

Article

# Long-Term City Innovation Trajectories and Quality of Urban Life

Alina Irina Popescu

Department of International Business and Economics, The Bucharest University of Economic Studies, 010374 Bucharest, Romania; alina.popescu@rei.ase.ro

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**Abstract:** The main aims of this paper are to examine the technological trajectories of city innovation, to provide a picture of the current state in the most significant technologies, and to propose an explanation for the long-run evolutionary trajectories of technological developments that contribute to the quality of urban life through innovation. In the conceptual part of the paper, we develop the argument that the explanation may rest on the interrelationships between the concept of urban transformative capacity and the theory of path dependence. In the empirical part, we analyze patent data on city-related innovations to examine the trajectories of technological developments over the period 1980–2020. Our main findings at a technological field level (i) confirm the path dependence theory in general and the institutional approach in particular, (ii) acknowledge the rapid transformation towards ‘smart cities’ through the explosive growth of digital technologies, and (iii) confirm the environmental sustainability concerns when developing new technologies. In our study, we focus particularly on the technological sectors (‘clusters’) that provide a significant contribution to quality of urban life, namely environment, public services, and leisure and participation. Our findings provide theoretical, managerial, and policy implications for future research activities on the technological developments that benefit quality of urban life.

**Keywords:** technological innovation; technological development; quality of urban life; city sustainability; city innovation; patent analysis; data mining; knowledge space; trajectory

## 1. Introduction

Cities are increasingly complex and multi-dimensional urban systems that are central to human life on our planet. Their importance is acknowledged by the global recognition that we live in an urban age of near-planetary urbanization [1,2]. Urban areas are home to the majority of the world population, generate more than 75% of global GDP, and contribute to about 75% of carbon emissions from global final energy use [3].

Issues related to growing urban populations, protecting the environment, adapting to the changing climate, and others alike require a transformative change of cities towards achieving sustainability [4]. Cities are now at the forefront of all sorts of global agendas that culminated with the inclusion of a United Nations (UN) Sustainable Development Goal (SDG) that focuses explicitly on urban areas, in addition to the existing multilateral frameworks of the UN New Urban Agenda, the Paris Agreement on climate change, or the Sendai Framework for disaster risk reduction.

Innovation is critical for solving the challenges that our society is facing today and for achieving sustainable city development. Disruptive innovation—understood here as an innovation that is able to successfully challenge an established practice—offers the means to create an emergent economic sector of ‘advanced urban services’ combining new technologies, new methodologies, and conventional forms of city development, with a market value rising to over USD 3 trillion by 2025 [5]. In the age of ‘smart cities,’ however, there are challenges to embracing innovation and technological developments

and, thus, transforming cities along the lines of the sustainability quest [6]. Initial studies on ‘smart city’ policies revolved around the concept of ‘sustainable cities’ with increased attention to information and communication technologies (ICTs) as a main driver of smartness and to environmental issues [7].

Three dimensions of urban transformation towards sustainability that operationalize different sustainability aims may be identified in order to help researchers and practitioners better understand the complexity of this transformative process. These are: quality of life, resilience, and resource efficiency [8]. In this paper, we focus particularly on the quality of life dimension of urban transformation towards sustainability, and we argue that innovation serves improving the urban quality of life from social, economic, and environmental perspectives.

The paper uses quantitative methods based on text data mining and text data visualization techniques to analyze patent data extracted from the European Patent Office (EPO), in addition to traditional descriptive statistics methods. We attempt to discuss the following research questions: RQ1: Can it be observed that technological development for city innovation has different growth patterns in different countries of the world? RQ2: Can a path-dependent evolution of technological development for city innovation be observed? RQ3: Can a change in the trajectories of different technological sectors’ developments in relation to city innovation be observed? RQ4: Can it be observed that technological development for city innovation has evolved towards increasing the environmental conditions of the city that favor individual and group wellbeing? RQ5: What can be inferred from the technology space of technological development for city innovation? RQ6: What is the positioning of ICT-related technological development and non-ICT-related technological development on the knowledge map of city innovation? RQ7: Can it be shown that innovation contributes to the improvement of quality of urban life?

This study contributes to the field of innovation studies and introduces a new instrument for the purpose of analyzing city innovations that have the potential to improve the environmental conditions (e.g., livability, air and water quality, safe neighborhoods, energy efficiency) that favor individual and group wellbeing [9]. Patent data related to city innovation that are available online at the European Patent Office have been examined within the scope of this study to gain deeper understanding of the areas of city innovation and their evolution over four decades (January 1980–August 2020).

## 2. Conceptual Framework

In this paper, we propose an explanation for the long-run evolutionary trajectories of technological developments that contribute to city innovation. A growing concern has emerged to theorize, explain, and predict a city’s capacity to absorb innovation in order to improve overall quality of life.

Quality of life is a broad term that may refer to ‘immaterial as well as material, subjective as well as objective, individual as well as collective elements of welfare, satisfaction, and happiness’ [8]. Quality of life is usually represented by multiple sets of indicators reflecting the multi-dimensional character of this concept. A vast number of studies have used objective, subjective, or behavioral measures to investigate the quality of urban life (for a review, see [10]). Among the objective indicators, we find: air quality, crime statistics, incidence of chronic diseases, amount of green land, employment rates, and educational attainment. Subjective indicators of quality of urban life are equally important. This category includes: life satisfaction, overall happiness and overall wellbeing, perceptions of healthcare services, feelings about congestion and crowding, perceptions of school quality, and satisfaction with health, neighbors, jobs, friends, etc. Among the behavioral aspects of the quality of urban life, we mention: residential mobility patterns, participation in local decision-making, visits to parks and cultural amenities, social life, and participation in sports [8].

In the process of urban transformation towards sustainability and, therefore, ensuring a high quality of life, a basic question that emerges refers to the enablers of a city’s capacity to absorb new knowledge and innovation through what has been referred to as the ‘transformative capacity’ of a city. Previous studies along this line of argument have explored the pivotal role of ‘institutional capacity’ or ‘governance capacity’ for sustainable development in cities and regions [11,12] and the design of

local governance processes for accelerating urban change [13,14]. An institutional capacity for dealing with the challenges of sustainability requires a broader scale of societal activities, including a collective effort made by different public and private actors working together. This collective product is the result of the formation of appropriate and inclusive city governance mechanisms that include all urban stakeholders.

In this paper, we focus on the technological innovations that have the potential to contribute to a city's transformation towards a sustainable city, a city whose development considers the social, economic, and environmental impacts. City transformation refers to the commitment to ensure social inclusivity, sustainable economic growth, and environmental quality for its residents. These lead to the creation of favorable living conditions and wellbeing for all the residents.

Long-term patterns of technological developments have been previously explained by studies from the fields of geography of innovation (e.g., [15]) and evolutionary economic geography (e.g., [16–18]). The development of technologies has been argued to be path-dependent because it is the result of numerous interdependent choices that, over time, accumulate into technological trajectories. Within the path-dependence theoretical framework, the sectoral development of city economies evolves in a path-dependent manner over long periods of time and conditions the scope and possibilities of future development [19].

Transformative studies aiming at understanding trajectories towards new socio-technical regimes that are likely to encompass a range of innovations argue for agency-centric perspectives to explain processes of change. From this perspective, agency is conceptualized as creating properties and features within a system that make it more conducive to the establishment of new practice and the phasing out of the old one. In addition, change agents are important for creating system-level conditions that increase the capacity to transform [20].

In line with the agency perspective, technological innovation trajectories were found to be influenced by institutions. Creating the conditions for the profound and systematic transformations in system functioning requires changes to the institutional foundations in which established practices reside. In addition, it has been argued that changing a dominant practice is not driven by a single powerful actor, but by many actors who contribute in different ways and at different phases of the change process [21,22]. As such, institutional settings are a significant aspect to investigate when attempting to understand knowledge production and technological developments over the long run. This is in line with insights included in the national innovation system (NIS) literature [23,24]. According to [25], a NIS is a network of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies.

Along this line of thought of path-dependent technological developments, recent studies have proposed the concept of actor-centric transformative capacity of a city focusing on the unique role city–university partnerships [6] and the concept of institutional entrepreneurship in order to investigate the processes of agency that relate to the introduction, diffusion, and establishment of alternative practices in societal systems [21,26]. Governments have been recognized to play a significant role in stimulating technological innovation [27,28]. In what concerns the role of a university, the Triple Helix [29] thesis contends that a university needs to be directly linked to the industry to maximize the industrialization of knowledge. Nowadays, universities go beyond their traditional roles in society—namely education and pure science—and engage increasingly in the exploitation and commercialization of the knowledge that they create, most often in partnership with the other actors from a NIS. This know-how exploitation through patents by universities was the definitory characteristic of the so-called 'third-generation university' (3GU) [30].

City innovation trajectories can also be examined by building the 'technology space' of technological developments, which can be collected from patents. The technology space is a network-based representation of the relatedness between all the technologies that can be found in a patent portfolio [31]. A technology space expresses knowledge trajectories that are shaped by path-dependent, recombinant, and co-evolutionary network dynamics by providing a multitude of

information on the opportunities for future diversification and on the current innovative capacity of a region [16].

### 3. Data and Methods

Technological development that contributes to city development through innovation was investigated by using patent applications submitted to the European Patent Office (EPO). Patent data represent a rich source of information on the latest technological developments related to a field of interest—in this case, city innovation. These data allowed us to formulate and test theoretically informed hypotheses and to provide data-rich arguments regarding the technological evolution in national economies [31–33]. According to [34], patent data provide a wealth of information pertaining to the creation and diffusion of technical knowledge in regions.

Several studies have agreed with the suitability of patents for analyzing technological trends in a comprehensive manner [35–41]. With regards to specific aspects related to city or urban innovation, patent analysis has demonstrated its reliability in previous works [7,16,32,42].

Our dataset comprising patent information on technological developments was downloaded from the Worldwide Patent Statistical Database created by the European Patent Office, henceforth 'Patstat'. Data retrieval was performed by running a query on the Patstat Database ("EP full-text search") aiming at identifying the patent documents that included the string 'city' in the patent application title, abstract, or claims, and that were filed between January 1980 and August 2020. The description was excluded, since it provides generic information and/or is used for discussing macro-trends that do not specifically pertain to the searched string, as argued by [43]. We made a distinction between the city area and the urban area, the latter being a larger area that includes, in addition to the city, the areas surrounding the city. We decided to focus on the city as the focal point of our research, as the agglomeration negatively affects the quality of life of city residents. More so, some suburban areas are recognized as areas with high quality of life, in a strong contrast to the situation in the city area.

Many previous studies have adopted this data collection approach for examining technological trends (e.g., [35,36,38,42]) and have demonstrated its reliability [44,45].

Initially, the query resulted in a sample of 386 documents containing patent information related to the broader topic of city innovation. This initial dataset was then subject to data-cleansing operations that removed duplicate documents and documents that, despite including the string 'city' in the title, abstract or claims, were irrelevant to our analysis. This resulted in a final dataset comprising 287 documents with data on patents related to the topic of city innovation.

A document from the final dataset comprised the following information about a patent application: application number, application date, title (in English), abstract (in English), description, international patent classification (IPC) class, name of applicant/proprietor, country of applicant/proprietor, publication date, and type of publication. The patent data structure enables us to differentiate between geographical, cognitive, and social maps [46]. Accordingly, concepts of proximity, distance, and related varieties can be distinguished in these various dimensions [47].

The paper makes use of the "technology space" framework [31] to measure the relatedness between technologies. This analysis increases the level of detail and shows the growth (entry) and decline (exit) of certain technologies defined by key terms, as well as the relationships between them. To investigate the relatedness of the technological developments collected from patent data, we employed quantitative methods based on text data mining and text data visualization techniques, like key term extraction, key term frequency, patent documents clustering based on similarity, co-occurrence of words, multidimensional scaling, and correspondence analysis [48–50]. Due to the limited reliability of automatic key term extraction, key terms were manually extracted. Thus, a total of 7353 key terms were extracted for 287 documents, resulting in approximately 25 key terms per patent document, on average.

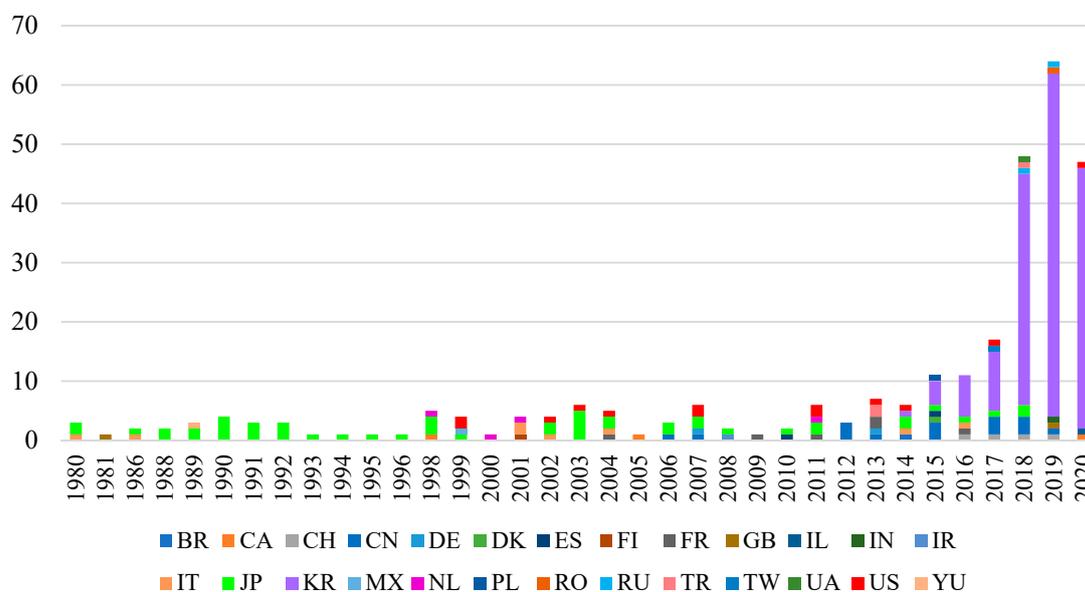
This paper examines the following research questions:

- RQ1. Can it be observed that technological development for city innovation has different growth patterns in different countries of the world?
- RQ2. Can a path-dependent evolution of technological development for city innovation be observed?
- RQ3. Can a change in the trajectories of different technological sectors' developments in relation to city innovation be observed?
- RQ4. Can it be observed that technological development for city innovation has evolved towards increasing the environmental conditions of the city (e.g., livability, air and water quality, safe neighborhoods, energy efficiency) that favor individual and group wellbeing?
- RQ5. What can be inferred from the technology space of technological development for city innovation?
- RQ6. What is the positioning of ICT-related technological development and non-ICT-related technological development on the knowledge map of city innovation?
- RQ7. Can it be shown that innovation contributes to the improvement of quality of urban life?

#### 4. Geographical, Temporal, and Technological Field Analysis of City Innovation

In this section, we begin to look at the landscape of the technological developments that contribute to city innovation. Then, we perform analyses of geographical and temporal trends and technology classes.

We start by presenting the geographical distribution of the technological developments with contributions to city innovation. Figure 1 shows the evolution of technological innovation by country over the period 1980–2020. Geographical distribution by country is as follows: Korea (57.1%), Japan (17.1%), China (5.2%), USA (3.8%), Italy (2.8%), France (1.4%), and the Netherlands (1.4%), while the rest of the countries represent 1% or less of the total number of investigated patent application documents. In terms of speed, countries such as Japan and the USA have shown a continuous and steady pace of technological innovation over the entire period. A second platoon of countries formed by France, the Netherlands, Switzerland, and Canada has more recently joined the arena of technological development for city innovation (since 1998), also showing a steady rate of technological innovation.



**Figure 1.** Evolution of technological innovation by country over the period 1980–2020. Source: author's elaboration.

What draws the attention is the exponential increase in the technological advancement of Korea and China since 2014. In particular, Korea has seen an explosion of technological innovation over the last five years, with a total of 162 patent applications in the technological fields related to digital data

communication that can be used for providing intelligent city services and vehicular communication systems (V2X—vehicle to everything), all of them being submitted by a large Korean company. This massive growth can be explained by the implementation of the governmental project called “Giga Korea” (2013–2020), which aimed at pushing Korea to take the lead as a global ICT power by pursuing shared growth in all areas of the IT ecosystem, including software, terminal, platform, and content. Other researchers have also found that the Korean NIS can be characterized by a “twin dominance” of large companies (called chaebols) and the government, which implies a weak role of other actors from the NIS, like universities and small and medium-sized enterprises (SMEs) [51,52]. The Korean government actively supports technological innovation through a number government research institutes (GRIs) established in specific technological fields of interest [53].

As regards China, our data show an increase in the level of technological development with potential contributions to city innovation since 2012, ranking the country third worldwide after Korea and Japan. In contrast to Korea, China has a more diverse technological innovation portfolio, covering a wide variety of fields, including traffic control, safety and security, construction, living improvements, and public services. Discussing the surge in China’s patenting activity, it has been argued that the Chinese government has promoted patenting as a target per se [42]. Notwithstanding its dependence on external knowledge inflows, China has built its own substantial, endogenous capacity for knowledge generation, particularly at universities [42,54]. Our findings show that 20% of the technological innovations were developed by universities (e.g., Southeast University of China), while the rest were developed by companies in cooperation with the government.

The long-term evolution of the urban technological landscape is subject to path dependency, whereby new knowledge emerges from existing knowledge. More so, the Korean and Chinese performances in knowledge creation that we previously discussed stress the role of institutions, with path-dependent roles in the production of new knowledge.

Technological innovation is accelerating, and the broader technological acceleration is creating enormous value for societal systems. This trend requires further investigation into the speed of transformative city processes and the factors that influence the speed of innovation adoption. The technological innovation must be coupled with institutional innovation, that is, co-inventing new institutional structures, processes, and models that leverage the advancement of technology and human skills.

Technological innovation is classified in distinct technology classes that reflect the scope of the approved claims listed in a patent document. The patent application data extracted from Patstat make use of the International Patent System classes (IPC). IPC provides a hierarchical system for the classification of patents and utility models according to the different areas of technology to which they pertain [55]. The analysis was pursued at the four-digit level, but for visualization purposes, IPC classes were presented under broader categories, as shown in Figure 2.

IPC class analysis is a newly established method employed to identify trajectories in technological development. It has been used to build maps of the technological inventiveness of cities (see [56]), to assess the impact of ‘smart city’ policies on urban innovation (see [7]), and to examine technological trends in Chinese regions (see [42]).

The explosive growth of technological innovations in several IPC classes associated with information and communication technologies (ICTs) is evident from Figure 2—more precisely, in: digital information transmission (H04), computing and calculating (G06), and signaling (G08). These IPC classes register developments of sensors, software, and other technologies used for the purpose of connecting and exchanging data with other devices over the Internet, the so-called ‘Internet of Things’ (IoT) [57]. Approximately 98% of the technological innovations included in H04 (digital information transmission) were developed in Korea. We can underline here a clear specialization of digital information transmission technologies stimulated by the Korean government through the Giga Korea program we mentioned earlier. We argue that this governmental program acted as a turning point in the innovation trajectories of Korea, which redirected the existing innovation trajectories along



The intensity of the link is indicated by the ratio of frequency of co-occurrence  $C_{ijk}$ , and it is defined as follows:

$$C_{ijk} = \frac{P_{ijk}^2}{P_{ik} * P_{jk}} \quad (1)$$

where  $i, j = 1, 2, \dots, n; k = 1, 2, \dots, m$ .  $P_{ik}$  denotes the frequency of key term  $k$  occurring in patent  $i$ ,  $P_{jk}$  denotes the frequency of key term  $k$  occurring in patent  $j$ , and  $P_{ijk}$  denotes the number of times key term  $k$  occurring with patent  $i$  and patent  $j$  at the same time.

The document-normalized correlation matrix  $C^N$  is then computed as follows:

$$C_{ij}^N = \frac{\sum_{k=1}^m C_{ijk}}{m} \quad (2)$$

where  $m$  is the total number of key terms. All values of the normalized correlation matrix ( $C^N$ ) range between 0 and 1.

We employed this quantitative analysis in addition to IPC analysis because it provides a better understanding of the scope of each technological development and its contribution to city innovation. From this perspective, IPC analysis provided, in our view, a narrower interpretation by showing the technological field to which the invention pertains. By contrast, a topic model analysis based on key term co-occurrence and the resulting clustering may generate connections between technological developments that may not be expected a priori. The resulting clusters following this analysis are presented in Table 1.

**Table 1.** Document clustering based on similarity.

Cluster No.	Cluster Name	No. of Documents	
Cluster 1	Digitization	170	Data communication technologies (5G/IoT/broadband/WiFi)
Cluster 2	Transport	32	Traffic control; navigation; vehicular communication systems (e.g., V2X); vehicle improvement
Cluster 3	Environment	21	Air and water quality; waste management; electric and hybrid vehicles
Cluster 4	Infrastructure	14	Utilities infrastructure
Cluster 5	Public services	14	Health; emergency services; education; safety and security
Cluster 6	Energy efficiency	13	Energy efficiency
Cluster 7	Leisure and public participation	9	Leisure; living improvements; shopping; public participation
Cluster 8	City management	7	City management; spatial agglomeration;
Cluster 9	Construction	4	Construction materials
Cluster 10	Other infrastructure	3	Financial infrastructure; parking infrastructure
	Total	287	

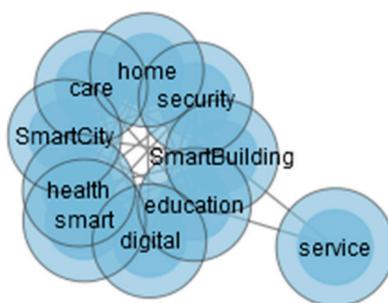
Source: author's elaboration.

In what follows, we briefly explain the composition of the main resulting clusters in terms of the number of documents, and we group them in terms of their contributions to the quality of urban life.

The first cluster was generically called "Digitization". By far, this is the largest cluster, comprising 170 documents containing technological innovation data. Here, communication techniques, methods, and apparatuses for sensor networks, cellular and mobile networks, wireless networks, machine-to-machine (M2M) communication, machine-type communication (MTC), and Internet of Things (IoT) were included. These can be utilized for intelligent service provision by and within the city. They all contribute to the development of the smart city as a whole, or to the creation and

provision of different intelligent things and services like smart homes, smart buildings, smart cars or connected cars, healthcare, digital education, smart retail, and security- and safety-related services.

We find that some key terms tend to be strongly associated with each other, as revealed by the analysis of co-occurrence of key terms. In Figure 3, we present a co-occurrence word map for Cluster 1. The size of the nodes describes the frequency of the most frequent key terms in the Digitization cluster. It can be easily noted that the sizes of the network's nodes are similar, meaning that these most frequent key terms in Cluster 1 tend to co-occur together.



**Figure 3.** Co-occurrence network of words in Cluster 1: Digitization. Source: author's elaboration.

Digitization offers the means to improve a plethora of aspects related to the quality of urban life. Several dimensions of the complex construct of the quality of urban life can be identified to co-appear with each other, and with the term 'digital' at the same time (e.g., health, education, construction, security, care for individual needs, aspirations, lifestyles, etc.). This suggests that there is a strong interdependence between the dimensions of the quality of urban life. The performance of one dimension clearly influences the performance of the others and the overall perception of quality of urban life. The co-occurrence of the term 'digital' with the various dimensions of the quality of urban life confirms the ubiquitous character of ICTs, which continuously reshapes and reconfigures all aspects of urban life, transforming the social and economic urban landscapes.

The second cluster in terms of number of documents was generically called "Transport" because it includes technological innovations aiming at improving various aspects of transportation within cities. It is the most closely associated item to the **urban mobility** dimension of the quality of urban life. More precisely, the technological innovations included here relate to vehicle navigation systems, methods, or apparatuses; frameworks for large-scale monitoring, collecting, analysis, modeling, and visualization of vehicular mobility over communication networks and other traffic control systems; vehicular communication technologies (e.g., autonomous cars, vehicle-to-grid, vehicle-to-everything); and traditional vehicle improvements (e.g., city bus, freight vehicles). The main benefit that these innovations bring to the city is the reduction of traffic congestion in the cities, thus leading to reduced air pollution and fuel consumption.

Next, we detail several other clusters that relate to aspects that exert a significant direct effect on the **quality of urban life**.

The "Environment" cluster includes technological developments contributing to the improvement of city water quality (e.g., city water filtration, city water aftertreatment, prevention of toxic substance leakage into city water), technological developments contributing to the improvement of city air quality (e.g., air quality measurement, air pollutant filtering), technological developments improving the processes of treatment and disposal of waste materials, and technological developments improving electric and hybrid vehicles (e.g., power switching according to the degree of pollution along the route, power loading systems).

Cluster 4, "Infrastructure", groups the technological developments aiming at improving the utilities infrastructure of a city (e.g., pipelines for water, city gas, heat, electricity, petroleum, and the sewage system). Smart metering technologies, which optimize network performance with new control

systems, and smart grids are but a few current developments that cities can implement to improve their overall economic, social, and environmental performance.

The “Public services” cluster (Cluster 5) includes the technological developments related to the provision of emergency services, education, health, parking, surveillance, and remote security scanning. These developments show a great potential to increase the quality of life of urban residents. The city is a complex socio-technical system in which public services can be optimized through the use of digital telecommunication technologies.

Cluster 6 includes technological innovations related to increasing the energy efficiency of a city, such as the development of intelligent households’ IoT energy systems, the optimization of warming, heating, and lighting devices, the building of power generators, the development of hybrid and integrated wind–solar–diesel–city power supply systems, and the increasing of the heat value of fossil fuels.

Leisure and public participation (Cluster 7) groups technological developments that boost citizen wellbeing and support the delivery of more efficient, inclusive, and sustainable urban services and amenities. We included here: methods and platforms for citizen engagement; ‘one-stop shops’ for solving resident inquiries; free public WiFi areas; co-creation and co-production methods (with citizens); maps of recreative activities; augmented reality, 3D city modeling, or virtual spaces within cultural, sport, and touristic initiatives; and city furnishing and urban décor materials. Additionally, technological innovations for the improvement of public security and public safety in the urban environment in general and in recreational areas in particular (e.g., in parks, playgrounds, museums, sports fields, and other cultural amenities) contribute to the quality of urban life.

Institutions play a decisive role in fostering the transformative capacity of a city, which upholds the efforts that cities make in their transformative journey towards sustainability. Technology by itself will make a city neither smarter nor more livable, but it is the city governance that puts the technological advancement at the service of the citizen. Particular attention must be given to the political understanding of technology with particular focus on social, economic, and ecological gains.

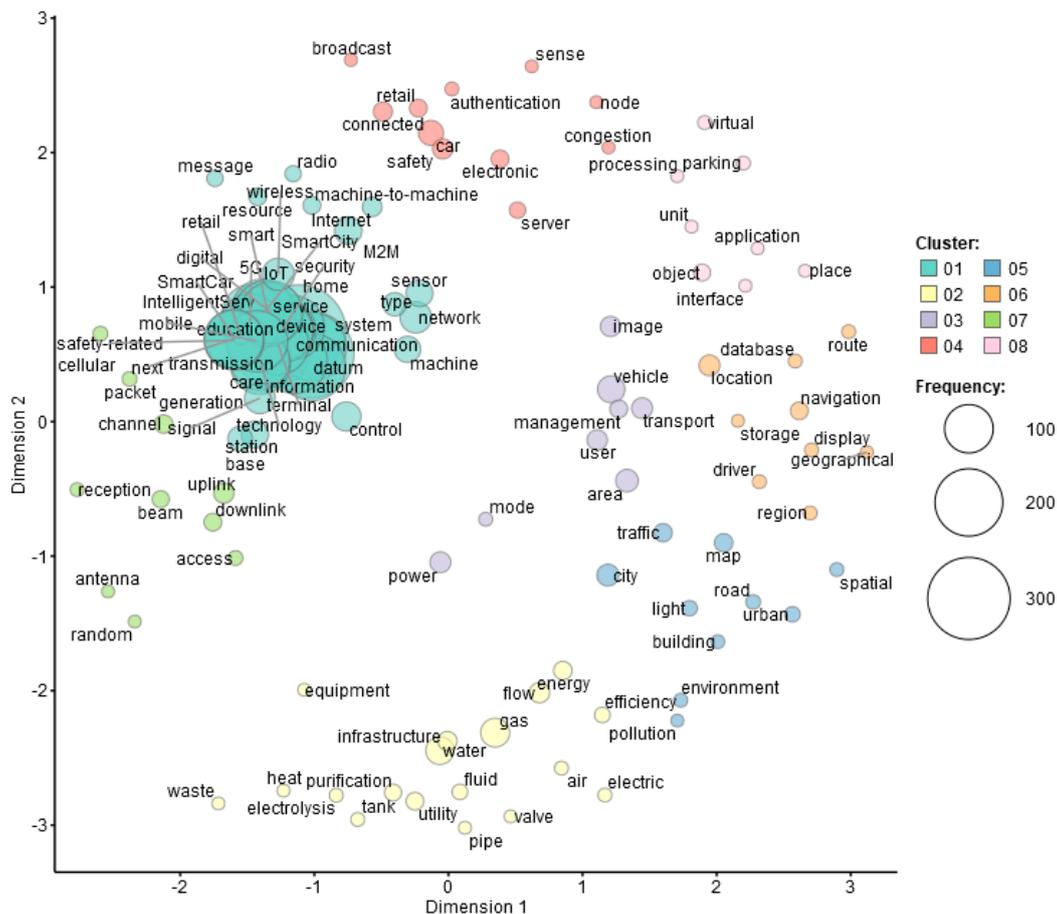
Technological developments related to city innovation interfere in the institutional context of a city in several ways. First, by providing real-time data on different variables of interest (e.g., air quality, traffic, water and heat flows, public participation), technological innovations uphold city governance in making the right policy choices and implementing them in an efficient and effective manner. Secondly, technological developments from the field of digitization contribute to the increasing of the rationality of the city government by supporting the decision-making processes and the implementation of the decisions. Thirdly, technological developments allow city governments to interconnect and integrate information, processes, institutions, and physical infrastructure, transforming towards a new state of electronic city governance to better serve citizens and communities. Last, but not least, the latest technological developments enhance urban collaboration among different institutional actors in order to maximize the social, economic, and ecological performance of cities.

Further on, we employed text data visualization techniques to analyze our dataset. Data visualization allows us to recognize patterns that can be further tested.

In order to identify the structure in the set of proximity measures between patent data documents, we used multidimensional scaling. Multidimensional scaling (MDS) is a set of related statistical techniques often used in data visualization for exploring similarities and dissimilarities in data [58]. An MDS algorithm starts with the matrix of item–item similarities and then assigns a location in a low-dimensional space to each item, making it suitable for visualization [59]. This is performed by assigning observations to specific locations in a conceptual low-dimensional space such that the distances between points in the space match the given (dis)similarities as closely as possible. The result is a least-squares representation of the objects in that low-dimensional space [60].

The MDS plot shown in Figure 4 provides us with the technology space of city-related technological developments over the investigated period. The nodes (or bubbles) that appear in the same broad technology cluster share a similar knowledge base, or show that the competencies used in the production

of one technology can be easily reconfigured to develop another related one. The size of the nodes illustrates the number of patent documents that mentioned the respective key term.



**Figure 4.** Multidimensional scaling (MDS). Source: author’s elaboration.

The technological innovation similarity analysis through MDS shows the inter-connectedness of different urban amenities that play key roles in the quality of urban life. Urban amenities are precisely those that make places attractive for living and working. We identify a corresponding nexus between urban amenities and public goods and services. In addition, we note that the ICT cluster is located the closest to the urban mobility dimension of quality of urban life, showing a greater involvement of ICTs in providing urban mobility and transport. The most distant from the ICT cluster is the utility infrastructure cluster. Here, we find technologies that ensure the quality of utilities—the basic elements that define the quality of urban life (e.g., heat, water, gas, electricity, sewerage).

In order to describe the relationships between key terms in a low-dimensional space while simultaneously describing the relationships between the patent documents they pertain to, we used the correspondence analysis. Correspondence analysis (CA) is “an exploratory multivariate technique that converts a matrix of nonnegative data into a particular type of graphical display in which the rows and columns of the matrix are depicted as points” [61]. It has been used extensively as a method of graphical data analysis in other fields of study for a long time [62,63].

Both MDA and CA analyze high-dimensional datasets, capture the essential components, features, or structures, and represent them in a lower-dimensional space. In particular, CA is a fundamentally graphic method of data interpretation that involves two categorical variables [64].

In our case, the two categorical variables are represented by patent applications (documents) and their associated key terms. The contingency table has 287 rows (total number of documents) and 7353 columns (total number of key terms). Figure 5 shows the “map” of the contingency table

resulting from applying correspondence analysis. Technological developments are mapped according to their similarity in their distribution of key terms, with closer technological developments being more similar, while distant ones are more different. The plot shows only the most important key terms that contribute highly to the positioning of the patent documents on the map.

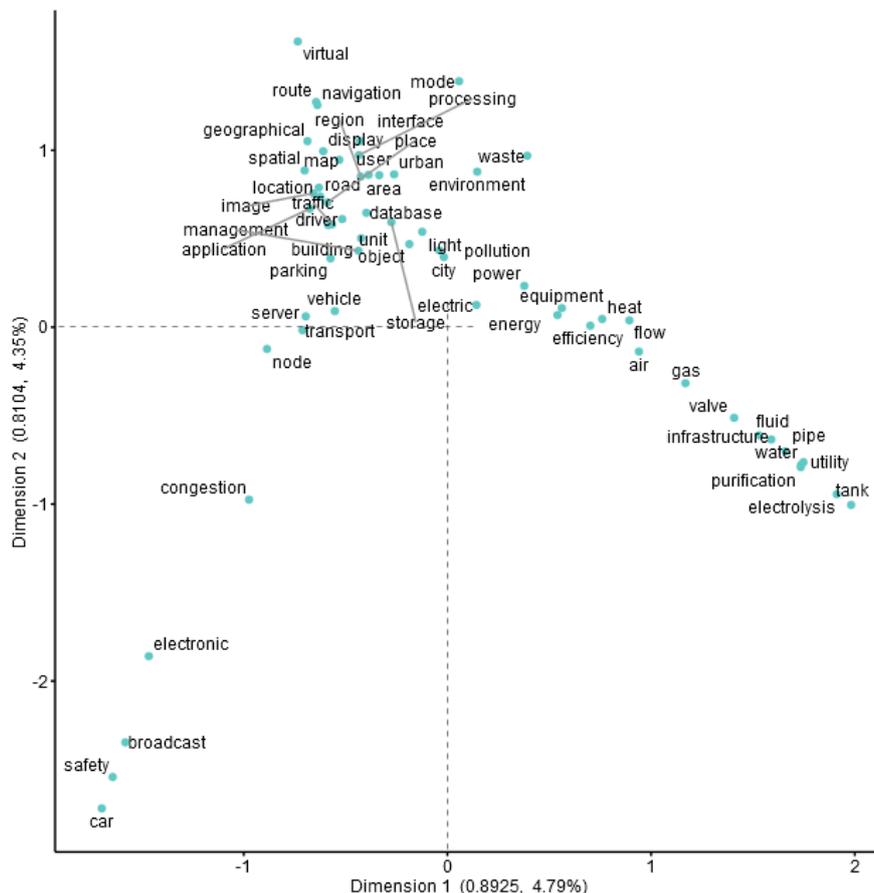


Figure 5. Correspondence analysis. Source: author's elaboration.

The correspondence analysis clearly shows a large set of key words and documents positioned in the upper left side, and a small set of key words and documents emanating from the larger set and spreading towards the bottom right corner of the map. The larger group comprises technological innovations (and their key terms) that intensely rely on information and communication technologies (ICTs), whereas the extension towards the bottom right corner comprises mechanical engineering innovations (and their key terms).

Although further analysis of each of these technological developments related to city innovation is needed to fully understand the individual nuances, this analysis is a useful way of considering the trajectories of city innovation developments in various countries, the overall technology space of city innovation, and what stage of development a technology is in. Examination and prediction of patterns of technological developments guide city officials on the opportunities and timings of their adoption.

## 6. Technological Innovation for Increasing the Quality of Urban Life

In this section, we discuss how the identified technological innovations contribute to the improvement of the quality of urban life.

**Digitization** offers the means to improve all aspects of urban life (e.g., urban mobility, urban infrastructure, urban environment, city services, citizen participation in public decision-making, energy efficiency, etc.). As digitization accelerates, city managers have large volumes of data

(i.e., ‘big data’) at their disposal—data that can be analyzed via machine learning algorithms that automatically produce descriptive (what happened), predictive (what will happen), and prescriptive (recommendations to achieve the goals) analyses, which can be further used to improve the quality of urban life. Digital technologies help city managers to punctually and accurately analyze interdependent systems that are too complex for human analysis.

Urban quality monitoring systems are of particular interest in our discussion. They may monitor one or several quality performance measures of urban life, such as air quality, urban noise level, heat level, water quality, and traffic. ICT developments largely contribute to the development of such systems in the following ways:

- ICTs for data acquisition: sensor network development for real-time measurement of the quality performance of the relevant aspects, and sensor–platform communication techniques and methods; IoT technologies for signal conditioning, sensor calibration, and inference;
- ICTs for data storage: cloud and server technologies;
- ICTs for data processing: artificial intelligence, including virtual agents and machine learning algorithms for calculating the actual performance on the relevant urban quality indicators, including traffic light labeling for performance visualization; provision of predictive and prescriptive analyses; data analytics engines in the cloud;
- ICTs for communication to the urban environment: the development of application programming interfaces (APIs), user interfaces (UIs), and cloud and web services for third-party developers; real-time communication with public actors, nongovernmental organizations (NGOs), or citizens via web-based platforms or via wireless or mobile communication (e.g., cell phone alerts, mobile apps, etc.)

The quality of urban life is dependent on the scale of analysis. The urban environment is characterized by a great heterogeneity and by a wide functional diversity. The analysis at different scales (e.g., entire city, neighborhood, street, dwelling) may lead to the identification of significant differences in the quality of urban life. Digital technologies help overcome the limits of simple average values of performance and allow for intra-urban differentiation.

Next, the contribution of the **urban environment** to the urban quality of life was evaluated on the following aspects: ecology, urban mobility, public services, public participation, and leisure.

A high quality of urban life is defined by clean air, clean and safe drinking water, effective wastewater treatment, proper waste disposal, availability of utilities, and low levels of criminality and violence. Air pollution is a major problem in urban environments and results in different damage components (e.g., human health damage, ecosystem damage, architecture damage). Individual health and wellbeing depend on air quality, which has social and economic implications. Air quality-related innovations identified by this study include: air quality performance (e.g., systems, modules, and methods for air quality monitoring and public alerts; personal protective equipment (PPE) that detects harmful substances in the ambient air around a user, such as particulate matter and toxic gases, and communicates this information to the user and other interested parties), city air purification and methods for the automatic cleaning of air filters, and the removal of carbon dioxide from city gas in order to obtain a methane-rich gas mixture with less harmful effects on the urban environment. Even so, recent innovations on carbon capture and storage (CCS) allow firms to recycle the extracted carbon emissions instead of storing them underground.

**Urban mobility and transport** are among the issues considered in the multidimensional model of the quality of urban life. A well-organized transport system favors the reduction of air pollution and traffic noise, and improves urban safety, citizen mobility, citizen health, and exploitation of public amenities. Given the fact that urban transport generates large amounts of emissions of carbon dioxide and noise that affect human wellbeing, innovation was assumed to build smart urban mobility systems that optimize the urban transport and logistics system, eliminate traffic congestion, and ensure rapid movement to any point in the city. For instance, technological innovations can be used to build systems

for large-scale monitoring, collection, analysis, modeling, and visualization of vehicular mobility over a communication network and, in particular, to predict urban mobility patterns based on the mobility history of each individual, to build traffic control and management systems that use the “green wave” approach, and to control the urban congestion by re-routing traffic. These result in less idle time in traffic, in lower fuel consumption, and, therefore, in a lower environmental impact.

In addition, technological innovations allow for the development of collaborative transportation platforms and the development of new value-added services that are in line with the approach of people-centric urban mobility. According to this approach, transportation should not be only convenient, but it should also be enjoyable, meet the needs and lifestyles of users, be fast, reliable, and on-demand, and lead to healthy lifestyles. Mobility as a service (MaaS) is an example of such a collaborative urban mobility platform that provides users with a choice of transportation options that best suit their needs. Urban mobility also has to meet the growing need for cleaner modes of transport. A large number of technological developments that we identified relate to the development and the operation of electric and hybrid electric vehicles, and to vehicular communication systems (e.g., vehicle-to-grid, vehicle-to-everything autonomous cars).

Clearly, the provision of **public services** is paramount to ensuring the quality of urban life. Technological innovation enables public institutions to radically improve the ways in which they operate to better respond to the needs of city residents. Additionally, residents demand greater efficiency, transparency, and improvements in management of public goods and services. Technological innovations offer the means to develop data platforms through which municipalities gather demands and needs from residents in a timelier manner regarding the provision of the public services.

**Municipal waste management** affects human health and city ecology without a doubt. The use of technological innovation for the improvement of municipal waste management leads to a better quality of life. More precisely, in terms of waste collection, sensors can be used to collect data on weight and volume at every waste collection point, which can be used to schedule waste transport or to predict waste production volumes. In terms of waste disposal, we found technological innovations for recycling, for recovery (such as ‘energy from waste’), for treatment of waste materials, and for improved final disposal followed by monitoring.

A good quality of urban life means access to all the needed utilities. **Utility infrastructures** influence the quality of the provided good (e.g., water, electricity, heat, gas, sewerage), and need to be reliable. A good water management system not only provides city residents with clean fresh water, which is vital to their health, but also cares for the ecological environment. In this respect, we found technological innovations for water waste reduction (e.g., smart meters), water filtration, water aftertreatment, and prevention of toxic substance leakage into city water. Similarly, technological development allowed for the electrical system to incorporate extensive monitoring capabilities, extensive communication, autonomous control, and management functionalities (e.g., smart grids).

**Public security and public safety** (including fire and emergency medical services) contribute to the quality of urban life by ensuring a safe urban environment for living. The performance of these public services determines the health of the citizens, while their associated satisfaction leads to higher social involvement, interaction, participation, and, thus, the existence of happier citizens.

A high degree of **participation and control by the public** over the decisions affecting their lives, health, and wellbeing is another prerequisite for ensuring a high quality of urban life. With the use of technological innovations, citizens can identify problems, propose solutions, implement actions to solve them, or monitor how they are addressed by the municipality. Platforms for public engagement and methods for co-creation and co-production become realities due to technological innovation. Individual and community involvement promotes health and wellbeing in cities, increasing the quality of urban life. Active participation in communities makes a person feel happy, productive, and connected to others in his or her group.

In terms of leisure, cities provide a wide variety of resources and experiences that enhance social contact, human interaction, and communication. Parks, playgrounds, museums and other cultural amenities, sports fields, and recreation areas provide health benefits to the mind and body. We found here technological innovations for the monitoring and maintenance of these areas, digital recreational tools in the form of augmented reality, 3D city modeling, or virtual spaces for cultural, sport, and touristic initiatives, and urban furniture and urban décor materials. Leisure digitalization increases accessibility, social inclusion, community involvement, and free individual expression. Urban décor furniture increases the perceived quality of urban life by increasing the functionality and the usable amount of urban space and by improving the ambience of urban areas.

To conclude, technological innovation offers solutions to address the problems of the urban environment (e.g., pollution, traffic and congestion, waste disposal, resource limits). Additionally, we argued that technological innovation improves the quality of urban life in terms of human health, ecology and nature protection, citizen security, urban mobility and traffic control, urban public services, and leisure and public participation of citizens through co-production, co-creation, public opinion forming, and community development.

## 7. Conclusions

Technology has always been one of the main drivers of city development. Technological developments that contribute to city innovation allow for large-scale and fast-paced transformations towards city sustainability. This transition depends on the transformative capacity of a city to perform radical change within and across the multiple socio-technical, socio-economic, and environmental systems embedded in cities. The path dependencies of complex systems influence long-term trajectories of technological developments. New paths do not appear out of nowhere, but are generated within the context of existing structures and paths of technology and institutional arrangements.

In the last five years, technological developments have accelerated with exponential growth rates for ICTs, especially those related to digitization. This evolution of extremely rapid technological change lays the foundation for the implementation of the urban paradigm shift called the quest of sustainability. Information and communication technologies are by far the most rapidly evolving technological areas, comprising a number of technologies that have their own dynamics. With regard to cities, the Internet of Things (IoT) technologies provide means to link different technical platforms that service city life. From integrated traffic management to smart grids, to smart buildings, to smart cars, or to intelligent city services that monitor, predict, and react to flows in real time, city governance is now equipped with technical capabilities like never before.

In addition to the examination of national patterns of patent applications and the trajectories of technological developments according to technology class in the long run, the quantitative data mining analysis resulted in a 10-cluster framework of city innovation based on technological similarity of patent documents: Digitization, Transport, Environment, Infrastructure, Public services, Energy efficiency, Leisure and participation, City management, Construction, and Other infrastructure. In addition, the paper proposes a knowledge space of city innovation. This analysis shows the relatedness of different technological developments based on different aspects of similarity. The knowledge space of city innovation is explored with several techniques of data mining and visualization, such as multidimensional scaling, a co-occurrence network, and correspondence analysis.

Technological innovation is likely to continue to be an area of significant economic importance. We believe that this study has taken the literature one step further in the on-going debate on the trajectories of technological development and knowledge creation, which have the potential to contribute to city innovation. The findings represent a first step in clarifying the dynamics towards smart city models that were demonstrated to have a positive impact on overall city performance, defined in terms of quality of life, wellbeing, economic growth, and sustainability.

The study discussed the contributions of technological innovation to increasing the quality of urban life. Although defined by clean air, clean and safe drinking water, effective wastewater treatment,

proper waste disposal, availability of utilities, and low levels of criminality and violence, the quality of an urban environment is more than that. It is the urban environment that capitalizes on human life to its maximum potential while acknowledging individual differences in desires, needs, values, and lifestyles. Technological innovation offers the means for city managers to provide customized experiences and public services tailored to citizens' individual traits, increasing their quality of life. Public engagement and recreational activities highly contribute to the improvement of the life, health, and wellbeing of citizens.

The findings call for a holistic and integrated approach to the multidimensional concept of quality of urban life, in which there is a strong interdependence between the dimensions' performance. They offer valuable insight to policymakers as regards quality of urban life improvement, technology forecasting, enhancement of the transformative capacity of the city, and investment policy development for future sustainable development pathways of the city.

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