topics of complexity, an overabundance of information, and risk is needed. Rather than constituting threats, they are better envisioned as opportunities that can be exploited to their fullest potential through urban quantum technologies. The unpredictability at the heart of the

quantum city metaphor urges scholars to redefine conceptual attitudes toward urbanism as a way of thinking rather than a profession (Zohar, 1995).

3.5.2 Evidence from a semantic exploration of the potential relationship between urban quantum technologies and conventional smart city technologies

The analysis of academic literature on quantum technologies in social sciences with a focus on urban-related themes and topics revealed that quantum communication and quantum computing are the most critical quantum technologies regarding their potential relevance for future smart cities. Hence, investing in quantum communication and computing could give smart cities a significant first-mover advantage in terms of technological development, innovation potential, and increased appeal to heterogeneous smart city stakeholders (Santos, 2021).

To emphasize the managerial relevance of the application of quantum technologies in smart cities, the impact of quantum technologies' integration into smart city infrastructures can be framed according to the following observations:

- when addressing a problem, quantum technologies can accommodate more variables (Khan & Robles-Kelly, 2020);
- quantum technologies could potentially store higher volumes of data and, at the same time, prevent data-sieving errors (Dowling & Milburn, 2002);
- using quantum technologies makes it possible to solve complex city-related problems with high precision. Consequently, quantum technologies allow for more exact predictions and forecasts (Kim et al., 2021; Proctor et al., 2022);
- quantum technologies can sustain complex communication networks (Bassoli et al., 2021);
- quantum technologies can also provide a substantial increase in computational speed for specific types of algorithms, allowing urban managers, administrators, and planners to address the complexity and variety intrinsic to a smart city with better precision and efficiency (Amiri, 2003; Wack et al., 2021);
- quantum technologies can significantly affect privacy and security standards and procedures in different smart city subsystems (Kumari et al., 2021).

Integrating fully functioning quantum devices into existing smart city infrastructures can lead to a substantial leap in the capacity of all conventional smart city technologies. Accordingly,

numerous benefits of such integration can be identified. For example:

- more precise urban-related forecasting made possible by quantum technologies can be critical in the context of the high uncertainty and complexity typical of contemporary cities (Kim et al., 2021; Proctor et al., 2022);
- as a result of the increase in computation speed, more complexity and variety (in terms of the number and types of variables) can be integrated into the forecasting and cost-benefit analyses of different smart city initiatives (Amiri, 2003; Wack et al., 2021);
- quantum AI can be used in decision-making to incorporate a greater number of social, cultural, economic, financial, environmental, and technical variables in order to provide urban managers, administrators, and planners with a variety of equifinal policies and strategies to meet the needs and expectations of the highest number of inhabitants and other smart city stakeholders (Khan & Robles-Kelly, 2020);
- quantum technologies can help prevent errors caused by improper data handling in highly digitalized smart cities (Dowling & Milburn, 2002);
- by implementing complex quantum communication networks, urban managers, administrators, and planners can aspire to design smart cities in which various technological, social, and environmental actors are structurally integrated and operate in agreement (Bassoli et al., 2021);
- quantum cryptography and communication systems can provide advanced safety and security algorithms for data and information protection (Kumari et al., 2021; Portmann & Renner, 2022; X. Zhang et al., 2015).

Conversely, the supposed technological leap may result in a number of issues:

- including too many variables in decision-making processes may lead to a loss of sense of control for some. Moreover, it could be worrisome for others to rely excessively on technology in their day-to-day decisions;
- storing a large amount of city-related information without a proper system to evaluate the relevance and reliability of each piece of data may lead to over-investment in resources, policies, and decisions that are ineffective, resulting in unnecessary expenses as well as an increased likelihood of unintended consequences;
- exact predictions may be used for conflicting goals by different urban actors. This could lead to an increase in conflicts as opposed to the desired cooperation and, consequently, a rise in inequality;

- higher network complexity could be incompatible with human perceptual and knowledge capabilities. To avoid being excluded from decision-making processes, individuals may be constrained to manually oversee city-related solutions suggested by quantum-integrated AI. Overall, the increasing complexity of quantum systems could potentially undermine the more "humane" aspects of city-related decision-making and management;
- a substantial increase in problem-solving speed may not be consistent with people's rate of understanding and accepting those changes, widening the divide between technology and humans;
- quantum technology advancements could have an ambiguous impact on security and privacy. Improvements in quantum cryptography may result in a "cold war" between developers of more powerful tools for undermining security systems and those who strive to protect infrastructural safety and security;
- the potential benefits of integrating quantum technologies into smart cities can be challenging to hypothesize due to their perceived "futuristic" and speculative aspects.

If quantum technologies reach widespread usage, radical social changes might follow (Zohar, 1995). For this reason, urban decision-makers are advised to start strategizing quantum technologies' introduction in their smart cities as a lever for urban growth and aim to reduce barriers to adopting quantum technologies in order to decrease the related inequalities (Bhasin & Tripathi, 2023). Presently, the race is on to build the first effective quantum computer as researchers initially envisioned it (Lele, 2021). On the one hand, only simple proof-of-concept quantum computers have been developed so far, and most academics agree that an advanced, fully performant quantum computer remains just a theoretical possibility (Prince, 2014). On the other hand, today's progress in quantum computing could help us conceptualize complexity as a potential rather than a barrier or a threat (Cuffaro, 2018).

3.6 Conclusions, theoretical implications, research gaps, limitations, and suggestions for future research

In evaluating the impact of quantum technologies on conventional smart city technologies, it was observed that many researchers (over-) emphasize the security dangers posed by quantum computers and the related solutions intrinsic to quantum communication. However, such a pessimistic outlook on quantum technologies could only catalyze a new type of a "cold war" (this time between technologies, not countries), consuming resources and producing tension without contributing to people's welfare or improving everyday life. On the other hand,

quantum technologies can make most computational processes in smart cities considerably more efficient. Accordingly, city managers, administrators, and planners are advised to start considering the potential benefits quantum technologies could bring to urban infrastructure while planning and allocating the resources for future smart city initiatives.

Conversely, researchers on the topic should be encouraged to investigate practical everyday applications of quantum technologies in smart cities more often in addition to a frequently studied topic of quantum defensive strategies (mainly associated with digital warfare) (Lele, 2021). Indeed, as the latent semantic analysis of related literature revealed, thematic connections between the topics of quantum computing, quantum communication, and seven facets of smart city technology (AI, ICT, IoT, blockchain, big data, cloud computing, and smart transportation) are already present but not yet strong, indicating a significant research gap.

Quantum technologies rely on quantum mechanics' counterintuitive and, sometimes, abstract principles. Adopting quantum technologies for everyday use in cities makes it necessary for urban managers, administrators, and planners to effectively communicate the benefits and drawbacks of urban quantum technologies and the fundamental principles of their operation, which, in turn, requires increasing people's "quantum literacy." To reach a conceptual shift of focus from quantum defense strategies to everyday quantum technologies' applications in cities, a novel form of education and training should orient future generations to perceive the world in a safer, although equivocal terms are in line with urban quantum development and theorizing. As a result, in addition to investing in quantum technology development, educational investments are also critical (Arida, 2008a).

Openness and accessibility are some of the ways to ensure that the benefits of quantum technologies outweigh their negative impacts. Therefore, related scientific knowledge should be made publicly available and actively communicated, and if possible, quantum technologies' higher computational capacity should be made accessible via the cloud (de Wolf, 2017). Moreover, to reinforce the positive impacts of quantum technologies in cities, the crucial step is to ensure that urban residents start thinking in new ways compatible with quantum technologies (Arida, 1998, 2002). It does not mean people should start thinking in a manner similar to a quantum computer, but rather that they need to understand what it can and cannot do and how to make sense of its outputs. This can be achieved through education and the gamification of education in the field of quantum technologies (DeBenedictis, 2020; Gordon & Gordon, 2012; Mykhailova & Svore, 2020; Uhlig et al., 2019).

To conclude, several limitations characterized the analyses in this chapter. Concerning Study 2, only the Scopus database was used to assess the literature. As a result, some critical papers on the topic could have been omitted. Additionally, only keywords derived from the taxonomy of quantum technologies by Acin et al. (2018) were used for the related searches. Those keywords were also used separately, without Boolean concatenation in the queries. Again, this increases the likelihood of omitting important academic records from the review. However, given the initial number of identified quantum technologies-related records (more than 200), the search criteria were deemed sufficient for proper exploratory analysis and identification of the most significant themes and topics.

When it comes to Study 3, the relationships between quantum technologies and conventional smart city technologies were hypothesized based on the frequency of corresponding keywords in the retrieved academic papers on quantum computing and communication within the broader social science domain. As such, the related variables should not be considered the exact operational definitions of quantum or smart city technologies. What was studied here is the semantic interrelatedness of research ideas, emerging topics, themes, and ongoing academic discourses rather than the concrete contributions of quantum computing and quantum communication to seven types of smart city technologies (Landauer et al., 1998). Such a study would necessarily require advanced and ubiquitous quantum technologies, which, for now, are only in the nascent phases of development. Additionally, only simple Boolean queries were used for the related literature search. Therefore, the existence of several relevant papers that could have been omitted from the analyses should not be excluded. However, given the high number of analyzed documents (eighty quantum technologies-related papers for what concerns the content and thematic analyses and 567 abstracts used for the derivation of the conventional smart city technologies taxonomy), the theoretical saturation is considered appropriately reached. Therefore, it is unlikely that further insights could have emerged from the omitted academic literature. Indeed, as was noticed early on, most articles were variations on the few fundamental themes and topics continually re-emerging during the qualitative coding.

Finally, several prospects for future research directions can be outlined based on the above considerations. First, additional research can be conducted to identify and explore how quantum communication and quantum computing can improve urban efficiency and make cities more attractive to hi-tech investors. Second, researchers could also examine the potential limitations and challenges in embracing quantum technologies in urban contexts. To

this scope, action research could be conducted with the goal of developing educational programs and tools to increase people's quantum literacy, a fundamental requirement for adequately implementing the quantum urban paradigm. Third, further research can be performed to explore the potential benefits of embracing these concepts as opportunities rather than threats in urban contexts. Specifically, more particularized empirical research is also needed, such as on how quantum technologies may interact and synergize with existing smart city technologies, including AI, blockchain, cloud computing, and others.

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4 INTEGRATING CIRCULARITY, SMARTNESS, AND QUANTUM TECHNOLOGY FOR A CONSOLIDATED FRAMEWORK OF SMART SUSTAINABLE CITIES

4.1 Introduction

4.1.1 An outline of the chapter

This chapter is mainly integrative and serves as the broader conclusion to the overall work. Hence, it elaborates and is based on the results of the two previous chapters of the thesis. For this reason, while the previous chapters can be read as stand-out works, it is advised to get familiar with all the preceding results before continue reading Chapter 4, as those results are frequently referenced herein. The chapter, however, also presents novel empirical findings and, as such, ends with respective discussion and implications sub-sections that are exclusively pertinent to the empirical findings of Chapter 4.

In particular, the environmental urban aspect is discussed again, as related to the notions of circular economy, circular cities, and smart circular cities, by reasoning on how quantum technologies, through their effect on conventional smart city implementations, might enhance the “circularity” of a city. The final result constitutes the definitive empirical buttressing of an integrative holistic model of smart sustainable cities, with a particular emphasis on an environmental sustainability pillar that emphasizes circular economy initiatives in smart sustainable cities.

Like the two previous chapters, the analytical part of Chapter 4 is divided into three macro-sections. In particular, the first study elaborates more in-depth on the conceptualizations of Chapter 2 by tracing the narrative evolution of the circular city concept through ad-hoc bibliometric techniques. In the second study, the key conditions for a circular city to emerge are investigated through the necessary condition analysis. Finally, Study 3 relates the smartness and quantum technologies thorough an advanced semantic analysis technique based on partial least squares structural equation modeling, determining which components of smartness are the most influential and are influenced by the two classes of quantum technologies deemed essential within the urban context. The discussion and conclusions presented at the end of Chapter 4 are specific to the results of the three studies presented here. Conversely, the integrative part consisting of the summary of the overall framework resulting from the totality of the analytical contributions in the thesis, including those in Chapter 2 and Chapter 3, is presented in Chapter 5, in which the holistic conceptualization of

environmentally sustainable smart cities based on the results of all nine analytical sections of the work is outlined and discussed, emphasizing, in particular, the complex relationship between different components of urban smartness, greenness, circularity, and quantum technologies.

4.1.2 Sustainability and circular economy

While in Chapter 2, the topic of circularity is presented and discussed, here it assumes a cardinal position requiring, therefore, a more in-depth and systematic scholarly evaluation.

It is impossible to talk about the circular economy without first examining the pressing issue of environmental sustainability (Giovannoni & Fabietti, 2013). As a topic of scholarly inquiry, it is far from novel. Already at the end of the Sixties, Hardin (2000) postulated his "tragedy of the commons" metaphor, an observation that, should a collective of people enjoy unrestricted access to a finite amount of resources, like the environmental resources or similar, eventually, they will tend to over-use them to the point of scarcity, destroying the resources altogether. For example, environmental pollution can be perceived as caused by the consequences of organizational and other social actors ignoring the effect of their harmful actions on the environment, as the contribution of a single (and here, it is important to specify—selfish and own utility-maximizing) social actor to the degradation of the environment is minimal. As such, the problem is close to another famous concept in economics: the free-riding paradox (Albanese & Van Fleet, 1985) and the related problem of managing public goods and externalities (Cornes & Sandler, 1996).

The problem runs even deeper and has its roots in personality and group psychology, as reflected in the notion of social loafing, also known as social inhibition—the tendency of individuals to exert less effort while working in groups, proportionally related to the size of the group (Liden et al., 2004). In relation to environmental degradation, while multiple rational arguments have been proposed to convey the seriousness of the problem and to call for more effective collective action (for example, the corollary of the prisoner's dilemma and the associated argumentation for the cooperation), both from the producer and consumer sides (Ostrom, 2010), apparently, the rate at which heterogeneous collective actions are implemented, as well as their efficacy, lags behind the ever-increasing seriousness of the environmental issues, to the point, indeed, scholars posit the looming "point of no return" when it comes to our ability to reverse environmental damaged caused by two hundred years

of unremitting industrial progress, as well as the related environmental catastrophe on the horizon (Kalantidou, 2023). In this regard, one can also mention Gidden's paradox, formulated by the famous British sociologist Anthony Giddens. The paradox's main point is that problems that appear to be irrelevant and unseen at the short-term level can actually have significant repercussions and impacts in the future due to their cumulative effect (Isenhour, 2013).

Given the considerations above, it is not surprising that more and more organizations, private or not, are starting to realize the seriousness of the environmental issues and concerns, but also the utility and long-term gain, both financial and reputational, of "walking the walk" or even merely "talking the talk" when it comes to environmental sustainability (Griskevicius et al., 2010). Indeed, in this regard, even mere acts of "greenwashing" have a positive connotation (Du, 2015). Again, the arguments of Giddens might be of use here, especially his notion of structuration, as sometimes, even merely talking about a pressing issue is enough to make it more socially salient and hence stimulate further concrete steps toward solving it (Giddens, 1991).

The transition toward environmental sustainability involves different stakeholder categories and often leads to new products, services, and business models (Markard et al., 2012). Of the latter are so-called circular business models—intended to introduce and promote the notion of circularity in organizations (Fedele & Formisano, 2023). The idea of circularity (or circular mindset) is not entirely new. On the contrary, one could claim that the "repair, reuse, and eliminate the waste" mindset was the dominant way of doing things of our progenitors (Winans et al., 2017) and is still prevalent in societies rife with poverty and driven, for example, by moral values of religious austerity (Frazer, 2006). Conversely, the linear economy, a still vastly dominant way of production (and consumption), is more recent and is connected to the externalities of late-stage capitalist dynamics (Valenzuela & Böhm, 2017). As a dedicated academic field, the circular economy, however, is the most recent of the two (Winans et al., 2017).

Commonly, circular economy principles include the so-called 3Rs (reduce, reuse, recycle) (Wu et al., 2014) and the 6Rs (reuse, recycle, redesign, remanufacture, reduce, recover) (Jawahir & Bradley, 2016). However, those are not entirely fixed, and other principles have been introduced based on the specific context of the circular business model applications (Fedele & Formisano, 2023). As such, the circular economy is an "umbrella concept" encompassing a vast range of managerial and engineering strategies to "enclose" linear

production into a sustainable loop of re-usage and waste elimination (Castro et al., 2022). As a result, no shared nor all-encompassing definition of circular economy exists. The definitions in the literature are heterogeneous and emphasize the different facets and goals in relation to the focus of the specific study. For illustrative purposes, Table 4.1 reports some of the most important definitions of circular economy, chosen in a way to emphasize its heterogeneous aspects.

According to	**Circular economy is**	**Main focus**
(Zhijun & Nailing, 2007)	"an ecological economy that follows the principles of 'reducing resource use, reusing, and recycling,' with the objectives of reducing the resources that enter the production process, affecting multiple uses of the same resources in different ways, and reusing waste from one facility as a resource for other facilities."	production, ecology, systems' perspective
(Geng et al., 2008)	"an economy based on a 'spiral-loop system' that minimizes matter, energy flow, and environmental deterioration without restricting economic growth or social and technical progress."	technology, circularity
(Mathews & Tan, 2011)	"becoming a business and competitive concept, where benefits are experienced not by firms acting on their own so much as in concert with each other, reducing their collective costs and making systemic gains that reduce the ecological toll of industrial activities."	business model, production
(Ghisellini et al., 2016)	"a way to overcome the current production and consumption model based on continuous growth and increasing resource throughput."	production, consumption
(Lieder & Rashid, 2016)	"an economy which is environmentally and economically regenerative."	regeneration, ecology
(Singh & Ordoñez, 2016)	"an economic strategy that suggests innovative ways to transform the current predominantly linear system of consumption into a circular one while achieving economic sustainability with much-needed material saving."	corporate strategy, production
(Geissdoerfer et al., 2017)	"a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling."	regeneration, production
(de Jesus & Mendonça,	"a multidimensional, dynamic, integrative approach promoting a reformed sociotechnical template for carrying out economic development, in an environmentally sustainable way, by re-	society, technology, production, consumption, systems'

2018)	matching, re-balancing and re-wiring industrial processes and consumption habits into a new usage-production closed-loop system."	perspective
(Khan et al., 2020)	"a key strategy to achieve corporate sustainability."	corporate strategy

Table 4.1 *Heterogenous definitions of the circular economy. Based on the elaboration by Fedele & Formisano (2023)*

As can be seen from heterogeneous definitions of circular economy in Table 4.1, different authors have put emphasis on its various aspects. For example, while some strictly emphasize its role as a business model and a specific corporate strategy (Khan et al., 2020; Singh & Ordoñez, 2016), others elaborate on its role from a consumer standpoint as well (Ghisellini et al., 2016). Finally, the definitions most relevant to this thesis point to the circular economy's role as a complex interconnected system going beyond mere production and consumption activities (de Jesus & Mendonça, 2018). In this regard, the notion of a circular economy can be applied to the most complex of loosely coupled social entities, the cities. In this specific case, it is typically reified in the concept of so-called circular cities (CC).

4.1.3 An overview of circular cities

Since the original publication of the influential book of Saskia Sassen (Sassen, 2013) in 1991, the discourse on the centrality of cities as hubs of innovation, worldwide connectivity, and economic growth has been brought forward to the attention of not only academics but the general public as well. Since then, the increasing urbanization of the so-called developing world has only contributed to our understanding of cities' central role as macro-sociological agents of economic activity, with the predominant majority of the global population residing now in what can be classified (under different normative regimes) as urbanized areas (D'Amico et al., 2022). In contrast to the rural areas, those now generate most of the world's GDP and are expected to increase their influence at least up to the year 2050 (D'Amico et al., 2022).

This unconstrained urban growth, however, has been one of the primary culprits of modern-day environmental challenges, including the emission of greenhouse gasses, the production of waste and the related poor waste management initiatives, excessive and unbalanced exploitation of resources, and many others (Fatimah et al., 2020; Shishegar et al., 2021). As a

consequence of the unremitting and unsustainable growth, major cities nowadays face increasingly pressing challenges related to the management of freshwater (Shishegar et al., 2021), waste (Fatimah et al., 2020), insufficiency of renewable energy sources (Strielkowski et al., 2021), poorer social cohesion and inadequate diseases (Macke et al., 2019; Muzammal et al., 2020), and so on (D'Amico et al., 2022).

As shown by many scholars, again and again, the cost of linear unsustainable growth for the sake of the growth itself is not only unsustainable but also, in line with Gidden's paradox, potentially undermines the delicate balance of the entire social fabric (Isenhour, 2013). From the optics of both the prisoner's dilemma and the "tragedy of the commons" perspective (Hardin, 2000), a necessary change would necessarily call for collective action of sorts, either organically bubbling up from local grassroots initiatives or imposed top-down by governments and regulations, but also more gradually through an eco-centric education and socialization of the future generations. The latter, however, no matter how laudable, contradicts the sense of urgency that the existing environmental situation imposes (Bellofiore & Vertova, 2024).

Recognizing the pressing need for radical and practical solutions to cities' contribution to looming environmental catastrophe (Bellofiore & Vertova, 2024; Prendeville et al., 2018a), the concept of the circular city has emerged as an interesting variation within the framework of the discourses on sustainable urban development (D'Amico et al., 2022).

A circular city is a concept that has gained prominence in sustainability-oriented urban planning, design, and management discourses quite recently and in parallel with the rise in popularity of a circular economy concept, especially as promoted by numerous EU initiatives (Aggeri, 2020). At its core, the circular city metaphor envisions cities as complex social (Barile & Saviano, 2010) and eco-systems in which energy, resources, and materials are conserved, reused, and recycled in a closed-loop arrangement, with the minimum (if any) waste and pollution (D'Amico et al., 2022). The circularity approach to urban environments seeks to minimize environmental impact, enhance urban resilience, boost the so-called "urban metabolism" (D'Amico et al., 2022), and contribute to a more livable and prosperous urban life.

In Chapter 2 of the thesis, major definitions of the circular city concept were proposed in chronological order since the concept's inception in the early 2010s'. Based on the analysis and synthesis of existing heterogeneous definitions of a smart city concept in Table 2.2, a circular city was defined as a *city that embodies regenerative and sustainable practices,*

aiming to minimize waste, optimize resource use, and enhance resilience through circular economy principles by integrating the collaboration among city stakeholders for self-sustaining, inclusive, and eco-friendly environments, preserving natural capital for long-term prosperity.

Contrary to the emerging circular model, the linear model of urban development is characterized by the extraction, consumption, and then complete disposal of resources, which has weakened the resilience of contemporary cities and resulted in further environmental degradation therein (Corcelli et al., 2019; Horn & Proksch, 2022a). The notion of the circular city represents a paradigm shift toward regenerative and symbiotic systems that prioritize resource efficiency, the reduction of waste, and long-term environmental sustainability (Corcelli et al., 2019; Horn & Proksch, 2022a). As such, a circular city framework treats urban environments as complex eco-systems capable of combining novel technologies and social practices to integrate circular economy principles, thereby addressing challenges of social, economic, and environmental orders in a holistic manner (D'Amico et al., 2022; Paoli et al., 2022).

As some contemporary cities strive to overcome the limitations of the linear production and consumption models and transition toward more prominent circularity-based initiatives, there is a growing recognition of the interrelatedness between technical and social elements in achieving efficient urban environmental sustainability transition (Paoli et al., 2022). According to Paoli et al. (2022), a circular city "not only offers an economic model for efficient resource management but also serves as a holistic approach to promoting environmental sustainability and enhancing social cooperation among various stakeholders."

Researchers have suggested various initiatives and components that could potentially contribute to the development of a circular city. These include a built environment focused on environmentally sustainable buildings (Horn & Proksch, 2022a), localized waste management and resource loops (Horn & Proksch, 2022a), sustainable transportation models (D'Amico et al., 2022), the development of an urban bioeconomy through the usage organic materials and biowaste (Pegorin et al., 2024), and production systems that are completely circular relying on business models such as 9Rs and similar (Horn & Proksch, 2022a). When it comes to the proper city management tools through which the outlined initiatives could be implemented, these include urban planning policies that support circularity (e.g., circularity-oriented zoning regulations, building codes, and land use planning), the promotion of recycling, sharing, and reuse practices (comprising the infrastructure to support the said practices), digital

technologies integration for better data-driven decision-making (the so-called smart circular city), and, finally, all the necessary social measures for establishing the community engagement, comprising all the related urban stakeholders (inhabitants, institutions, and organizations) (Pegorin et al., 2024). Indeed, when it comes to the latter, "by integrating social considerations into circular city strategies, it becomes possible to address equity, inclusivity, and social cohesion alongside environmental and economic goals" (Paoli et al., 2022; Pegorin et al., 2024).

4.2 Study 1: Tracing the evolution of the circular city metaphor through bibliometric analyses

4.2.1 Basic bibliometric evaluation of the research field

To assess the state of the art and the evolution of discourses on circular cities within the academia, an in-depth bibliometric exploration of the topic was performed. Hence, on the 28th of April 2024, a Scopus search was conducted. The Scopus academic search system (and abstract/citation database) was selected deliberately as it is currently one of the biggest (82.4 million records) academic search systems suitable for general purposes of literature review (Gusenbauer & Haddaway, 2020). Indeed, unlike Google Scholar and similar algorithm-driven academic search engines, it produced reliable and replicable results for a specific query (Gusenbauer & Haddaway, 2020). Furthermore, unlike some academic search engines, it allows a bulk download of metadata in a format suitable for further bibliometric evaluation (e.g., BibTex). In this regard, it is also similar to Web of Science, another general-purpose academic search system. However, the latter was not used in this section's analyses, as not only is it of a smaller size (79 million records in the core collection), but also, most of the documents identified on the Web of Science tended to coincide with those found of Scopus.

To perform the broadest but also context-specific search possible, the only keyword searched was "circular cit*." The asterisk at the end of the keyword allowed for the possibility to include both *city* and *cities* unigrams as units of search. The quotation marks restricted the results to the instances when the unigrams *circular* and *city* are in this precise order and are not separated by other words. The search was performed by limiting the search context to titles, abstracts, and keywords of documents, and only documents in the English language were assessed. Other than that, no restrictions were put on the type of documents, area of

research, or publication stage[8]. In total, 354 scholarly documents were identified.

As expected, most documents were pertaining to domains of either social sciences (20.7%) or environmental sciences (17.4%; or 25.7% if coupled with the "energy" category). If considered jointly, "economics, econometrics and finance" and "business management and accounting" were in third place, with 15.3%. If those are counted as a part of the social sciences domain, the latter category would contain 36% of all the related documents. In terms of the document types, almost 70% were journal articles, followed by conference papers (12.7%) and book chapters (8%).

According to the temporal distribution of identified documents, the first mentions of circular cities date back to the early Seventies. Upon more detailed inspection, it was noticed that those early works actually have little to nothing to do with circular cities as currently widely intended (i.e., environmentally-friendly cities in which circularity principles are widely applied). Indeed, most of those early works dealt with optimization problems concerning more efficient land use and transportation infrastructure, and the concept of a circular city was used, quite literally, as an idealized mathematical representation of a perfectly round-shaped city (Blumenfeld & Weiss, 1970) adopted to find optimal-cost routes (Brakke & Zitron, 1980; Rossi-Hansberg, 2004). As such, those documents largely pertain to "economics" (Scalera & Zazzaro, 2008; Wang & Chen, 2007) and "mathematics" (Zitron, 1981) categories (in particular, journals dealing with the topic of optimization).

Upon further investigation of every single abstract and title in chronological order, the first paper dealing with the topic of circular cities, as understood in this thesis, was found to date back only to 2013. It is the paper of Theeuwes et al. (2013) modeling the influence of open water surfaces on the temperature and comfort in the city in summer. In the study, the authors hypothesize that the so-called urban heat island effect can be mitigated by introducing open surface water in urban management and design (Theeuwes et al., 2013). The next mention of circular cities, as intended in the thesis, dates back to 2014 (Saint, 2014). In the related article, the author calls for the creation of "brand new circular cities that operate with minimum energy use, which is supplied by the cleanest renewable technologies available; have efficient transport systems so there's no need for cars; and use indoor hydroponic facilities and outdoor agricultural belts to grow a wide variety of organic plants for food self-sufficiency" (Saint, 2014). However, regardless of the first early mentions, it was the year 2018 when the concept of circular cities, as connected to that of the circular economy, really started to emerge,

[8] TITLE-ABS-KEY ("circular cit*") AND (LIMIT-TO (LANGUAGE , "English"))

ultimately foreshadowing the other "circular city" concept dear to urban economists (Krysovatyy et al., 2018; Prendeville et al., 2018b; Vrijhoef, 2018). Indeed, around that time, in their commentary on the newly emerging topic, Jones & Comfort (2018) noticed that "there is growing interest in the concept of the circular city, which looks to embed the principles of the circular economy across all urban functions."

Accordingly, given the above considerations and the analysis of trends, the results of the Scopus query were restricted to the year 2018 and onward, resulting in a total of 256 scholarly documents[9]. The complete U-turn in the meaning attributed to the concept of circular cities is not surprising, though, as even a broader concept of circular economy, although impossible to trace historically to a single source or an author, has only started to become popular internationally in 2010, following the publication of several related-reports (Aggeri, 2020).

Figure 4.1 shows the distribution of the final set of documents by subject area. In first place is the "social sciences" category, with 21.6% of documents, followed by the "environmental sciences" category containing 20.1% of documents. However, if coupled with the related "energy" subject area, the latter becomes 30.7% of all the scholarly documents on the circular city topic. In terms of the document type, 63.7% were proper journal articles, followed by 15.2% of conference papers, and 11.3 % were book chapters or books.

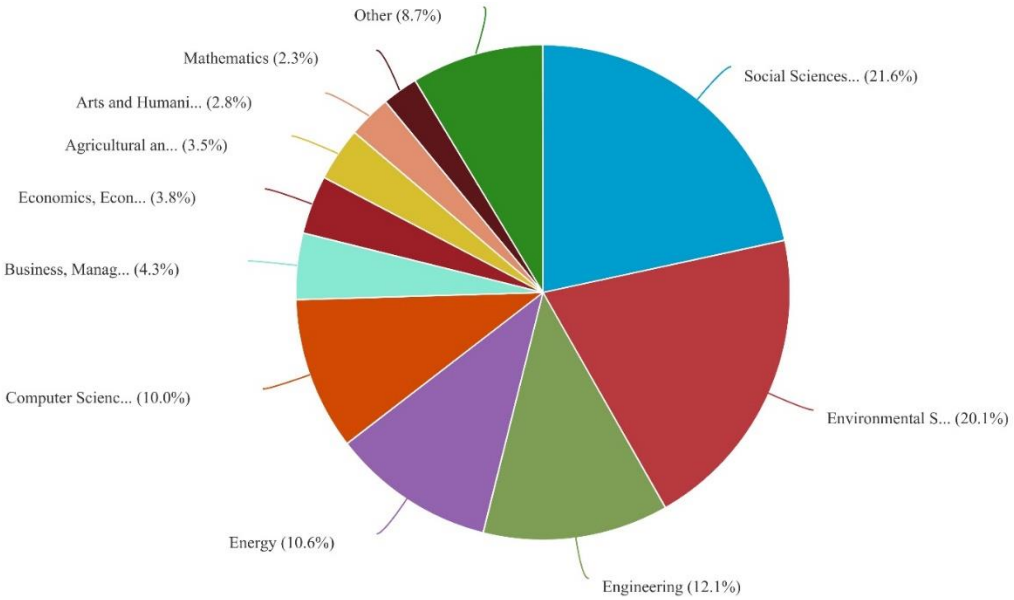


Fig. 4.1 *Distribution of all circular city-related scholarly documents on Scopus by the subject area*

Overall, the annual growth rate in scientific production was 14.23%. 751 authors in total have

[9] TITLE-ABS-KEY ("circular cit*") AND PUBYEAR > 2017 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English"))

contributed to the research area, publishing their work in 142 distinct sources, primarily as journal articles, conference proceedings, and book chapters. Among those, only 37 documents were authored by a single author. The rate of international co-authorship is relatively high, around 36.61%. The latter is counted if at least two authors from institutions of different countries have contributed to the research. The average number of co-authors per document is also high and is equal to 4.05%. On average, each scholarly document is cited around 14 times. Finally, as most of the following analyses in this section revolve around the keywords used, 865 distinct keywords were identified across all the 256 documents.

Figure 4.2 shows the distribution of analyzed documents by publication year. According to the chart, there has been a significant growth in interest in circular cities, as defined in the thesis, starting from the year 2018. 2019 has seen a slight slowdown, followed by the most rapid period of growth from 2020 until 2021, peaking at more than 60 related research studies in 2021. Since the year 2021, also coinciding with the heyday of the COVID-19 pandemic, there has been a slowdown in the interest in the topic (the year 2024 should be excluded from the analysis since by the time the review was performed, less than five months of that year have passed).

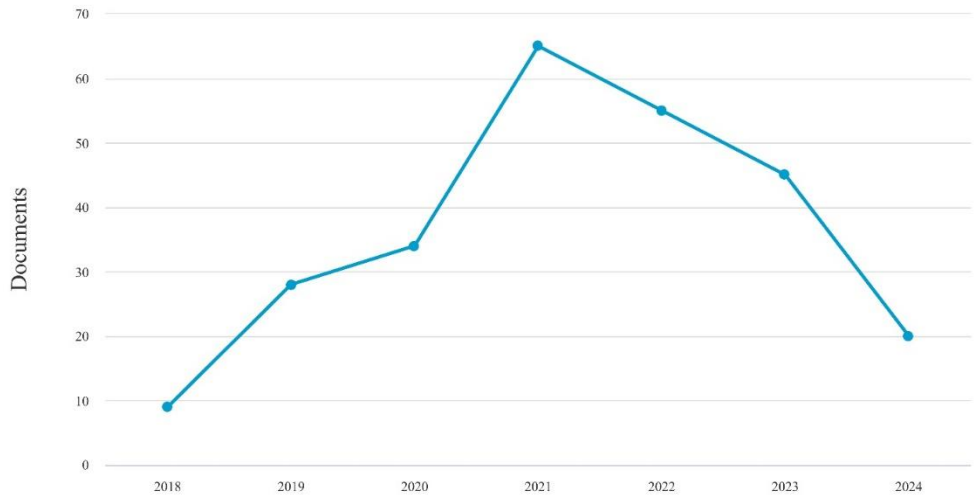


Fig. 4.2 *Distribution of all circular city-related scholarly documents on Scopus by the year of publication*

Figure 4.3 displays the three-filed plot reporting the interaction of most contributing institutions, scholars, and the most popular journals in which the majority of the research on circular cities has been published so far. The height of the rectangles (i.e., nodes) is proportional to the frequency of occurrence of a particular institution, scholar, or journal

within the related network of collaborations (Koo, 2021). The width of the lines connecting the nodes is proportional to the number of connections between the three categories (Koo, 2021). Among the contributing universities, the University of Ljubljana is the one with the most cross-university collaborations. University of Naples Federico II, although the most contributing institution in absolute terms (17 articles), is also the least connected among the 13 reported in Figure 3, with most of its researchers within the area not collaborating with other institutions.

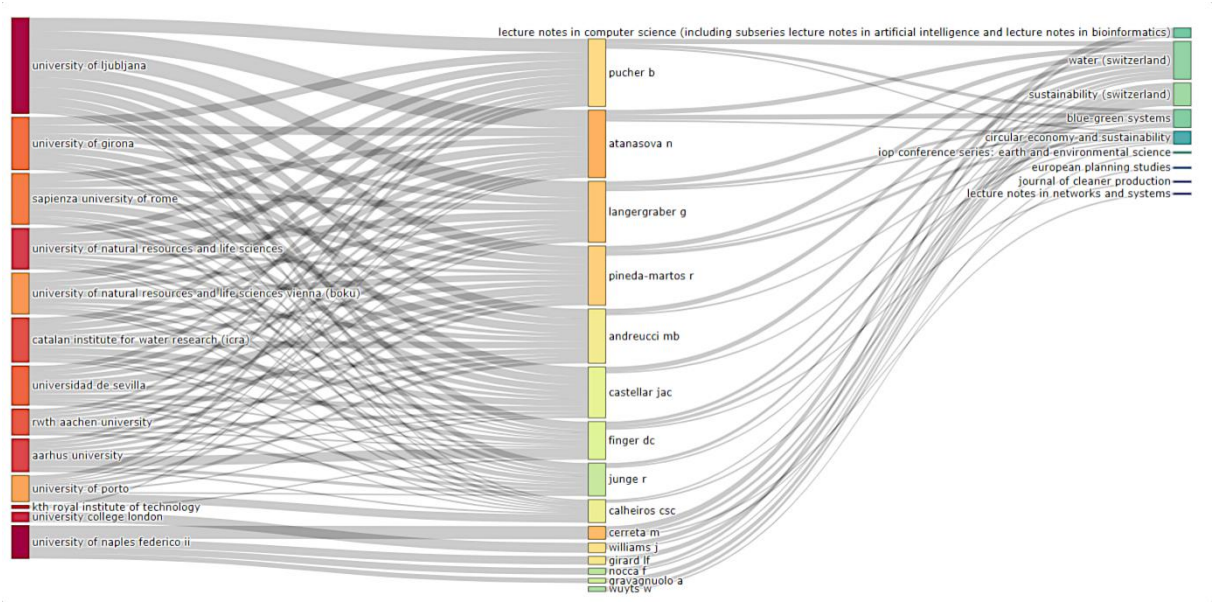


Fig. 4.3 *There-field plot relating the most contributing universities, scholars, and the most popular journals in the field of circular cities*

One thing, in particular, emerges from a close observation of the left column in Figure 4.3. Indeed, all of the most contributing universities turned out to be European. As such, one could rightly conclude that the entire corpus of research on circular cities is heavily Europe-centric. This is not surprising, however, as a substantial number of publications are closely connected and sponsored by particular European projects, such as Horizon 2020, and directly by the European Commission (see Figure 4.4).

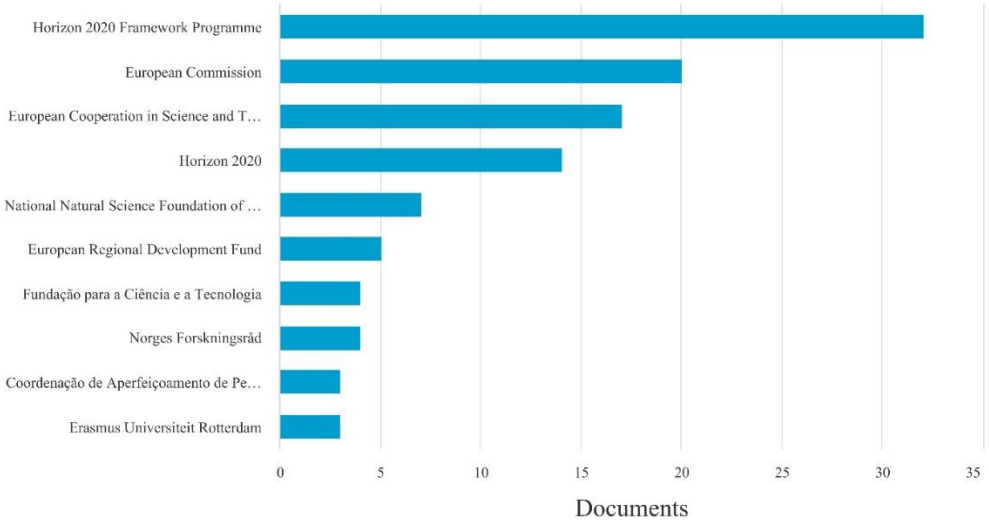


Fig. 4.4 *Distribution of sponsors of circular city-related research*

When it comes to the core collection of sources in which most scholarly documents on circular cities are published, an appropriate lens for its determination is Bradford's law (Venable et al., 2016). A particularization of Zipf's law and the Pareto distribution, it states that when journals in a field (or within a research area) are sorted by the number of articles, most articles are published in a relatively small minority of journals (Venable et al., 2016). In regards to the circular city-related sources, the core collection of the journal is reported in Figure 4.5. These include *Sustainability*, *Water*, *Blue-Green Systems*, *Sustainable Cities and Society*, *Circular Economy and Sustainability*, *Cities*, *Computer*, and *European Planning Studies*.

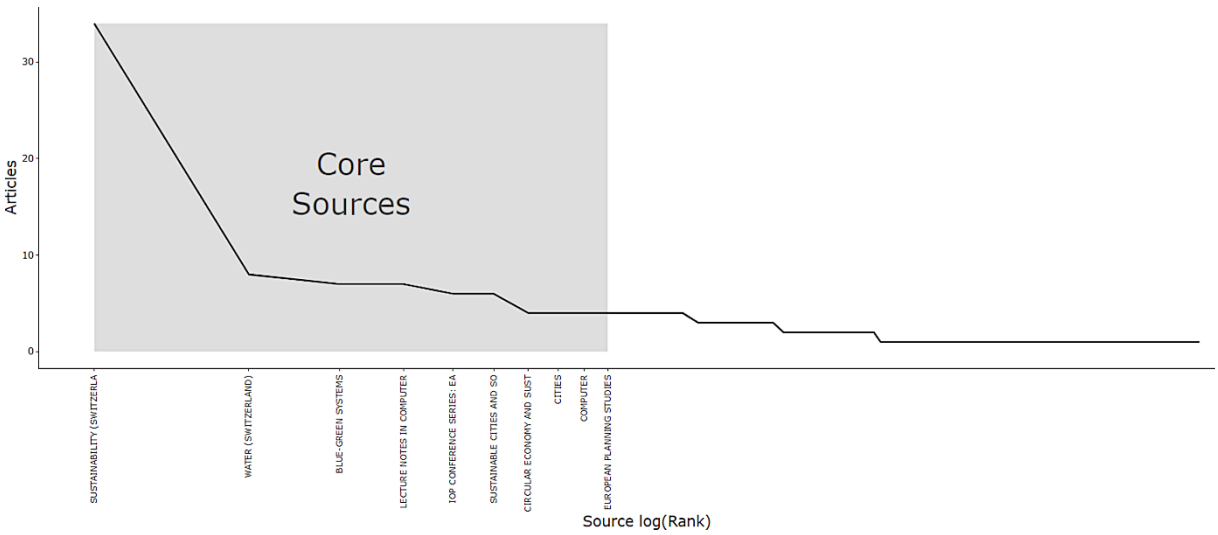


Fig. 4.5 *The core collection of circular city-related journals according to Bradford's law*

As already hinted by the distribution of most contributing universities (see Figure 4.3), most contributing countries were within the EU and the European continent in general (Figure 4.6), with Italy leading the research in terms of the absolute number of publications, followed by the Netherlands and the UK. In terms of the total number of citations, Italy is still in the lead (726 citations) but is closely followed by the UK (with 583 citations). Regarding the most cited articles, the leading position is occupied by Prendeville et al. (2018) (246 references), one of the first articles within the research area, mapping six cities in the transition toward becoming more "circular." It is followed by a review of nature-based solutions for urban water management in European circular cities (Oral et al., 2020) (160 citations) and a study of circular economy strategies in eight historic port cities of Europe (Gravagnuolo et al., 2019) (122 citations).

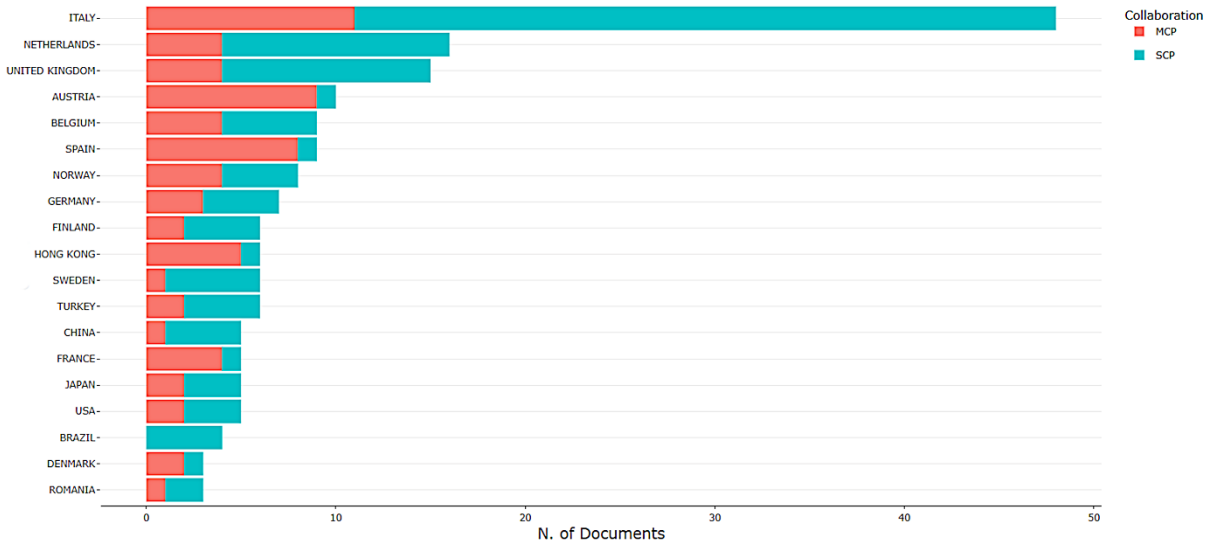


Fig. 4.6 *Distribution of circular city research by countries SCP single country publication, MCP multiple country publication*

4.2.2 In-depth bibliometric evaluation of the semantic evolution of the circular city concept

What follows is an in-depth analysis of themes and topics central to the circular city concept as well as its evolution since the first research efforts published in 2018. The analyses therein are primarily based on the author's keywords as well as their co-occurrences across the scholarly documents. To begin with, Figure 4.7 shows the world cloud reporting the fifty most used authors' keywords. The size of each term is linearly proportional to the absolute frequency of the reported keywords across documents. For better presentational clarity, the

three most frequent (but also tautological to the analysis) keywords were excluded (*circular economy*, *circular city*, *circular cities*).



Fig. 4.7 *Fifty most used authors' keywords within the circular city field*

Figure 4.8 shows the results of the trend topics analysis performed through *bibliometrix* package and *biblioshiny* app in RStudio and considering the authors' keywords used in the documents. In particular, the analysis shows which keywords and for how long were the most predominant within the research area (as previously, *circular economy*, *circular city*, and *circular cities* keywords were excluded). The dot represents the median year in which the keyword was mentioned. The interval denotes the first and third quartiles. The dot's width represents the total number of documents with that keyword (as a parameter, the minimum number of occurrences of a particular keyword per year was set to three).

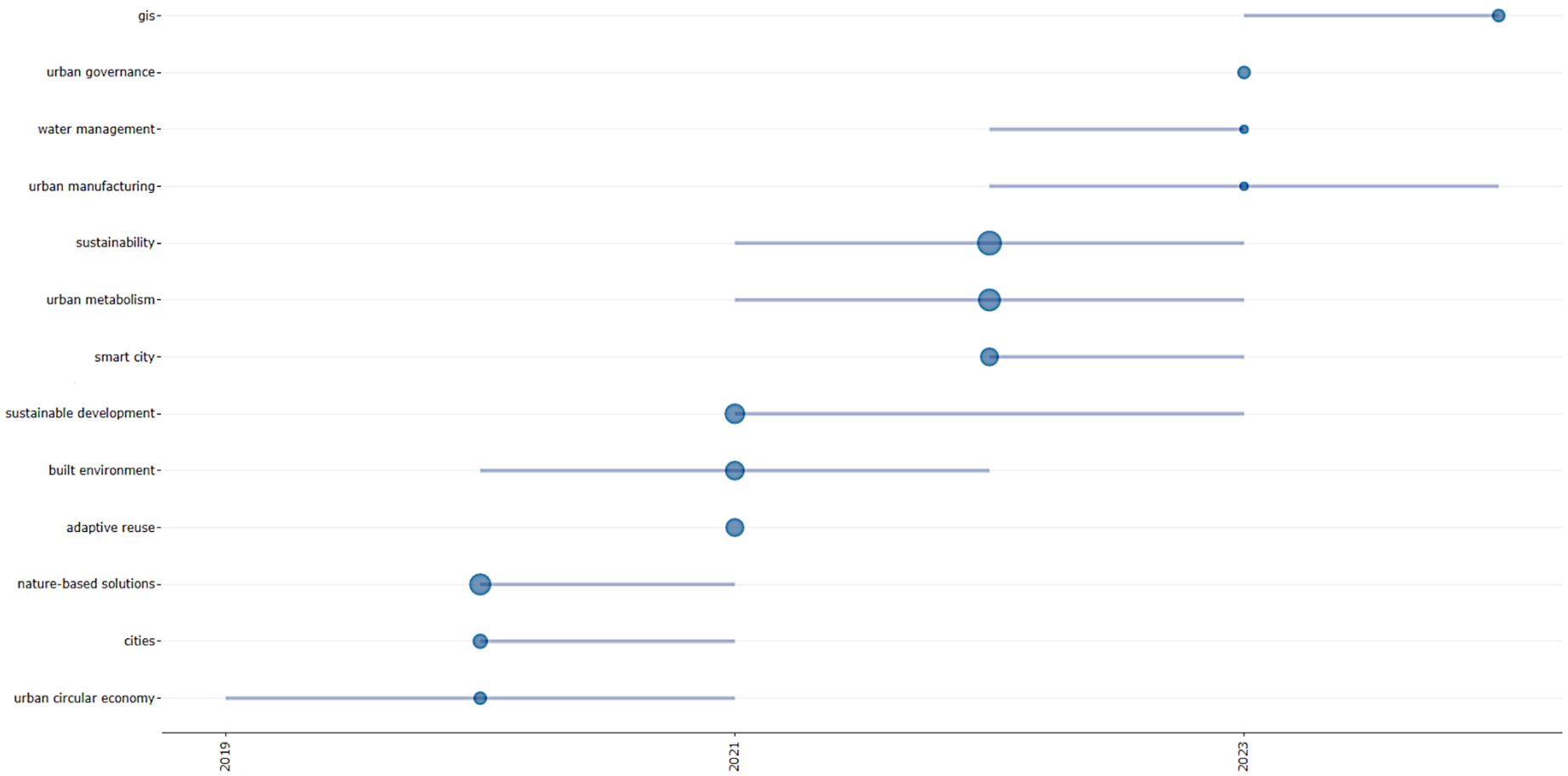


Fig. 4.8 *Circular cities. Trend topic analysis*

As can be deduced from Figure 4.8, in the beginning, the topic of circular cities was mostly concerned with urban circularity at large (*urban circular economy*), emphasizing the natural mimicry (i.e., *nature-based solution*) and the adaptive reuse of resources. After 2021, the themes and topics related to smart cities have been gradually introduced into the research program. Hence, the blend of two types of city metaphors resulted in the concept of the so-called smart circular cities, i.e., cities in which circularity is achieved by typical smart city solutions. This can also explain a perceived decline in interest in the topic, as revealed here. Indeed, instead of an actual decline, there could have been a conceptual shift for some researchers toward smart city-related research. Hence, even if closely related to circularity, those academic documents could have been omitted from the resulting dataset due to the strict nature of the Scopus query used herein. The latter development is followed by a more general re-focus on issues of sustainability at large (and not only the environmental pillar of it), including topics as broad as urban governance and urban manufacturing in the last two years of research in the field. Finally, the usage of geographic information systems (GISs) is the most recent methodological evolution of the research program, according to the analysis (Figure 4.8).

To further confirm the intuitive interpretation of trend topic analysis, a multiple correspondence analysis (a dimensionality reduction technique for nominal categorical data) was performed on the first twenty most frequent authors' keywords (again, excluding *circular city*, *circular cities*, and *circular economy* as tautological to the goal of the analyses). The number of clusters to identify was set to five. Figure 4.9 shows the bi-plot of the first two most significant dimensions resulting from MCA. Together, the two accounted for around 65% of total inertia, suggesting a high degree of correlation of themes and topics across different documents.

Two clusters are important in confirming the results of the trend topic analysis. These are 1) the most numerous (green) cluster and 2) the next according to numerosity (red) cluster. The former captures the core preoccupations of the first two years of the circular city-related research and is more centered on "classical" themes of circularity like urban circular economy, urban regeneration, and urban waste management. The latter is the result of the post-2021 "contamination" of the topic with issues and themes close to the smart city concept and the shift of the focus from strictly environmental concerns to the issues of sustainability at large (for example, *urban governance* keyword). Indeed, diminishing rates of scientific production within the "pure" circular city perspective can be explained by the rise in

popularity of smart circular city and sustainable city concepts, as can also be seen in the shorter but bibliometric evaluation in the introductory chapter of the thesis.

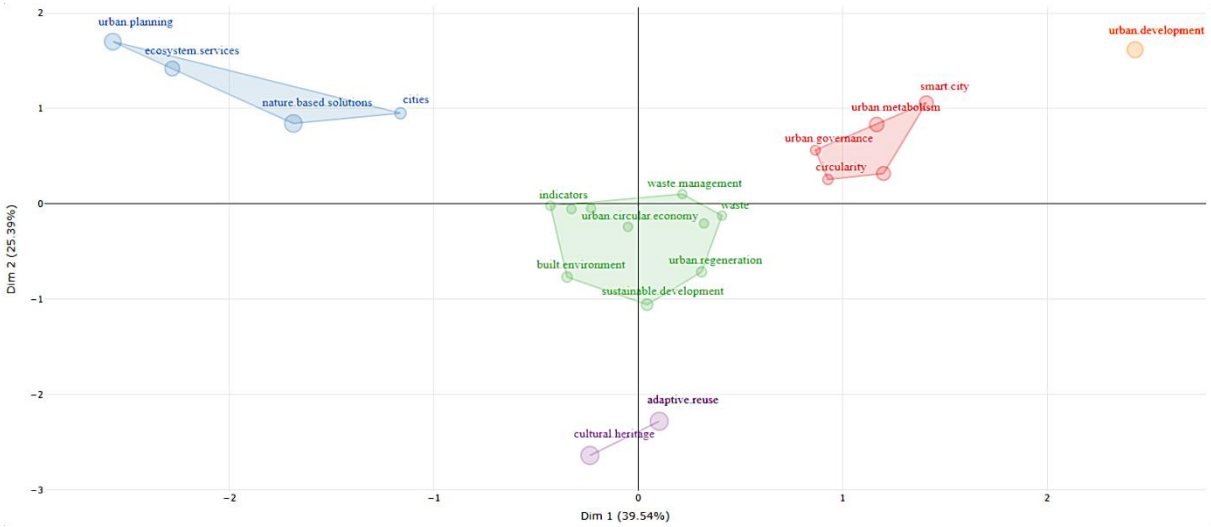


Fig. 4.9 *Multiple correspondence analysis of the first twenty most frequent keywords within circular cities research domain*

To cross-validate the results of the previous analyses, a thematic evolution analysis was performed, again using *bibliometrix* R package and the related *biblioshiny* app. As before, the keywords *circular city*, *circular cities*, and *circular economy* were excluded from the analysis to avoid the potential distortion of the results and to enhance overall presentational clarity. 250 most frequent keywords entered the analysis. The minimum cluster frequency per thousand documents was set to five, the minimum weight index was set to 0.1, and the inclusion index was weighted by word occurrences. A Louvain clustering algorithm was applied. Figure 4.10 shows the results of the analysis. In particular, 2021 was chosen as the cutoff point according to the previous considerations. In particular, it was the year when 1) the interest in the topic of circular cities started to slow down, and 2) the topic became "contaminated" with general themes of sustainability and smart cities.

Figure 4.10 shows how a set of themes has evolved across the two subperiods. The thickness of the lines is proportional to the inclusion index associated with each keyword. A thematic evolution is considered as such if the related keywords are present in both associated thematic networks (Chen et al., 2019).

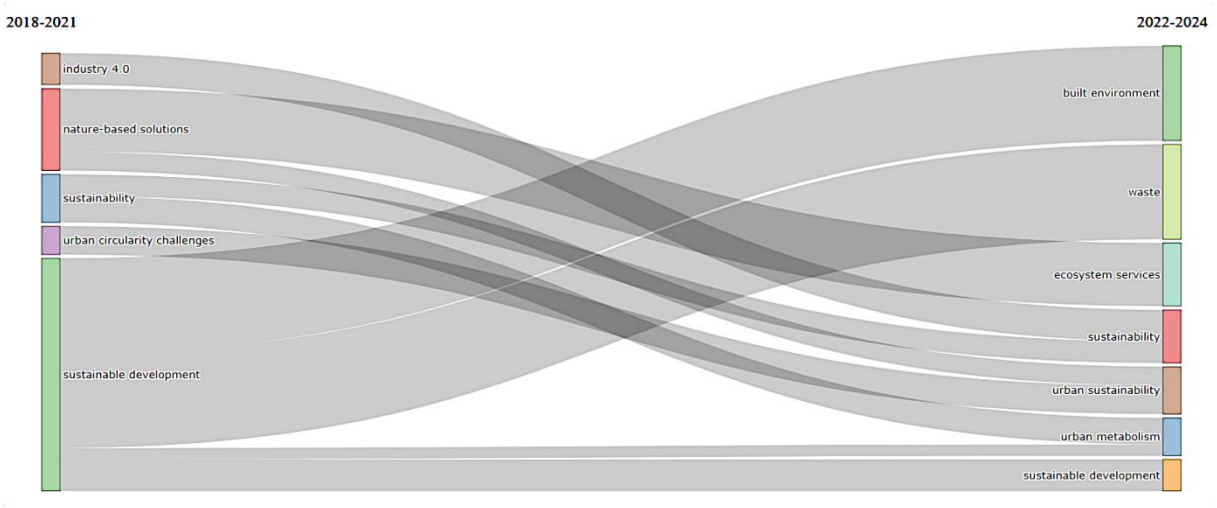


Fig. 4.10 *Thematic evolution analysis of circular cities research domain*

One thing that is noticable is a more significant heterogeneity of themes and topics in the second subperiod. In particular, a "sustainable development" theme has evolved into more nuanced topics of waste management, built environment, and urban metabolism. Another trend is the shift from topics of a more theoretical nature to topics and themes that are of proximal potential for application. This is particularly evident by observing how the more theoretical *nature-based solution* keyword has morphed into the theme of eco-system services, of more direct applicability in real-life circular city-related situations.

Finally, to ensure the most robust results, the dataset was important in the VosViewer (version 1.6.19), and a co-occurrence analysis of authors' keywords was performed. A full-counting method was applied, and the minimum number of occurrences of a keyword was set to five. Out of 1900 keywords, sixty-two met the threshold. Among those, *circular city*, *circular cities*, and *circular economy* were again excluded to avoid the distortion of the results due to their high frequency and to maintain the presentational clarity of the resulting graph. The association strength method was chosen for the normalization. Five thematic clusters were automatically identified. Figure 4.11 shows the network of authors' keyword co-occurrences both in terms of identified thematic clusters and as an overlay visualization, tracing the predominance of certain topics over the last few years. The size of the nodes represents the frequency of the respective keywords (Bruni et al., 2021). The thickness of each link represents the strength of the co-occurrence relationship between two keywords, while the distance indicates the relatedness of the links they each have (Vaishya et al., 2022).

Indeed, the results of the co-occurrence analysis confirmed the intuitive interpretations above.

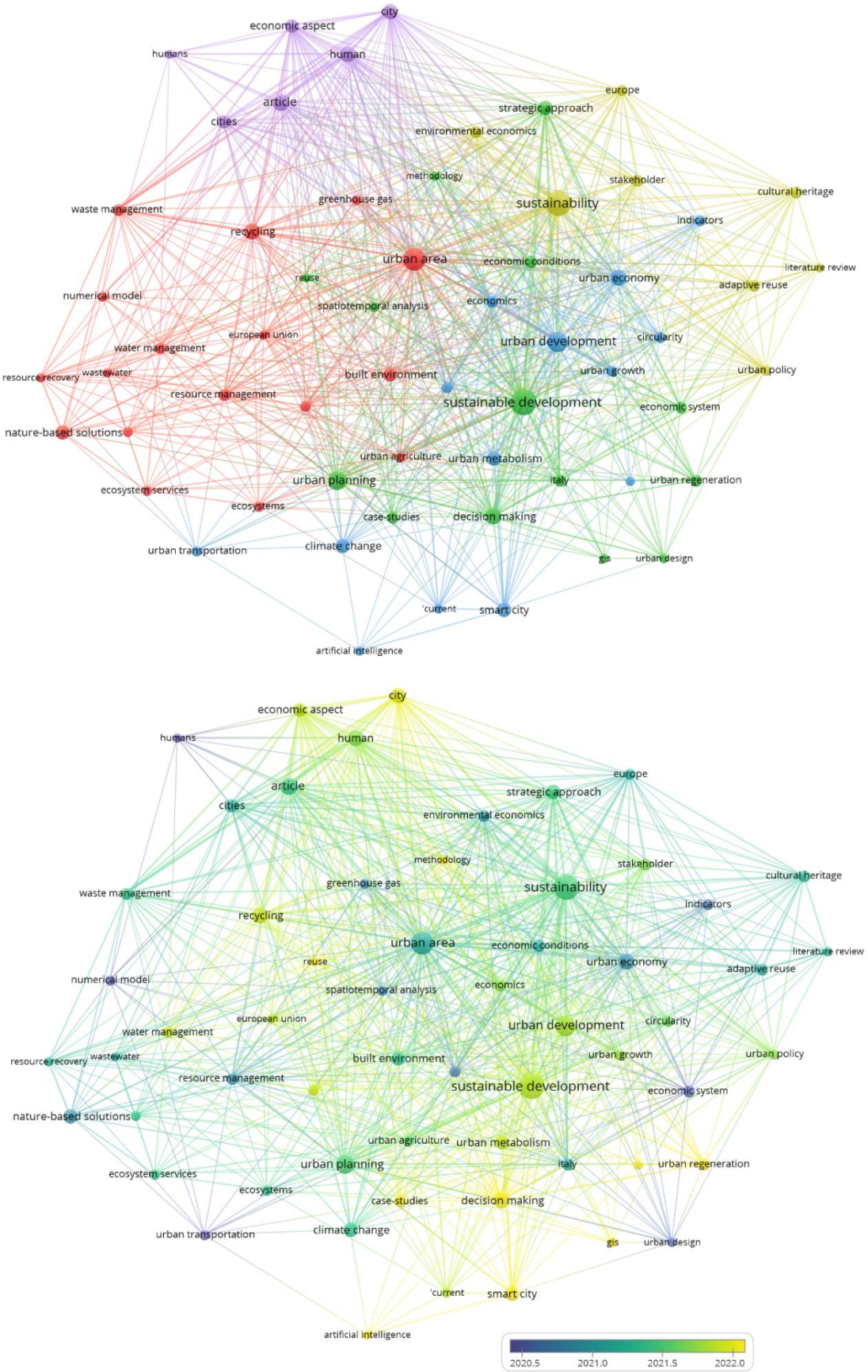


Fig. 4.11 *Keyword co-occurrence analysis of circular cities research domain*

Note: top—network visualization; bottom—overlay visualization

First, as can be seen in the overlay visualization graph, the shift toward smart cities and the related concepts is the most recent and has mostly happened after the year 2021. Accordingly, the decline in interest in the "pure" circular city concept can be explained by the shift of the attention of scholars to more nuanced concepts such as smart eco-city, smart sustainable city, and smart circular city. Second, around 2021, a shift has happened toward themes and topics that are less theoretical but more managerial in nature (see the red cluster on the top graph in Figure 4.11, including *waste management* and water *management* keywords). The vital role of EU institutions in promoting circular city research is also confirmed, as the only three geographic and institutional mentions in the graphs are the European Union, Europe, and Italy. Among other topics becoming more prominent are *recycling*, *reuse*, *decision-making*, *GIS* (geographic information systems), and *urban regeneration*. The topics falling out of flavor include more general *urban design*, *urban transportation*, *urban economy,* and *economic system*.

4.3 Study 2: Relating circularity, its components, and the components of smartness

4.3.1 Methodology

Similarly to Study 2 of Chapter 2, the subset of EU cities was selected as the starting point of analysis. Again, EU cities were chosen chiefly for several reasons. First, there is a degree of homogeneity on the supra-national level in terms of the types of circular economy and smart initiatives, usually trickling down from major EU institutions in the form of regulations, directives, decisions, recommendations, and opinions (Domenech & Bahn-Walkowiak, 2019; Gargiulo et al., 2013; Hartley et al., 2020; Paskaleva, 2011). Second, there is also a considerable degree of cultural homogeneity between the EU Member States due to the geographical proximity and cultural/historical relatedness (Akaliyski, 2017). As in the case of Study 2, Chapter 2, in which the indices of smartness and circularity were initially derived, by removing the problem of heterogeneous contexts, those were rendered neutral and comparable across the EU countries. More importantly, however, given the "developed countries" status of most of the EU Member States and the interest of major EU institutions in promoting circularity initiatives, as was shown in the bibliometric assessment of the field (Aggeri, 2020), the cities of the EU are the proximal candidates for being both smart and actively implementing circular economy initiatives.

Contrary to Study 2, Chapter 2, only the biggest EU cities were analyzed, again relying on the

data from the updated edition of the free-to-use version of the World Cities Database (*World Cities Database | Simplemaps.Com*, 2020). This was primarily done to align the results of the NCA with those performed in Study 3. Chapter 3. In particular, like in the case of Study 3, Chapter 2, the EU cities with more than one million inhabitants within the metropolitan area region were considered. In total, thirty-nine such cities were identified in this manner. For those, the micro-level indices of circularity (*Waste Management* index, *Renewable Energy* index, *Recycling* index) and smartness (*AI* index, *ICT* index, *IoT* index, *Big Data* index) were fetched from Study 2, Chapter 2. The overall macro-level *Circularity* index from the same study was also included in the new dataset. All the said indices were standardized, i.e., rendered mean-centered and with a standard deviation equal to one.

As the related methodologies applied to derive the said indices are based on the attention of the academia to the topics of city smartness and circularity, none of those are entirely immune to distortion due to the "popularity" or the opposite, "unpopularity" of certain cities compared to others when it comes to the urban circularity research. Accordingly, for some cities, the related frequencies in denominators (i.e., total results in terms of Google searches) could have inflated or deflated the respective indices in a significant manner. To overcome the negative systematic effects of those few observations, four outliers were taken out of the new dataset, denoting those cities that scored disproportionately high or low on the *Smart Circular City* index and *Smart Green City* index. These are Sofia, Paris, The Hague, and Porto. Accordingly, thirty-five cities have entered the final analyses.

The criterion for city selection is a result of a compromise. On the one hand, a larger sample size obtained, for example, by considering all the EU cities with more than 100.000 inhabitants, could have produced more robust results. On the other hand, smaller cities are more prone to create related indices that are distorted, especially while taking into account the methodology applied herein. However, as a necessary condition analysis is the main analytical tool of this section, the preoccupations related to the sample size are not overly important. Indeed, NCA also works well when the sample size is not overly large. In contrast to regression analyses that require larger sample sizes in order to obtain smaller standard errors, NCA can be performed even with a single case (i.e., N = 1, denoting the absence/presence of the condition) (Dul et al., 2021). Thus, the sample size of 35 observations was more than sufficient for the analysis' robustness.

To briefly summarize how the indices were calculated, a set of Google Scholar searches was performed for each city in the samples. All the searches were performed using the *in-title*

specifier. To begin with, only the city name was searched for every city in the sample. This resulted in a variable coded *all Google results for a city*. Then, for each city, another set of Google Scholar searches was performed with the *in-title* specifier (the name of a city paired with a specific circularity or smartness-related keyword). The selection of keywords was based on the result of the literature review of Chapter 2. as well as the result of the bibliometric evaluation earlier in the current chapter. Each keyword was chosen to identify a specific technological component of a smart city or a particular circular economy element related to the implementation of circularity initiatives in the urban context. Four keywords were used concerning a smart city domain (*Internet of Things, ICT, Big Data, Artificial Intelligence*), and three keywords for a circular economy domain (*Waste Management, Renewable Energy, Recycling*). While the second set of keywords denotes the most critical elements of the circular economy (Korhonen et al., 2018; Moraga et al., 2019), the first set of keywords identifies technologies that are typically most frequently implemented in conventional smart cities (Lopez-Quiles & Rodriguez Bolivar, 2018). The number of Google Scholar results for each of those searches was coded as *all 'keyword' Google results for a city* variable, where *'keyword'* is a specific keyword among the seven mentioned above. To determine indices that measure a city's performance in the core aspects of smartness and circular economy, for each of the 35 EU cities in the sample, the following set of formulas was applied:

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

This resulted in a set of seven micro-level indices, four for a smart city domain (*Internet of Things* index, *ICT* index, *Big Data* index, *Artificial Intelligence* index) and three for the circular city domain (*Waste Management* index, *Renewable Energy* index, *Recycling* index) measuring how well a particular EU city is doing in the related aspects of smartness and circular economy. Another micro-level index was calculated using the same methodology, by means of the *Circular Economy* keyword. This was done to capture all the results that could not be identified using the three more specific circular economy-related keywords as reported above.

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

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

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

The obtained indices operationalize overall circularity (*Circularity* index) and its constituent components (*Waste Management* index, *Renewable Energy* index, *Recycling* index), as well as constituent components of a conventional smart city (*Internet of Things* index, *ICT* index, *Big Data* index, *Artificial Intelligence* index), for each specific city in the sample. Again, as in the previous case, the biggest concern here is how closely an operational definition matches the reality. Those concerns and the related justifications are discussed in detail in the parallel sub-section of Study 2, Chapter 2.

Like in the previous cases (Study 1 and Study 2, Chapter 2), both macro-level and micro-level indices obtained through the aforementioned means have the advantage of being relative and expressed by pure numbers, making the comparison between different EU cities in the sample possible while simultaneously transcending the issue of heterogeneous units of measurement. By definition, the indices vary between zero and one. Zero denotes an EU city that has generated no academic literature related to circularity and smartness with its name in academic documents' titles (which operationally defines the lowest possible score in the city's smartness/circularity). One represents a case in which all the scholarly literature on the city relates to either a smart city and its components or a circular economy and its components.

The goal of the current study is to test which micro-components of smartness and circularity are, strictly speaking, necessary for a circular city to emerge. For this exploratory goal, a necessary condition analysis (NCA) (Dul, 2016) methodology was applied to the obtained micro-level indices of smartness (*AI* index, *ICT* index, *IoT* index, *Big Data* index) and circularity (*Waste Management* index, *Renewable Energy* index, *Recycling* index), relating them to a macro-level index capturing the overall urban circularity or, better, a degree to which an EU city is a circular city (*Circularity* index).

According to the author of the methodology, while "the hypotheses in organizational sciences frequently imply sufficiency" pertinent to "X causes Y" logic (i.e., as in the linear regression case), the hypotheses of necessity, i.e., "No Y without X," are "rarely formulated and tested in organizational sciences" (Dul, 2016, 2019). Conventional methods, such as ordinary least square regression, estimate the relationships in terms of averages (Dul, 2016). In this regard, NCA emphasized the necessity of having a certain level of independent variable to obtain a certain level of dependent variable (Hauff et al., 2021). Instead of considering the regression

line, NCA builds the so-called "envelope," or ceiling line separating the two areas in a bi-plot: the area with observation and the area without observation. The size of empty space above the ceiling line in relation to the total space of the bi-plot represents the degree of "necessity" or "criticality" of the independent variable with respect to the dependent variable (Dul, 2016, 2019). Hence, the larger the empty space, the larger the constraints that the independent variable puts on the dependent variable (Dul et al., 2019). The dedicated R package provided all the necessary tools for the evaluations, including effect sizes and significance testing (Dul et al., 2021).

Lastly, when it comes to descriptive statistics of the sample, those are already reported in Study 3, Chapter 2, as the set of the EU cities analyzed here coincides with those analyzed in the aforementioned study.

4.3.2 Analyses and results

To perform the necessary condition analysis, the dataset was imported into RStudio, and the *NCA* package was used. The *Circularity* index entered the analysis as the independent variable, while the seven micro-level indices of smartness and circularity were treated as dependent variables (i.e., the potential necessary conditions). Standardized versions of indices were used (hence, they were mean-centered, and the variance was set to one).

NCA results revolve primarily around the so-called ceiling line on the top of the data points within a bivariate scatter plot. The more there is empty space above the ceiling line (i.e., the upper left corner), the higher levels of the dependent variable are not possible with lower levels of the independent variable (or the condition) (Dul et al., 2021). NCA typically produces two ceiling lines: the so-called ceiling envelopment with a free disposal hull (CE-FDH) and ceiling regression with a free disposal hull (CR-FDH).

According to the guidelines of the methodology, the so-called CE-FDHs (red functions in Figure 4.12) are suitable ceiling envelopes when the two variables are discreet (Dul, 2024). Instead, when the two variables are continuous, CR-FDHs (yellow functions in Figure X) are the appropriate ceiling line. The green functions in Figure 4.12 are the estimated regression line. Hence, as the data in the dataset are continuous, only ceiling regression lines are of interest here (CR-FDHs).

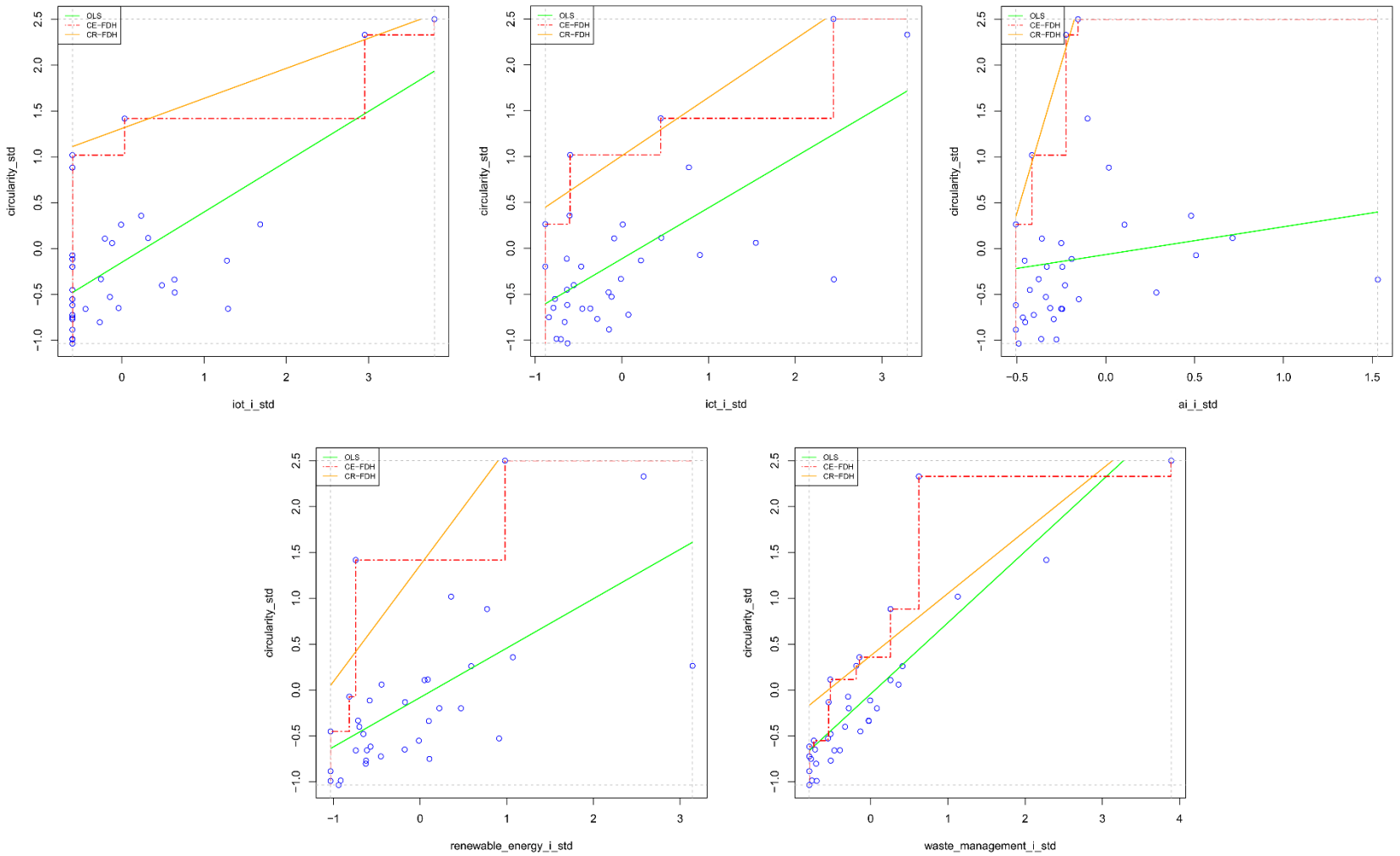


Fig. 4.12 *Relating circularity and smartness. NCA results. Scatter plots with ceiling lines for conditions that are necessary*

The bottleneck table (Table 4.2) relates the necessary levels of conditions to the different levels of urban circularity. In particular, the numbers in the table denote the percentages. 100 percent of circularity denotes the EU city in the sample scoring the highest on the related *Circularity* index. *NN* means that, at the given level of urban circularity, the related condition is not necessary. The columns in the table are ordered in terms of how quickly the related conditions become critical. For example, the *Waste Management* condition turned out to be the most critical early on for initial increases in urban circularity. For instance, according to the bottleneck table, to pass from 0% of the *Circularity* index to 30% of the *Circularity* index, a 6% of the *Waste Management* index is necessary. However, to go from a 0% to 40% increase in urban circularity, waste management initiatives are not enough, as both a 6% of the *Renewable Energy* index and 0.2% of the *AI* index are needed alongside the 17.1% of the *Waste Management* index (an 11.1% increase from the previous step).

Circularity (%)	**Big data (%)**	**Recycling (%)**	**IoT (%)**	**ICT (%)**	**AI (%)**	**Renewable energy (%)**	**Waste management (%)**
0	NN	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN	6.0
40	NN	NN	NN	NN	0.2	6.2	17.1
50	NN	NN	NN	10.7	2.9	12.9	28.2
60	NN	NN	NN	24.1	5.6	19.6	39.3
70	NN	NN	22.7	37.4	8.2	26.2	50.4
80	NN	NN	47.2	50.7	10.9	32.9	61.5
90	NN	NN	71.7	64.0	13.5	39.6	72.6
100	NN	NN	96.2	77.3	16.2	46.3	83.7

Table 4.2 *Relating circularity and smartness. NCA bottlenecks for different conditions*

Note: smart city components are in blue; circular city components are in green

Interestingly, IoT-related initiatives appear to be the most critical, but only at the already high percentages of the *Circularity* index. Indeed, to achieve a 70% initial increase in urban

circularity, 22.7% of the IoT index is required. At the same time, it is not necessary for the previous increases. Moreover, the IoT becomes increasingly relevant very quickly, suggesting that further improvement in urban circularity is not possible without heavy investment in the IoT infrastructure and components.

Two of the conditions turned out to be not necessary for any level of urban circularity. These are *Big Data* (a smart city component) and, surprisingly, *Recycling* (a circular city component). Hence, while those might as well be sufficient, they are not strictly necessary for a circular city to emerge. This is, indeed, the case of the *Recycling* index, which highly correlates with the *Circularity* index (see Figure 4.13), implying the so-called sufficiency logic between the two (Dul, 2016, 2019). However, regardless of the positive correlation (0.57), high values of the *Circularity* index are also present when the *Recycling* index is low. On the contrary, the *Big Data* index does not significantly correlate with urban circularity. Hence, big data implementations are neither necessary nor sufficient for the emergence of a circular city.

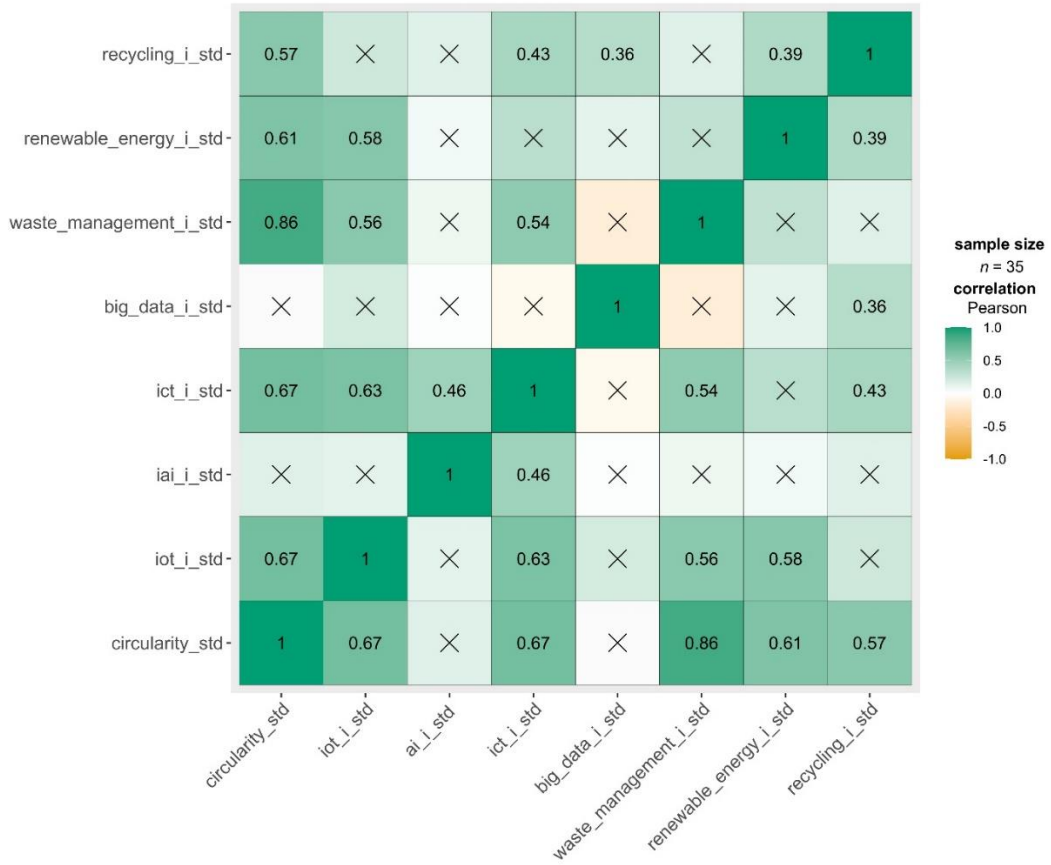


Fig. 4.13 *Relating circularity and smartness. Correlation matrix of analyzed indices*

Note: X = not significant at p-value < 0.05

Dul et al. (2021) suggest two criteria for the interpretation of the validity of the results of NCA. First and foremost, central to the interpretation of NCA results is a *d-statistic* (representing an effect size ranging from zero to one). The statistic is obtained by comparing the empty ceiling space to the overall area of the bi-plot. According to Dul (2024), the following evaluative criteria are applied: $0 < d < 0.1$ small effect; $0.1 < d < 0.3$ medum effect; $0.3 < d < 0{,}5$ large effect; 0.5 very large effect. Additionally, the p-value based on the permutation test (by bootstrapping) should be smaller than 0.05 to ensure that the *d-statistic* is not a result of mere randomness. Hence, to check the statistical significance of the results, a bootstrapping was performed by extracting 500 subsamples and building the distribution of effect samples under the assumption that the independent variable is not a necessary condition for the dependent variable (i.e., $d = 0$).

Additionaly, in case a ceiling line is considered instead of the ceiling envelopment, the accuracy of the analysis (*c-accuracy*) should be taken into account. The accuracy is calculated as the number of observations above the ceiling line divided by the number of all observations (and then multiplied by 100%). According to the methodology, 95% or more is good accuracy, while everything lower but above 80% is also acceptable (Dul et al., 2021).

Condition	Method	c-accuracy	Effect size (d)	p-value
Big data	CR-FDH	100%	0.000	1.000
Recycling	CR-FDH	100%	0.000	1.000
IoT	CR-FDH	94.3%	0.189	0.004*
ICT	CR-FDH	94.3%	0.225	0.012*
AI	CR-FDH	94.3%	0.049	0.244
Renewable energy	CR-FDH	97.1%	0.160	0.044*
Waste management	CR-FDH	85.7%	0.316	0.002*

Table 4.3 *Relating circularity and smartness. NCA significance checks. Asteriscs denote significant necessary conditions*

Note: smart city components are in blue; circular city components are in green

The related significance checks are reported in Table 4.3. According to the results of the bootstrapping, Only *IoT*, *ICT*, *Renewable Energy*, and *Waste Management* are highly important critical factors for the emergence of circular cities (in the EU). According to the

bottleneck table (Table 4.2) between the two significant smartness components, the presence of a more general ICT infrastructure becomes critical sooner, but its role slows down as city becomes becomes more "circular." On the contrary, for higher levels of circularity, IoT becomes increasingly essential.

4.4 A semi-systematic literature review and thematic synthesis of urban quantum technologies

Currently, quantum technologies are still primarily prototypes. Hence, the only viable way of relating them to a notion of circularity is to look at the potential contribution of quantum technologies to conventional smart city devices and then determine what conventional smart city devices could contribute to the emergence of a smart circular city.

As discussed in the previous chapter, the notions and concepts of twentieth-century urban theory are no longer suitable to deal with modern cities' growing complexity and uncertainty (Arida, 2002; Joss et al., 2022; Macionis & Parrillo, 2010). While grand and, sometimes, utopian narratives of the past lose their explanatory power, novel urban conceptualizations are increasingly pertinent (Lynch, 1990). The emerging need for novel urban theorizing is due to the complex interplay of emerging social, economic, demographic, and technological factors (Anthopoulos, 2017). As for the latter, two categories of technology-driven urban changes can be distinguished when it comes to urban-related narratives, discourses, concepts, and themes. Firstly, a shift toward smart cities is underway, and, in particular, a sustainable smart city paradigm seems to dominate the emerging discourses (Bifulco et al., 2016). In this regard, an argument can be advanced for the importance of investing in the development and use of conventional smart technologies for the sake of further urban economic and social appeal. Indeed, cities' growth can be governed more effectively through advanced technological means (Bibri, 2018). In addition, when it comes to sustainability, technologies such as artificial intelligence, the Internet of Things, blockchain, and big data are often considered crucial (Bifulco et al., 2016; Gouvea et al., 2018; Quan et al., 2019). Secondly, the concerns with the growing complexity of future smart cities and the recent developments in the field of quantum technologies (QTs) make the adoption of those technologies in future smart cities more appealing. The latter development also gives rise to a quantum city metaphor, a particular type of smart city in which conventional smart city technologies coexist and synergize with novel quantum urban technologies.

The quantum urban paradigm is a fertile metaphorical foundation for theorizing solutions to increasingly complex urban-related problems. As described in detail in Chapter 3, its theoretical conceptualization relies on major quantum physics principles, chiefly uncertainty, duality, and entanglement, to address the problems of urban complexity and uncertainty more effectively (Arida, 2002). When it comes to the substantive and practical core of the quantum city conceptualization, it can be envisioned as a type of smart city in which quantum technologies are used in conjunction with the so-called conventional smart city technologies, potentially offering greater accuracy, computational power, speed, and efficiency to future smart city solutions. In this regard, the implementation of the first prototypical quantum cities, like Hefei in China (Courtland, 2016), serves as a proof-of-the-concept example of how a smart city of the future can be.

Due to the emerging nature of technology, the detailed taxonomization of quantum devices is rare in the literature. Among the few existing, one of the most detailed and comprehensive is the taxonomy proposed by (Acin et al., 2018). As specified in the previous chapter, the authors distinguish four classes of quantum technologies (Acin et al., 2018):

- quantum communication, in which entangled particles (typically photons) are exploited to send and receive data in a demonstrably safe manner;
- quantum simulation, in which well-controlled quantum systems replicate the conduct of other, less precise quantum systems;
- quantum computation, which uses the concepts of quantum physics to accelerate complex calculations significantly;
- quantum sensing and metrology, in which higher sensitivity of quantum systems to outside disturbances is used to increase the quality of measurements of certain physical quantities.

A structured semi-systematic literature search was performed to understand which types of quantum technologies are of proximal applicability in urban contexts. As stated in Chapter 3, five separate searches on Scopus were carried out based on the above taxonomy of quantum cities (Acin et al., 2018) (*quantum communication, quantum simulation, quantum computation*, *quantum sensing*, and *quantum metrology*). The *in-title* modifier was used to restrict the results to articles closely related to the topic of interest. The results of the query were also restricted to the domains of "Social Sciences," "Business, Management and Accounting," "Decision Sciences," and "Economics, Econometrics, and Finance." This was primarily done in order to exclude literature that was not pertinent to the urban domain topics.

Additionally, no restrictions on the types of scholarly documents were put in place, allowing for insightful "gray" literature to be included in the assessment. No forward or backward searches were conducted. Therefore, to ensure that all the fundamental articles on the topic within the specified domains were included, a complementary set of searches was performed on Google Scholar according to the suggestions of Gusenbauer and Haddaway (2020). In total, 196 scholarly documents were initially identified.

The Preferred Reporting Items for Systematic Review (PRISMA 2020) flow diagram was closely followed to identify, screen, and include articles in order to ensure a higher degree of replicability (see Figure 3.5, Chapter 3) (Brennan & Munn, 2021; Liberati et al., 2009; Page et al., 2021). After assessing the abstracts of the identified initial documents concerning their relatedness to the topic, eighty articles were included in the final review.

The final set of articles was imported into MAXQDA and the related qualitative open coding was then performed. As a result, two categories of quantum technologies emerged as the only ones from the initial taxonomy of Acin et al. (2018) connected to the urban-centered scholarly domains: quantum computing (QC) and quantum communication (QCM). Conversely, quantum simulation, sensing, and metrology (Acin et al., 2018) did not emerge as separate code categories. Nonetheless, the primary goal of this section was not to assess the totality of scholarly literature on the topic but to determine which quantum technologies are the most relevant in urban contexts. It is not excluded, therefore, that some important scholarly documents have been excluded from the analyses. However, those included in the review were considered sufficient to achieve theoretical saturation, as the two relevant types of quantum technologies (quantum communication and quantum computing) emerged early on and no additional upper-level codes were created (Low, 2019). Table 1 reports the result of thematic synthesis of the lower-level categories denoting main themes and topics that have emerged in the process of coding of the papers (for a more in-depths semantic analysis and a more detailed systematic literature review, see the related section of Chapter 3).

Upper-level codes	**Lower-level codes**	**Main themes and topics**	**Contributions**
Quantum communication	Quantum-based information exchange	The secure transfer of quantum information between distant urban communication nodes by means of qubits is the basis of quantum communication in cities.	(J. Liu et al., 2022; Sauge et al., 2007)
	Quantum teleportation	Quantum teleportation is an important feature of quantum communication. It is a technique that could potentially allow the transport of an arbitrary quantum state across a city from one communication node to another communication node without using physical means to carry the state. The latter is not achievable with conventional communication technologies.	(Aspelmeyer et al., 2005; Chehimi & Saad, 2021; Lele, 2021)
	Quantum communication networks	High-performance long-distance quantum channels are an essential part of quantum communication with a potential for applicability in future cities. Quantum communication networks in cities are characterized by their ability to connect heterogeneous conventional smart city implementations in a reliable, modular way. Consequently, the efficient implementation of urban quantum communication can benefit a wide range of smart city solutions, including weather forecasting, blockchain, 6G networks, IoT, financial modeling, traffic optimization, weather forecasting, artificial intelligence, and others.	(Al-Mohammed & Yaacoub, 2021; Aspelmeyer et al., 2005; Carvacho et al., 2021; Chehimi & Saad, 2021; Chou et al., 2014; Lele, 2021; Nema & Nene, 2020; Resch et al., 2005)

	Quantum Internet	Quantum Internet technology allows information to be exchanged between smart city stations, hubs, and sensors almost simultaneously. The security and efficiency of the smart city ICT infrastructure can be significantly improved by such technology. Nonetheless, to sustain the robustness and the capacity of Quantum Internet communication channels, a city-wide distribution of physical entanglement is necessary. Therefore, in order to deploy the first workable Quantum Internet solutions, city managers, administrators, and planners should be prepared to improve and significantly invest in the present-day communication infrastructures.	(Lele, 2021)
	Quantum communication security	Security is one of the most prominent issues in urban quantum communication. Information security is now a top priority for planners, administrators, and managers of smart cities. Conversely, existing cryptosystems can be hacked by fully functional quantum computers. Because of this, conventional communication protocols might no longer be secure, which motivates scientists to search for more secure cryptographic systems.	(Lele, 2021; Malluh et al., 2014; Monz et al., 2016; Tsai et al., 2005; Wei & Zhang, 2019)

	Post-quantum cryptography	Post-quantum cryptography, sometimes referred to as quantum-safe, quantum-proof, or quantum-resistant encryption, is the denomination given to public-key cryptography techniques that are protected from quantum computer attacks. The goal of post-quantum cryptography is to enhance present standards and algorithms in order to get systems ready for the quantum vulnerability age. When applied in an urban setting, an effective post-quantum cryptography system should be able to survive attacks by quantum computers on the infrastructure of the city while protecting communication-related attributes like confidentiality, identifiability, variability, and unforgeability.	(Aspelmeyer et al., 2005; Bennett & Brassard, 1985; Chou et al., 2014; Malluh et al., 2014; Piacentini et al., 2015; Tsai et al., 2005; X. Zhang et al., 2015)
Quantum computing	Technological discontinuity	Due to its reliance on fundamental concepts from quantum physics, like quantum superposition and entanglement, quantum computing transcends traditional von Neumann architecture. The social, industrial, academic, and economic landscapes of cities could be drastically altered by the introduction of quantum computers, a potential key enabler of forthcoming technological discontinuity.	(Elhaddad & Mohammed, 2016; Inglesant et al., 2021; Meng, 2020; Salehi et al., 2022; Taha, 2016; Ten Holter et al., 2023; Trabesinger, 2017; Uhlig et al., 2019)
	Qubit	Bits, as fundamental carriers of digital information, can assume the values of either 1 (true) or 0 (false) and are stored one at a time. As such, conventional computers rely on principles of Boolean algebra for computational and related purposes. On the other hand, quantum bits, or qubits, are principal carriers of information in quantum computers. Unlike conventional bits, a single qubit can represent a zero, a one, or a mixed state that is a zero and a one. Stated differently, a quantum computer's functioning relies on probabilities rather than a given certainty.	(Amiri, 2003; Cuffaro, 2018; Elhaddad & Mohammed, 2016; Sotelo, 2019; You et al., 2009)

	Replacement vs synergy	The primary benefit of quantum computers is their ability to tackle computationally complex issues that would otherwise require an exponentially growing amount of time, money, and effort to solve on a conventional computer. This does not mean that quantum architectures will necessarily replace conventional computing. On the contrary, quantum computers can work in tandem with conventional computers, complementing them in a variety of city-related computations.	(DeBenedictis, 2020; Mosteanu & Faccia, 2021; Raisinghani, 2001; Yetis & Karakoes, 2021)
	Artificial intelligence	One of the fields where the synergistic effect of quantum computing will be most evident and important is artificial intelligence. Firstly, two of AI's most important contributions to quantum computing are the automation of computer systems and the minimization of human intervention. Secondly, quantum algorithms have the potential to greatly enhance unsupervised machine learning.	(Bhatia et al., 2020; Palmieri et al., 2020; Torlai et al., 2018)
	Use cases and inequality	5G and 6G communications, cryptography, power grid management, simulation and modeling, weather forecasting, artificial intelligence, big data, education, law, the aircraft industry, smart factory optimization, blockchain, drug discovery, database search improvement, banking, finance and business, market prediction, disease prediction, strategic management, the military, IoT, and art are fields that could all benefit from the integration with quantum computing in cities. Inter-regional inequality may rise as a result of the integration of quantum computers into urban infrastructure since some regions lack the knowledge or money to purchase cutting-edge technology. The only sustainable approaches to make sure that the advantages of quantum computing outweigh its detrimental effects on	(Aderman, 2019; Ahad et al., 2020, 2020; Alaminos et al., 2022; Atik & Jeutner, 2021; Chambers-Jones, 2021; de Wolf, 2017; Gutierrez-Salcedo et al., 2018; Heaney, 2019; Inglesant et al., 2021; Kumar Sharma & Ghunawat, 2019; Majot & Yampolskiy, 2015; Sazonova & Krendelev, 2018; Shubham et al., 2019; Singh &

		cities are transparency and accessibility. Therefore, public campaigns and initiatives should make relevant scientific knowledge available, and quantum computing capabilities need to become accessible through the cloud.	Ordoñez, 2016; Singh & Singh, 2016; Swarna et al., 2021; Uhlig et al., 2019; Weder et al., 2020)
	Quantum future	Broadly, three perspectives on the future in which quantum computing is ubiquitous may be distinguished. The first emphasizes that a new computing era is about to begin, with far-reaching effects on every facet of urban life. Conversely, according to the second, we should steer clear of futuristic conjectures and instead concentrate on figuring out the immediate practical applications of quantum computing. The third one presents a more gloomy picture of "quantum supremacy," focusing on the drawbacks and negative consequences due to a quantum computer's apparent advantage over conventional computing.	(Elhaddad & Mohammed, 2016; Gutierrez-Salcedo et al., 2018; Inglesant et al., 2021; Paraoanu, 2011)
	Quantum security	The possibility that a quantum computer will "break the internet" and render current data encryption techniques unsecure is one of the biggest concerns QC presents, according to the researchers. As a result, a significant rise in cryptographic vulnerabilities has the potential to compromise the security of banking and other vital public services in cities. Regulations that promote the safe use of quantum computers in future cities are, therefore, necessary.	(Covers & Doeland, 2020; Inglesant et al., 2021; Majot & Yampolskiy, 2015; Sotelo, 2019; F. Zhang, 2020)

Table 4.4 *Urban-related quantum communication and quantum computing. A thematic synthesis*

4.5 Study 3: Relating conventional smart city technologies and quantum technologies by means of semantic evaluation through SEM

4.5.1 Methodology

In this section, the connection between conventional smart city technologies and urban-related quantum technologies is explored. However, it is appropriate to specify that the existing relationship between the two would be impossible to currently assess, as 1) real-life smart cities are still not that many (Yigitcanlar et al., 2019), and 2) quantum technologies are still largely theoretical possibilities far from being commercialized at the industrial-scale levels (Cuffaro, 2018). Accordingly, given the state of technological readability of quantum technologies, only the theoretical possibility of emerging relationships between QTs and conventional smart city technologies can be adequately verified. Again, like in the case of a similar section in Chapter 3, it is achieved here by looking at the semantic relatedness (Kasneci et al., 2023; Y. Liu et al., 2023) between the literature on urban quantum technologies in social sciences (eighty documents) and heterogeneous facets of conventional smart city technologies identified through means of a scoping review performed in Study 2, Chapter 3.

The potential for the relationship between conventional smart city technologies and quantum technologies is assessed here by analyzing the connections between the semantic categories in the eighty identified scholarly documents on urban quantum technologies in the social sciences domain. The keywords denoting different aspects of quantum communication and quantum computing (the only two quantum technologies deemed relevant in urban contexts) were derived as a part of the thematic synthesis of the previous section by analyzing the related lower-level coding categories derived in the iterative inductive manner (see Table 4.4) (Chandra & Shang, 2019).

For the purpose of this study, the automated qualitative assessment was performed in MAXQDA (release 22.0.1). In particular, for all the documents, the unigrams, bigrams, and trigrams (i.e., keywords and their combinations) denoting the seven categories of smart city technologies (*artificial intelligence* (*AI*), *Internet of Things* (*IoT*), *information and communication technologies* (*ICTs*), *big data*, *blockchain*, *cloud computing*, *smart transportation technologies*), twelve quantum communication-related keywords (*key, network, security, communication, alice, cryptography, quantum communication, bob, quantum cryptography, optical, message, encryption*), and nine quantum computing-related keywords (*computer, compute, qubit, quantum computing, quantum computer, entanglement,*

computation, superposition, computational) were counted (see Figure 3.12 of Chapter 2). The numbers in Figure 3.12 indicate the absolute frequencies of the keywords and their combinations across eighty articles. In all cases, the lemmatized variations of semantic tokens were considered (e.g., "ai" and "artificial intelligence," "computer" and "computers" were treated as the same semantic token).

As a last step, structural equation modeling (SEM) was used to understand how conventional smart city technologies, quantum computing, and quantum communication are semantically related within the urban quantum technologies-centered literature. While it is uncommon to use the framework of structural equation modeling for exploratory purposes, partial least squares structural equation modeling (PLS-SEM) has been considered appropriate when the research goals are exploratory or, more in general, when identifying key "drivers" of constructs is a primary goal (J. Hair et al., 2017; J. F. Hair et al., 2011). In particular, PLS-SEM was preferred to the more conventional covariance-based SEM (CB-SEM) because it is typically regarded as less strict when it comes to the assumptions on the underlying data distribution and is often considered superior to other SEM techniques when the sample size is relatively small (Ravand & Baghaei, 2016) (like the eighty observations in the given case).

The frequency of twenty-eight keywords and keyword combinations related to quantum computing, quantum communication, and conventional smart city implementations were treated as observed variables. These were used to define three latent variables (SCTs, QC, and QCM, respectively, representing conventional smart city technologies, quantum computing, and quantum communications). Contrary to the analyses in Study 3, Chapter 3, the twenty-eight variables were not treated as relative frequencies but instead as occurrences. Consequently, they were coded as "0" or "1," depending on whether the related keywords and their combinations were present in the analyzed scholarly documents. While some variability of the phenomenon could have been lost in the process of categorization of variables, the discretization was crucial as it allowed for better results' interpretability. Moreover, according to (Kupek, 2006), the usage of binary variables within the SEM framework is legitimate as the classification performance is broadly similar to that of logistic regression.

4.5.2 Analyses and results

Two separate models were analyzed. Both were run using the path weighting scheme, with the maximum number of iterations set to equal 300. First, the relevance of quantum

communication and quantum computing topics for conventional smart city technologies was examined (Figure 4.14). Then, by reversing the logic, the relevance of seven categories of conventional smart city technologies within the retrieved quantum communication and quantum computing literature was explored (Figure 4.15). In both cases, the reflective measurement model was assumed. Accordingly, a consistent PLS algorithm (PLSc-SEM) was used instead of the conventional PLS-SEM (that assumes a formative model) in order to correct reflective constructs' correlations (Dijkstra, 2010).

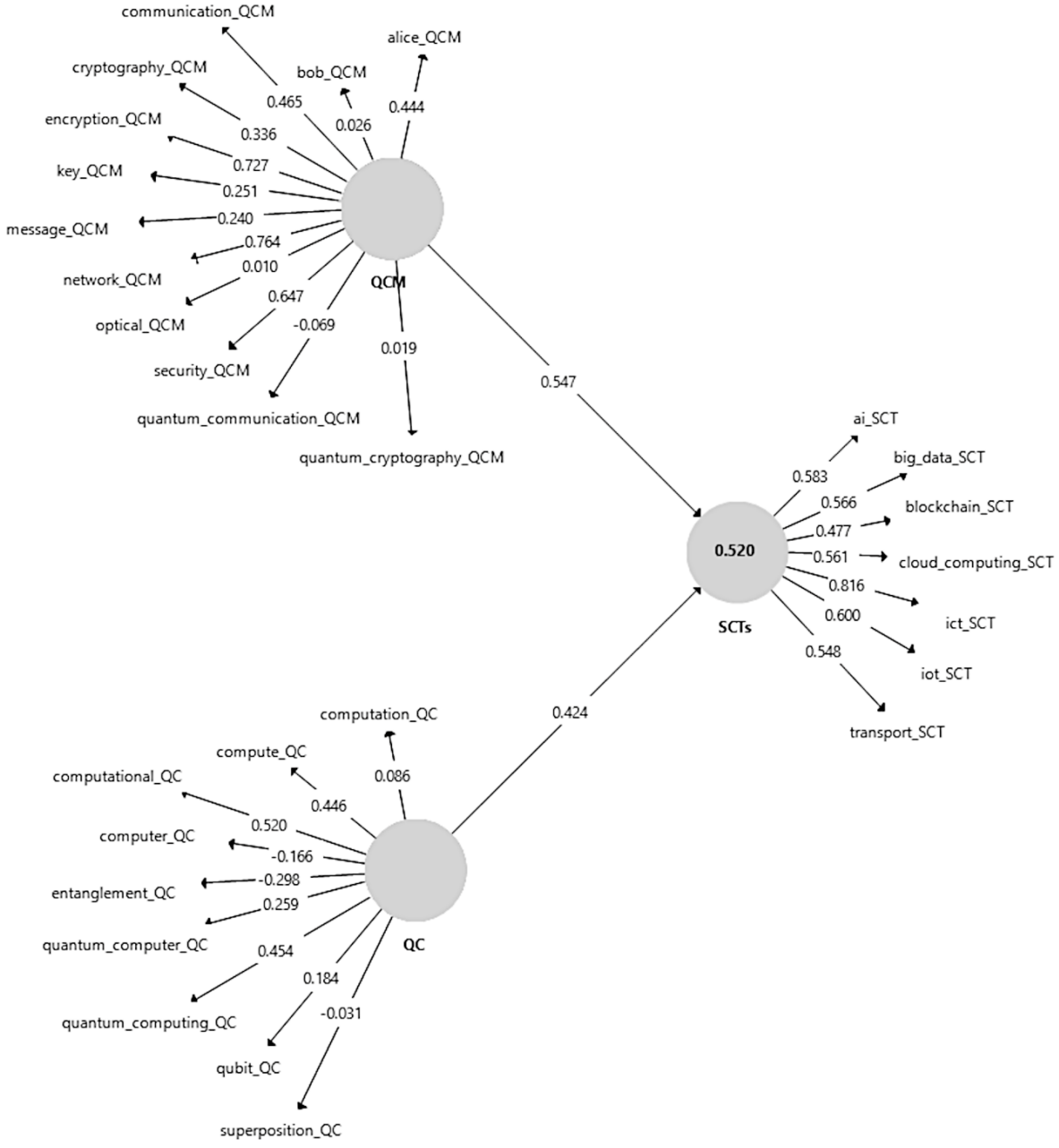


Fig. 4.14 *Relating smart cities and quantum technologies. PLSc-SEM. Model 1*

According to the resulting path coefficients of Model 1 (Figure 4.14), quantum communication is more strongly connected to smart city-related topics than quantum computing (path coefficients 0.547 and 0.424, respectively). Concerning construct reliability and validity, the three latent variables turned out to be well-defined, with most outer weights exceeding or close to the often-used cutoff value of 0.7. Nevertheless, several outer weights negatively correlated with QCM and QC latent variables. However, as the purpose of the study was primarily exploratory, those were kept in the model for more detailed analytical insight.

Bootstrapping significance testing revealed that both path coefficients are statistically not significant at the 0.05 level. The model's fit was also not great, as the standardized root mean square residual (equal to 0.173) exceeded the suggested threshold value of 0.1 (Hu & Bentler, 1999). Nevertheless, as the resulting model is not meant for confirmatory purposes, it can still be considered informative. Conversely, the interpretation of fit statistics for the PLS-PM framework requires precaution, as these are still in the early development stages (J. Hair et al., 2017). Moreover, the fit was substantially better when the formative model was estimated instead of the reflective one (standardized root mean square residual equal to 0.107).

Model 2 looked at the relationships between individual smart city technologies and the QC and QCM latent variables (Figure 4.15). As in the case of Model 1, the quantum communication turned out to be semantically more related to conventional smart city technologies than quantum computing (R squared = 0.303 for QCM compared to R squared = 0.182 for QC).

As for individual conventional smart city implementations (defined directly by the observed variables), ICT has the strongest semantic relationship with quantum communication topics (path coefficient = 0.584, the only statistically significant after bootstrapping at the significance level = 0.05). Conversely, the conventional smart city technology topic related the most to quantum computing is smart transportation (path coefficient = 0.366), followed by AI (path coefficient = 0.195) and big data (path coefficient = 0.167). The fit of Model 2 was higher than that of Model 1 (standardized root mean square residual equal to 0.140). As in the case of Model 1, not all outer weights for QCM and QC latent variables exceeded the cutoff value of 0.7.

To recapitulate, quantum communication is currently the most researched topic when it comes to the adoption of quantum technologies in smart cities (Figure 4.14). Concerning the singular component of conventional city smartness, ICT is the type of conventional smart city

implementation for which quantum communication is the most relevant (Figure 4.15). Conversely, the semantic (and, hence, thematic) connections between quantum communication and the remaining types of conventional smart city implementations are significantly weaker (in accordance with Model 2). The role of quantum computing is more heterogeneous, as it is important for several conventional smart city technologies (AI, big data, blockchain, and smart transportation). However, its overall relevance with regard to smart cities within the assessed literature is lower than that of quantum communication (in accordance with Model 1).

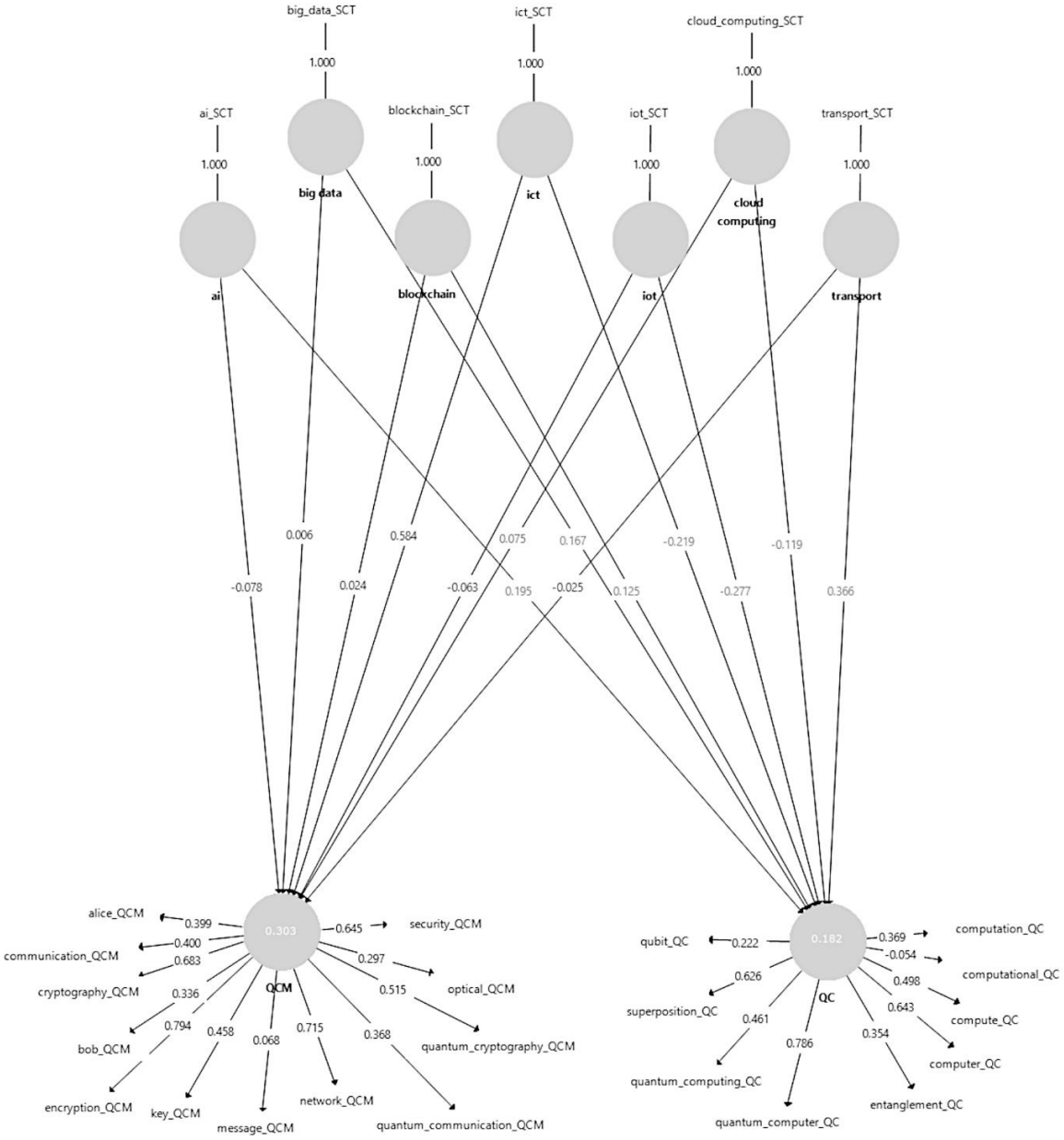


Fig. 4.15 *Relating smart cities and quantum technologies. PLSc-SEM. Model 2*

4.6 Discussion, implications, and conclusions: the integrative framework and final considerations

4.6.1 Discussion of the empirical findings of Chapter 4

Regardless of the conclusive and integrative nature of the chapter, the novel empirical evidence of the connection between smart cities, circularity, and quantum cities has also been provided here. Hence, before proceeding with the overall considerations related to the work in its entirety (see Chapter 5), a discussion on the empirical results of Chapter 4 is first presented.

To begin with, the necessary condition analysis in Study 3 revealed critical factors for the emergence of a circular city. In particular, two components related to circular initiatives and processes were deemed necessary: renewable energy and waste management. Surpassingly, the recycling component has not been deemed necessary, regardless of the high correlation between the *Recycling* index and the *Circularity* index as derived in Study 2, Chapter 2. Accordingly, the high values of the *Recycling* index were present even when the *Circularity* index was low and vice versa. Conversely, two smart city-related indices were also necessary for the emergence of urban circularity: the Internet of Things and the more general presence of well-developed ICT infrastructure. The difference between the two categories, however, is that circularity components result as necessary early on, even for a slight initial increase in city circularity. Smart city-related components, on the other hand, become necessary only when the city is already highly "circular." Thus, one conclusion is that the technological contribution is less relevant for the initial boost in the *Circularity* index. Later, however, further increases in circularity are almost impossible without the positive synergy with specific smart city components. Hence, while initially, it is legitimate to consider some circularity-oriented cities as mere circular cities, further increase in circularity is only possible if the said cities become smart circular cities, as, at the upper end of their efficiency, it is impossible to pursue circularity increases without substantial technological contribution.

Hence, a necessity logic appears to apply when it comes to the relationship between a smart green city and a smart circular city. In particular, being a smart green city constitutes a necessary (but not sufficient) condition for a proper smart circular city to emerge. Consequently, the relationship depicted in Figure 2.2 also implies a sufficiency condition: indeed, being a smart circular city appears to be a sufficient (but not necessary condition) to be considered a smart green city. In fact, according to Damianou et al. (2019), true smart circularity would necessarily require proper smart green city infrastructural support to

emerge—hence, it is hard to envision a smart circular city outside the framework of a smart green city. On the contrary, a city that relies heavily on circularity principles but is not technologically advanced would surely be considered a green city, but not a proper smart green city (Figure 2.2). As shown in Study 3, Chapter 2, smart green city initiatives appear to play a crucial role in facilitating the deployment of circular economy projects and related sustainability outcomes in cities (Damianou et al., 2019).

To recapitulate, two components of smart cities were considered necessary for a substantial increase in the circularity of cities that could already be considered circular: the more general ICT category and the Internet of Things (IoT). When it comes to IoT and circularity, according to Damianou et al. (2019), the use of blockchain combined with the well-developed IoT infrastructure is central for the effective transition from a linear to a circular economy in a city, as it can greatly improve the connectivity of the overall infrastructure of a circular city (i.e., water meters, environmental sensors, and others) (Ghorpade et al., 2021; Ghosh et al., 2019). IoT has long been a central topic in smart city research, as a brief bibliometric evaluation in Chapter 1 revealed. At the core of the IoT functionality are the connected devices that gather real-time information and communicate it to the cloud to store and analyze heterogeneous data streams simultaneously. These processes may involve privacy-related and security-sensitive information (Garcia-Morchon et al., 2015). Accordingly, protecting the entire network from malicious events is one of the salient issues associated with successful IoT implementation. Thus, well-integrated security features are necessary for providing optimal IoT functionality (Garcia-Morchon et al., 2015; Ghosh et al., 2019; Routray et al., 2017). This is also where the integration of current conventional IoT implementations with quantum communication and computing comes in handy. For example, post-quantum cryptography has been proposed as a viable approach to the issue of post-quantum security (Garcia-Morchon et al., 2015; Imran et al., 2020; Kumari et al., 2021; Nieto-Chaupis, 2018; Ning & Liu, 2015; Routray et al., 2017; Zhu et al., 2019). Quantum communication technologies can ensure safer IoT by increasing the efficiency and security of the networks of IoT sensors. For instance, as already mentioned in the thematic analysis of Study 3, Chapter 3, Quantum Photonic Computers can provide a set of countermeasures to 5G network abuses inside the IoT system (Kaatuzian, 2020). Additionally, an IoT chip with a quantum number generator can produce non-deterministic real random numbers for better protection of the IoT network (Kaatuzian, 2020; Ning & Liu, 2015; Ramachandran, 2018).

IoT solutions can also be applied in a variety of smaller-scale settings within a circular city

framework, for example, providing key support for the development of sustainable waste management solutions (Garcia-Morchon et al., 2015; Ghorpade et al., 2021; Ghosh et al., 2019; Imran et al., 2020). Waste management, indeed, is one of the central topics of an urban-related circular economy according to the thematic evolution analysis of Study 1, and, as mentioned before, it constitutes a necessary condition for an early deployment of circular city initiatives. Indeed, among all circular city implementations, waste management appears to be most closely connected to city smartness, according to the results of the second principal component analysis of Study 2, Chapter 2. Conversely, as the third PCA of Study 2, Chapter 2 showed, the component of smartness that is closest to the waste management facet of circular cities is AI. This emphasizes the critical importance of the successful and ethical deployment of AI solutions in cities, and the related issues are becoming ever more relevant, as recently pointed out by the EU legislator (*EU AI Act*, 2023).

When it comes to the more general ICT category, as argued by Akande et al. (2019), the research on smart sustainable cities, of which circular city could be considered an instance, should emphasize the effects and implications of ICT infrastructures on urban sustainability (Al-Nasrawi et al., 2016; Kramers et al., 2014). This is primarily possible through the development of integrated frameworks to measure the sustainable smartness of cities (Ahvenniemi et al., 2017), something that also constituted the cardinal point of the thesis.

Given the fundamental importance of a holistic approach to smart cities and the related collaboration when it comes to the successful deployment of circular initiatives, ICTs are essential in bringing about said collaboration by facilitating communication among stakeholders, hence rendering the constraints of time and space (sociologically) irrelevant. In fact, the holistic goal of societal integration around the notion of circularity is hard to imagine without the further sociological compression of time and space that recent integrated ICT solutions can potentially offer (Bifulco et al., 2016; Kramers et al., 2014). In this regard, while circular cities are not necessarily smart, and smart cities are not necessarily circular, a clear conceptual connection between the two exists (Viglioglia et al., 2021).

As the focus of this chapter is mainly on the EU, the importance of ICT solutions for circularity has also been recognized by the European Commission. According to the latter, ICT standards play an essential role in the successful deployment of circularity; in this regard, “the ICT sector … plays a key role in supporting interoperability and innovation of production processes related to industrial transformation and standardization can make a significant contribution in supporting industry, in particular SMEs, in successfully

undertaking the green transformation towards a circular economy. This is not just about the 'digitalization' of processes: a real digital transformation is needed, and processes have to be redesigned. The 'digital by design' principle must be applied systematically and consistently in many sectors, including policy measures and legislation. There will be an unprecedented need for collaboration between traditional sectors and ICT, especially in standardization activities" (*CIRCULAR ECONOMY | Joinup | European Commission*, 2021).

ICT is also a unique category among the identified smart city implementations, as it is the only one that can significantly positively synergize with quantum communication technologies, according to the results of Study 3 of this chapter. In this regard, quantum communication can positively contribute to the two key characteristics of ICT systems, such as future 6G implementations: higher data rates and increased security measures (Tariq et al., 2020). As in the case of the IoT, post-quantum cryptography is considered crucial for the safety of 5G networks and future 6G networks due to the possibility of a quantum attack. Quantum encryption can ensure the secure transfer of data within and between ICT networks (Kaatuzian, 2020; Tariq et al., 2020). Integrating conventional ICTs with quantum communication technologies can improve the connectivity between devices and sensors in a smart circular city. Moreover, communication costs can be significantly lowered as advanced communication technologies are implemented and commercialized (Liang et al., 2018; Toapanta et al., 2020). Overall, the integration of ICT systems and quantum technologies may contribute to the creation of highly efficient smart sustainable cities in which social, technological, and environmental sub-systems, including those circularity-oriented, operate harmoniously (Bassoli et al., 2021).

In conclusion, waste management and renewable energy initiatives are necessary for the emergence of circular cities. Recycling, albeit highly correlated, does not constitute the critical factor, unlike the two previous categories. For the further increases in circularity, however, the contribution of advanced digital technology is necessary. These are the well-developed ICT infrastructure and the Internet of Things. Hence, a smart circular city would necessarily score higher on the *Circularity* index than a mere circular city (as a sub-category of a green city). Furthermore, positive synergies of conventional ICT and IoT systems with quantum technologies, chiefly quantum communication technologies, could further increase circularity measures in a smart circular city, albeit indirectly, through the qualitative increase in efficiency of conventional smart city implementations that would then necessarily contribute to the additional rise in a *Circularity* index.

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5 GENERAL DISCUSSION, IMPLICATIONS, AND CONCLUDING REMARKS

5.1 Overview of the research questions and the respective findings

The work was structured as an in-depth, empirically grounded attempt to answer three research questions on smart cities that are of primary ontological and epistemic significance to smart city researchers, particularly to those working within the paradigms of urban studies, innovation and technology, and business and management. Given the forward-looking nature of the themes and topics of the thesis, as well as its analytical breadth, the empirical validation of its results was mainly achieved by analyzing the relevant narratives on smart cities (first and foremost, on their environmental sustainability dimension) and the related prospective trends in both academia and practice concerning novel technological implementations therein, like quantum communication and quantum computing. For the completeness of concluding remarks, the three research questions of the thesis are reported below, identical to how they were formulated in the Introduction:

RQ1: What is the best alternative to a techno-centric view of smart cities, the one that does not compromise the well-being of heterogeneous groups of urban stakeholders?

RQ2. What is the best way, in theory and practice, to deal with the issue of complexity in smart cities?

RQ3. What is the most systemic, holistic, and integrative way of conceptualizing a smart city?

5.1.1 What is the best alternative to a techno-centric view of smart cities, the one that does not compromise the well-being of heterogeneous groups of urban stakeholders?

The first research question concerns the techno-centricity narratives that are, to date, the most popular in smart city research and, more so, practice. Narratives that mainly ignore sustainability concerns and make technology the cardinal point of all things urban. Ontologically speaking, the techno-centric view of smart cities is a particular instance of what certain academics define as the fetishism of technology (Comor & Compton, 2015; Hornborg, 2013), chiefly "the habit humans have of endowing real or imagined objects or entities [in this case, technologies] with self-contained, mysterious, and even magical powers to move and shape the world in distinctive ways" (Harvey, 2003). As argued in the Introduction, this is not only wrong but also detrimental in the long run.

As an alternative to the techno-centric view of smart cities, the concept of smart sustainable cities was introduced in Chapter 2. By definition, the reconceptualization of a smart city through the lens of sustainability is more nuanced and inclusive, and the technology aspect becomes, in a way, "subservient" to the goals of the long-term prosperity of heterogeneous types of urban stakeholders. In sociological terms, the technocentric view of an ideal smart city is a typical expression of formal rationality (or rationality of means). Conversely, the sustainable smart city concept is more concerned with the goals of prosperity rather than technological manifestations; hence, in the final instance, it is an expression of the so-called substantive rationality, as was initially envisioned by Weber (Ritzer & Stepnisky, 2021).

Although Chapter 2 outlined a theoretical foundation of the smart sustainable city concept, including four pillars of sustainability (environmental, economic, social, and governance), only its environmental pillar was investigated in-depth through three empirical studies. Given the breadth of the smart sustainable city conceptualization, its complete ontological validation falls out of the scope of the current work. Hence, the empirical validation of one of the four pillars of smart sustainable cities mainly serves as a proof-of-concept and a starting point for more in-depth future research in the field.

Regarding the empirical results, in Study 1, Chapter 2, the positive relation between city smartness and greenness was proven. However, a potential moderating role of population size on the relationship suggested a presence of "tension" between the ideal (in the Weberian sense) green (environmentally sustainable) city concept and the conventional technology-centric smart city conceptualization. In particular, bigger city sizes can significantly contribute to city smartness due to agglomeration and scale economies. However, they can also hinder environmental sustainability in the long run due to the cumulative effects of technologies that are not entirely carbon-neutral or have no adverse effects on the environment. Accordingly, smart cities and green cities are two distinct city types, although, at their conceptual intersection, a smart green city can also be envisioned. The latter is intended as a city type in which the balance between urban smartness and greenness (i.e., environmental sustainability) is achieved and maintained, and the two do not compromise each other. By operationalizing urban smartness and greenness in terms of related online media attention for what concerns major cities all over the world (i.e., with more than one million inhabitants), and then by relating the two indices through a dimensionality reduction technique (a principal component analysis) and agglomerative hierarchical clustering, real-life examples of prospective smart green cities were also individuated. These include, for

instance, Nanjing in China and Portland, Oregon in the US, ranking highly on the so-called *Smart Green City* index, as defined by the PCA coordinates along the respective PCA dimension. Study 1, Chapter 2 offers an in-depth description of both cities, using them as short but illustrative cases of the validity of the methods applied therein. More importantly, a negative relationship between smart greenness and city size in terms of its population has also been proven. Accordingly, an environmental pillar of a smart sustainable city, of which a smart green city is an integral part, is no longer negatively affected by additional city growth. This further sets the concept apart from a conventional techno-centric view of smart cities—the one that puts technology on the "pedestal," shifting the perspective from the goals of well-being and prosperity to mere technological means of achieving urban smartness (McFarlane & Söderström, 2017).

In Study 2, Chapter 2, a particular type of green city was conceptualized, the so-called circular city. This was primarily done because of the relevance that the circular economy is increasingly gaining, both in academia and in practice. Moreover, circular business models and implementations represent a concrete and measurable way for a city to "go green" (Williams, 2019). Hence, the related outcomes are easier to operationalize and quantify, unlike in the case of more generic green cities. In the latter case, it is possible to envision a city that scores high on greenness without resorting to any particular advanced technological implementation or set of implementations. One example of such a city is El Pacecillo, described more in detail in Study 1, Chapter 2. In the case of El Pacecillo, little can be said about its infrastructural potential to become both smart and green, and the related greenness index is inflated due to the unique geographical location of the city (mainly because of how it is immersed in an untouched natural landscape, including the integration of green areas within the city limits). Circular cities, on the other hand, are, by definition, more technologically advanced and are the most proximal candidates for becoming the so-called smart green cities.

In parallel with Study 1, Chapter 2, a positive relationship was found between circularity and smartness. Unlike in the said study, the indices were operationalized based on academic attention to the topics on Google Scholar and in relation to cities that are exclusively within the EU area. The latter constituted a crucial and necessary reduction of scope because, as shown later in Study 1, Chapter 4, the concept of circular cities has been mostly relegated (when it comes to the academic output) to the confines of the European Union. Moreover, given the limited geographic scope, all cities with more than one hundred thousand inhabitants were considered. Once more, the obtained indices were analyzed using principal

component analysis and agglomerative hierarchical clustering. To ensure more robust results, the analyses were repeated three times, varying the inclusion of the so-called micro-level indices representing different sub-components of smartness and circularity. In all three cases, however, there has been a significant concordance of the results. Accordingly, the *Smart Circular City* index was obtained as an arithmetic average of the individual SCC indices derived as standardized coordinates of respective principal components. Consequently, as in the case of Study 1, Chapter 2, real-life examples of prospective smart circular cities were individuated and briefly described (Oulu, Finland, and Split, Croatia).

Like in the case of the results of Study 1, Chapter 2, the positive relationship between circularity and smartness hints at the theoretical distinctiveness of the so-called smart circular cities concept—a potential subset of smart green cities. Indeed, as proven by means of a necessary condition analysis in Study 3, Chapter 2, being a smart green city is necessary for becoming a smart circular city. The results of Study 3, Chapter 2 were obtained by relating the two indices, the *Smart Green City* index and the *Smart Circular City* index, as derived previously. Concerning the sample composition, only European cities with more than one million inhabitants entered the analysis. The results were derived through a novel methodology, the necessary condition analysis, which is increasingly gaining popularity as complementary to conventional inferential analyses (Dul et al., 2021; Hauff et al., 2021).

The relationship between the two city types can also be read in reverse: a smart circular city is necessarily a smart green city, as there are no smart circular cities that are not, by definition, green. On the contrary, not every smart green city is circular. A smart green city, however, is not yet a smart sustainable city. In this regard, Chapter 2 ends with the outline of a comprehensive theoretical conceptualization of a smart sustainable city. In line with the first research question of the thesis, it emphasizes the synergizing interconnection of all four pillars of urban sustainability within an enhanced ESG framework (the so-called ESGE, economic, social, governance, and environmental). According to the conceptualization, a truly smart sustainable city can only be considered as such when all four pillars are buttressed through advanced technological means, which, as was stated previously, should be treated not as inherently essential goals of a smart city development but as necessary means for the ends of maximizing the well-being of heterogeneous groups of urban stakeholders.

5.1.2 What is the best way, in theory and practice, to deal with the issue of complexity in smart cities?

The second research question is of paramount importance to the thesis and has to do with a search, both practical and theoretical, of the optimal way to deal with the increasing complexity of contemporary cities, specifically highly integrated smart cities. Assuming that such an optimal way is within the realm of possibility, the answer was given in the form of a quantum city metaphor, a novel urban conceptualization that is theoretically grounded in fundamental principles of quantum physics.

In particular, in Chapter 3, after outlining the reasons and giving examples of how existing conventional urban metaphors (the so-called Newtonian urban metaphors) fail to provide viable outcomes, especially when it comes to the first highly integrated examples of real-life smart cities (e.g., Songdo in South Korea), the quantum metaphor was developed as a viable alternative to existing urban conceptualizations.

In this regard, Study 1, Chapter 3 laid the foundations for the quantum metaphor and developed the topic from a theoretical point of view, showing how fundamental notions of quantum physics, including duality/parallelism, uncertainty, and relativity, can be used to understand and approach the complexity issue, central to the second research question. To reiterate, the urban quantum metaphor emphasizes the utility of looking at a city as a complex set of dialectical dualities existing on the space, time, social, and technological continua, with no possibility of optimal solutions but an unlimited sustainability-driven orientation for which the complexity and uncertainty should be actively embraced for rather than discouraged.

While the metaphor is universal in its reach, it is the most relevant in relation to smart cities. Indeed, a more practical vision of quantum cities, as a smart city type in which quantum technologies are integrated with conventional smart city technologies, was discussed in the remaining part of the chapter. Consequently, Study 2, Chapter 3, through an in-depth qualitative and quantitative assessment of the quantum-related literature in urban social science research, revealed the existence of two quantum technologies relevant to cities: quantum computing and quantum communication. In particular, the study was positioned as an in-depth systematic literature review. Accordingly, a PRISMA 2020 protocol was established for searching, evaluating, and including scholarly records (i.e., academic articles). Then, an advanced quantitative content analysis of the retrieved scholarly records was performed based on the study of the semantic content of documents through PCA and agglomerative hierarchical clustering. As a result, two classes of quantum technologies were

deemed relevant for future urban design and development: quantum communication and quantum computing. The two were also analyzed by means of qualitative deductive coding, which culminated in a respective qualitative thematic analysis showcasing how and in which urban context quantum communication and quantum computing could be of best use.

Finally, Study 3, Chapter 3 looked at how and to what degree heterogeneous conventional smart city technologies could synergize with the two classes of urban quantum technologies. In this regard, a taxonomy of conventional smart city technologies was first derived based on the semantic evaluation of the abstracts of 576 smart city-related academic articles identified through a scoping review methodology. Regarding the interaction between conventional smart city technologies and the two types of quantum urban technologies, an open (inductive) coding approach and a grounded theory methodology were applied to evaluate the articles retrieved in Study 2, Chapter 3. The resulting two-tier code structure was used as a basis for a latent semantic analysis (including PCA and agglomerative hierarchical clustering) to determine how and in which ways conventional smart city technologies, quantum computing, and quantum communication could potentially synergize in the context of urban planning, design, and development. Quantitative analyses were also complemented by a qualitative semantic analysis focusing on how each conventional smart city technology could potentially benefit from its integration with the two classes of quantum urban technologies.

To sum up, Chapter 3 was primarily focused on providing a viable answer to an "increasing complexity" dilemma, as formulated by the second research question and discussed in-depth in the Introduction chapter. The solution was proposed in the form of the urban quantum metaphor, which emphasizes the cardinal role of complexity as an opportunity rather than a threat. The metaphor was then reified in the form of quantum cities, a sub-type of smart cities in which conventional smart city technologies are synergic with quantum computing and quantum communication, once again, in the optics of long-term holistic sustainable development.

At this point, it is worth mentioning that unconventional (in business and management research) methodological tools were used to uncover the connections and potential synergetic effects between conventional smart city technologies and quantum technologies. The rationale for their usage and the evidence for their effectiveness are presented and discussed in depth in Chapters 3 and 4.

5.1.3 What is the most systemic, holistic, and integrative way of conceptualizing a smart city?

The third research question concerns the lack of integrative, systemic, holistic outlooks on smart cities in the literature and practice. A partial answer to the question was given in Chapter 4 by showing how the results of the previous six studies of the thesis can be integrated into a unified and cohesive framework (Figure 4.16). In this case, only an environmental pillar of sustainable smartness was considered. Indeed, the results of the chapter should be treated as an empirical proof-of-concept of how the integration of themes and topics can be achieved within the broader framework of smart sustainable cities.

Specifically, Study 1, Chapter 4 consisted of a bibliometric review of the circular city concept, tracing the change in related discourses and narratives from mere environmental concerns toward the integration with themes and topics relevant to a more conventional smart city research. Along with basic bibliometric evaluation, more in-depth bibliometric techniques were used to understand the development of the concept, including trend topic analysis, multiple correspondence analysis, thematic evolution analysis, and keyword co-occurrence analysis.

In relation to the ongoing shift toward more conventional smart city topics in the literature on circular cities, Study 2, Chapter 4 looked at which conventional technological components of a smart city constitute necessary conditions for urban circularity to emerge, hence contributing to the emergence of the so-called smart circular city. Again, this was achieved through the necessary condition analysis of the sample of cities isomorphic to that used in Study 3, Chapter 2 (all the EU cities with more than one million inhabitants). In particular, both ICT and IoT were deemed necessary for circular cities. Interestingly, those were considered necessary for the highest levels of circularity, while the lower levels can be achieved through efficient and effective waste management and renewable energy initiatives. The findings suggest that it is possible to envision circular cities that are not entirely driven by advanced technology, but if the highest levels of circularity are to be reached, the integration of conventional smart city technologies within the framework of a circular city is necessary.

Finally, Study 3, Chapter 4 complemented the above results, relating them to the topics discussed at length in Chapter 3. Specifically, by means of advanced semantic analysis based on the keywords determined through a semi-systematic literature review and thematic synthesis of social science articles on quantum technologies, more in-depth relationships between conventional smart city technologies and quantum urban technologies were

described. PLSc-SEM framework was used for the semantic analysis. The role of ICT emerged central, as it resulted in being the most semantically connected to quantum technologies (in particular, quantum communication, which itself resulted in being more influential regarding its overall potential effects on all identified types of conventional smart city technologies).

To conclude, as an answer to the third research question, the empirical finding of the thesis can be successfully integrated into a cohesive framework (Figure 5.1), emphasizing, in particular, the environmental pillar of smart sustainability. In brief, environmental sustainability can be achieved by means of a circular economy, and circular cities represent efficient and effective integration of the latter into urban development, planning, and design. Moreover, the efficiency of circular initiatives necessarily benefits from the adoption of conventional smart city technologies, such as IoT and a well-developed ICT infrastructure. The latter, however, potentially significantly benefits from the integration with quantum technologies—first and foremost, quantum communication. In the final instance, it is only by moving backward and forward through this complex chain of effects that one can see how intrinsically and deeply the topics of sustainability and smart cities are intertwined. A simple techno-centric reasoning would surely fail here. The opposite is true, however, for a complex, more nuanced, and holistic outlook, as reported in Figure 5.1.

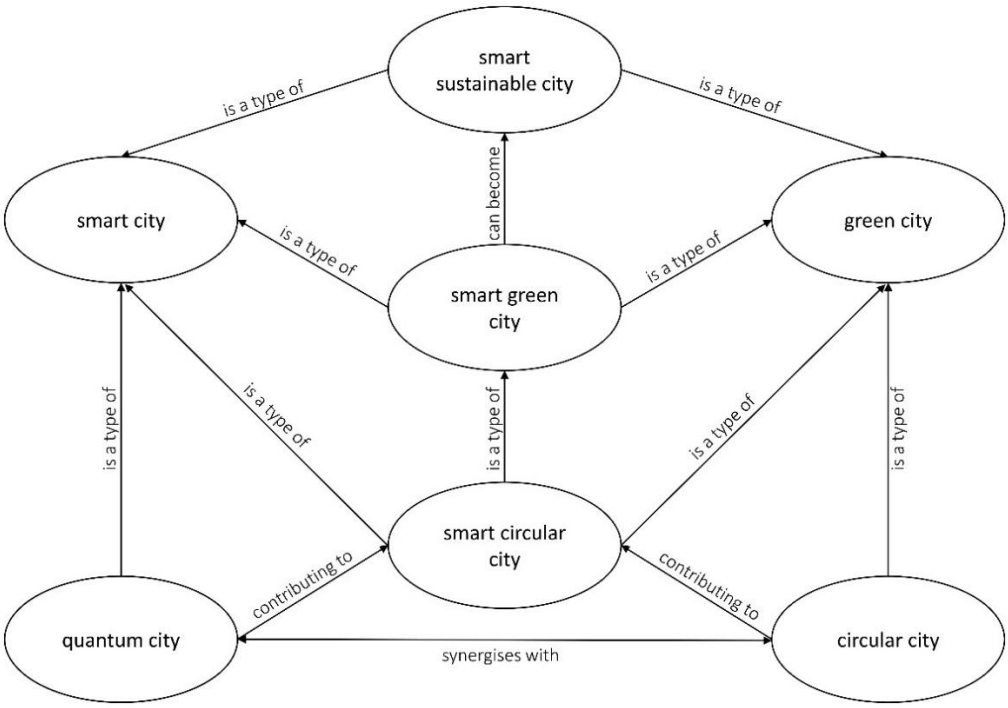


Fig. 5.1 *The review of the overall framework/results of the thesis*

5.2 Managerial and theoretical implications

The general implications of this work for urban practitioners and other stakeholders (i.e., businesses and institutions), as well as researchers, are straightforward. As was established in the thesis, in particular in Chapter 1, structured as an in-depth answer to the techno-centricity problem of current smart city conceptualizations, the heavy techno-centric view of smart cities is detrimental to the core premises of sustainability, including its environmental, economic, social, and governance aspects. Mere fascination with technology for technology's sake does not typically lead to the successful deployment of smart city initiatives but instead can hinder sustainable urban development. This, however, does not mean that technology-heavy solutions should be avoided at all costs. For example, from combining the results of Chapter 2 and Chapter 4, it is evident how, after a certain amount of circular development, no further increase in the circularity (and, hence, greenness) of the city is possible without relying on, first, conventional and then, in a long-run, quantum urban technology.

"Technology is neither good nor bad," according to Melvin Kranzberg, the historian of innovations, "nor is it neutral" (Kranzberg, 1986). In the final instance, smart cities are sociotechnical ecosystems in which one sustainability dimension should not be prioritized over the other. Hence, both practitioners and scholars are advised to be cautious when defining, researching, or effectively deploying smart city initiatives.

This conclusion also aligns with the third research question and the related issue of the need for more holistic and integrated frameworks for smart cities. In this regard, changing how researchers and practitioners talk, write, and reason about smart cities is essential. The complexity issue inherent to the second research question calls for more nuanced and drastically different ways of conceptualizing and dealing with the plurality of urban-related variables and outlooks. This is particularly evident when looking at how traditional Newtonian urban metaphors, with their reliance on cause and effect and simplification of complex urban issues, fail. From this point of view, the theoretical contribution of this work is of utmost importance. To reiterate the conclusion of Chapter 3, on the more abstract level, besides technology-related knowledge, a change in conventional views on topics of complexity is needed. Rather than constituting conceptual practical threats, the multiplicity and interconnectedness of urban-related variables should be envisioned as opportunities that can be exploited to their fullest potential, for example, by integrating urban quantum technologies in conventional smart city implementations.

Radical social changes might follow if quantum technologies reach widespread usage (Zohar,

1995). For this reason, urban decision-makers are advised to start strategizing the introduction and incorporation of quantum technologies in smart cities as a lever for urban growth and potential competitive advantage for businesses and institutions located therein. In this regard, a fully integrated (i.e., relying on both conventional and quantum computation) smart sustainable city presents advantages on both cost-effectiveness and differentiation fronts. When it comes to lowering costs, the combined effect of quantum technologies in synergy with conventional smart city technologies can help accommodate more variables for computational purposes (Khan & Robles-Kelly, 2020), store higher volumes of data (Dowling & Milburn, 2002), allow for more exact predictions and forecasts (Kim et al., 2021; Proctor et al., 2022), sustain complex communication networks (Bassoli et al., 2021), and provide a substantial increase in computational speed for specific types of algorithms (Amiri, 2003; Wack et al., 2021).

Concerning a differentiation advantage, more precise urban-related forecasting can be critical in the context of the growing uncertainty and complexity of contemporary cities (Kim et al., 2021; Proctor et al., 2022). Additionally, the integration of artificial intelligence (including its current-day machine learning iterations) with quantum computing (the so-called quantum AI) can be used in decision-making to accommodate a more significant number of social, cultural, economic, financial, environmental, and technical variables. This can provide urban managers, administrators, and planners with a variety of equifinal policies and strategies to meet the needs and expectations of the highest number of inhabitants and other smart city stakeholders, including businesses and institutions operating therein (Khan & Robles-Kelly, 2020).

Besides, both cost and differentiation advantages can be direct, bypassing the intervention of city managers and administrators, given that access to the benefits that novel technologies offer is granted directly to everyone in the city. Again, to reiterate the conclusions of Chapter 3, openness and accessibility are the most crucial in ensuring that the benefits of quantum technologies outweigh their negative impacts (for example, those related to the quantum vulnerability of the current generation of computers). To achive openness and accesibility, the related scientific knowledge should be made publicly available (DeBenedictis, 2020; Gordon & Gordon, 2012; Mykhailova & Svore, 2020; Uhlig et al., 2019). For example, the higher computational capacity of quantum computers could be made accessible via the cloud (de Wolf, 2017).

Chapter 4, in particular, shows how the integrated and holistic outlook on a smart sustainable

city could benefit its environmental pillar of sustainability. This could be achieved through circularity initiatives implemented by means of advanced smart city technologies, including the essential contribution of quantum communication and computing. Indeed, when it comes to the former, by implementing complex quantum communication networks, urban managers, administrators, and planners can design smart cities in which various environmental actors, including those operating through circular business models and strategies, are structurally interconnected and operate in agreement (Bassoli et al., 2021).

All of the themes outlined above are of utmost relevance for city actors operating within the confines of the EU. Indeed, as was shown by the bibliometric evaluation of circular city literature, most of the scientific production on the topic of smart and circular cities comes from the European Union. Most of the related literature is also highly interconnected (in terms of research collaborations) and is sponsored directly by the European Commission and/or through so-called European projects, such as Horizon 2020. According to Gargiulo et al. (2013), "In recent years European Commission has developed a set of documents for Members States tracing, directly or indirectly, recommendations for the transformation of the European city […] Although the three main documents (Cohesion Policy 2014-2020 of European Community, Digital Agenda for Europe and European Urban Agenda) face the issue of the future development of European cities from different points of view, which are respectively cohesion social, ICT and urban dimension, each of them pays particular attention to urban and territorial dimension, identified by the name of Smart City." In this regard, the value of the unified vision of smart sustainable cities, as proposed in the thesis, is hard to overestimate.

The research on smart cities has traditionally been transversal to a variety of disciplines, dealing with heterogeneous topics, from digitization and citizen involvement to governance and sustainability (Ibănescu et al., 2020). Conversely, a unified framework that is also inclusive and can accommodate different European initiatives, such as low-carbon policies (*Reducing Carbon Emissions*, 2018), managing climate risks (*Key Steps for Managing Climate Risks to Protect People*, 2024), and safeguarding of biodiversity (*Nature and Biodiversity - European Commission*, 2024), is, potentially, of paramount relevance to policymakers at different institutional levels. It can also be of great importance when it comes to local governance and authorities as, currently, "the rather incipient status of smart cities approaches" is rife with challenges such as "the insufficient resources allocated by local authorities, which rely extensively on EU funding, the lack of awareness from citizens and the

lack of a comprehensive and structured strategic approach" (Ibănescu et al., 2020).

5.3 Limitations and future research directions

An overreaching implication of the thesis is that the balancing act between technology and different dimensions of urban sustainability is more important than the technology itself. Indeed, the concept of a smart city (in a strict sense) is already losing its popularity in favor of a more inclusive notion of a smart sustainable city. In this work, only one of the said dimensions was investigated in-depth, the environmental pillar of smart sustainable cities. It does not mean, however, that the other three pillars, as defined in the thesis (social, economic, and governance), are of lesser significance. Cities are complex, ever-emerging entities, and practitioners in particular, including local and institutional governance, must understand and internalize that there is no best way (or even contingent solutions that are equifinal) when it comes to dealing with emerging smart city issues and challenges. The best one can do is to accept the related complexity, risk, and uncertainty as something that should not be occluded through simplified discursive practices but instead adopt frameworks that readily integrate the said complexity, risk, and uncertainty. One such framework was outlined and empirically validated in this thesis.

The emphasis on the environmental pillar was given here primarily due to the perceived urgency in the face of looming ecological challenges that are expected to happen in the remaining three-quarters of the twenty-first century (Isenhour, 2013). When it comes to the notion of good urban living, the remaining sustainability pillars, nonetheless, are equally essential. Hence, in future studies, those are needed to be investigated more in-depth. For instance, the social dimension of sustainability can be reified in the concept of the so-called serendipitous city, i.e., an urban environment that is designed and structured to facilitate and promote opportunities for seamless social interaction in day-to-day urban life, for instance, through initiatives and projects emphasizing the controlled unpredictability and uncertainty in the urban community. Similar considerations can be made regarding thorough investigations of the two separate albeit interrelated aspects of urban sustainability—its economic and governance pillars.

One might as well cite Italo Calvino in his excellent Invisible Cities as the most appropriate way to finish a work like this: "The hell of the living is not something that will be; if there is one, it is what is already here, the inferno where we live every day, that we form by being

together. There are two ways to escape suffering it. The first is easy for many: accept it and become such a part of it that you can no longer see it. The second is risky and demands constant vigilance and apprehension: seek and learn to recognize who and what, in the midst of it all, are not a part of it, then make them endure, give them space." In a world that is increasingly complex, in future cities where undecidability shall rule supreme, only through means of conscious collective effort to better the future of our children can we all escape the destiny of those shapes forever burned into concrete.

5.4 References

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