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Urban quantum leap: a comprehensive review and analysis of quantum technologies for smart cities

Abstract

Contemporary smart city solutions rely on standardized von Neumann architecture, in which single data units are coded as "0" or "1." Conversely, urban quantum technologies rely on the fundamental principles of quantum physics, transcending the conventions of the current computational paradigm. On the one hand, urban quantum technologies hold managerial relevance for future smart cities. On the other hand, they are often overlooked by smart city researchers. Accordingly, their value as a breakthrough technological paradigm is still largely unexplored. In this article, we look at how quantum technologies may contribute to existing smart city solutions, including the Internet of Things, cloud computing, big data, ICT, smart transportation, artificial intelligence, and blockchain. First, through a semi-systematic review of eighty articles on quantum computing within the social science domain, we identify two relevant classes of urban quantum technologies: quantum communication and quantum computing. Second, we establish a comprehensive taxonomy of conventional smart city solutions based on the automated content analysis of 567 abstracts of articles on the technological aspects of smart cities. Third, we investigate potential associations between two classes of technologies (conventional smart city solutions and urban quantum technologies) by analyzing the semantic relationships between eighty articles on quantum technologies according to the frequency of keywords denoting different types of conventional smart city solutions. Finally, we triangulate our findings through a thematic analysis of potential uses of quantum technologies within identified categories of smart city solutions.

Keywords: *smart city, quantum city, smart city technologies, urban quantum technologies, semi-systematic literature review, thematic analysis*

List of abbreviations

QTs	quantum technologies
QC	quantum computing
QCM	quantum communication
SCTs	smart city technologies
ICT	information and communication technology
AI	artificial intelligence
IoT	Internet of Things
PCA	principal component analysis
SEM	structural equation modeling
PLS-SEM	partial least squares structural equation modeling
PLSc-SEM	consistent partial least squares structural equation modeling

1. Introduction

The concepts and metaphors of twentieth-century urban theory (Joss et al., 2022) are no longer optimal in dealing with contemporary cities' growing complexity, uncertainty, and risk (Arida, 2002; Macionis & Parrillo, 2017). While grand narratives of the past lose their explanatory power, novel urban metaphors and concepts are becoming increasingly relevant (Lynch, 1984, 1990).

The changes in urban theorizing relate to various social, economic, demographic, and technological factors (Anthopoulos, 2017). As for the latter, we may distinguish two categories of technology-driven urban changes. On the one hand, there is a shift toward smart cities and, more generally, a sustainable smart city paradigm (Bifulco et al., 2016). Investing in research, development, and use of smart technologies influences future urban growth. Indeed, cities' growth can be governed more effectively by adopting innovative technologies (Bibri, 2018). Furthermore, those technologies, including information and communication technology (ICT), artificial intelligence (AI), Internet of Things (IoT), blockchain, and big data, are critical to urban sustainability (Bibri, 2018; Bifulco et al., 2016; Gouvea et al., 2018; Quan et al., 2019).

On the other hand, the further development of quantum technologies (QTs) makes their adoption in future smart cities more likely. The quantum paradigm is a fruitful metaphorical foundation for examining increasingly complex urban-related topics. It incorporates language, imagery, and concepts from quantum physics (Arida, 2002), such as uncertainty, duality, and entanglement, to address the issues of urban complexity and risk more effectively (Bashirpour Bonab, Fedele, et al., 2023). Unlike conventional smart city solutions, quantum urban technologies rely on the fundamental principles of quantum mechanics and, therefore, promise greater accuracy, computational power, speed, and efficiency.

Due to the complexities of quantum theory, the quantum city metaphor can be challenging to communicate to the public properly. Nonetheless, with the growth of practitioners' interest in quantum technologies, engaging end-users through effective communication is essential (Arida, 1998, 2002). Hence, the implementation of proof-of-concept quantum cities, like Hefei in China (Courtland, 2016), serves as a viable example of what the urban future might be.

In this article, we investigate how conventional and quantum smart city technologies are related. Accordingly, we first perform a semi-systematic review of eighty articles on quantum technologies within the broader social science domain. We prioritize urban-related academic contributions in selecting and including the articles in the review. After finding which QTs are the most important for cities, we derive a taxonomy of conventional smart city solutions based on the semantic analysis of 567 abstracts of articles on the technological aspects of smart cities. Then, we explore semantic connections between eighty articles on quantum technologies according to the frequency of selected keywords denoting different classes of conventional smart city solutions (as derived in the previous step). We investigate semantic relationships between the eighty articles by employing principal component analysis, agglomerative hierarchical clustering, and partial least squares path modeling. 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, we perform a methodological triangulation of quantitative results through a qualitative thematic analysis of potential uses of quantum technologies within the identified domains of conventional smart city solutions.

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

Detailed taxonomies of quantum technologies are still rare in the literature. Among the few existing, the taxonomy proposed by Acín et al. (2018) is one of the most comprehensive. The authors distinguish four classes of QTs: 1) quantum communication, in which entangled photons are used to transmit data securely; 2) quantum simulation, in which quantum systems are used to imitate phenomena that are impossible to simulate by a classical Turing machine; 3) quantum computation, in which quantum physics principles are used to speed up specific types of calculations; 4) quantum sensing and metrology, in which the higher sensitivity of quantum systems to outside perturbations is used to increase the precision of physical measurements.

To understand which types of QTs are potentially useful in smart cities, we performed a structured literature search. We carried out five separate searches on Scopus based on the keywords derived from the taxonomy of Acín et al. (2018) ("quantum communication," "quantum simulation," "quantum computation," "quantum sensing," and "quantum metrology"). We used the *in-title* specifier to limit the results to articles directly related to the topic of interest. We also restricted the results to the domains of "Social Sciences," "Business, Management and Accounting," "Decision Sciences," and "Economics, Econometrics, and Finance" to exclude literature that was too technical or not pertinent to the interests of urban scholars. Finally, we put no restrictions on the types of articles, allowing for insightful "gray" literature to be included.

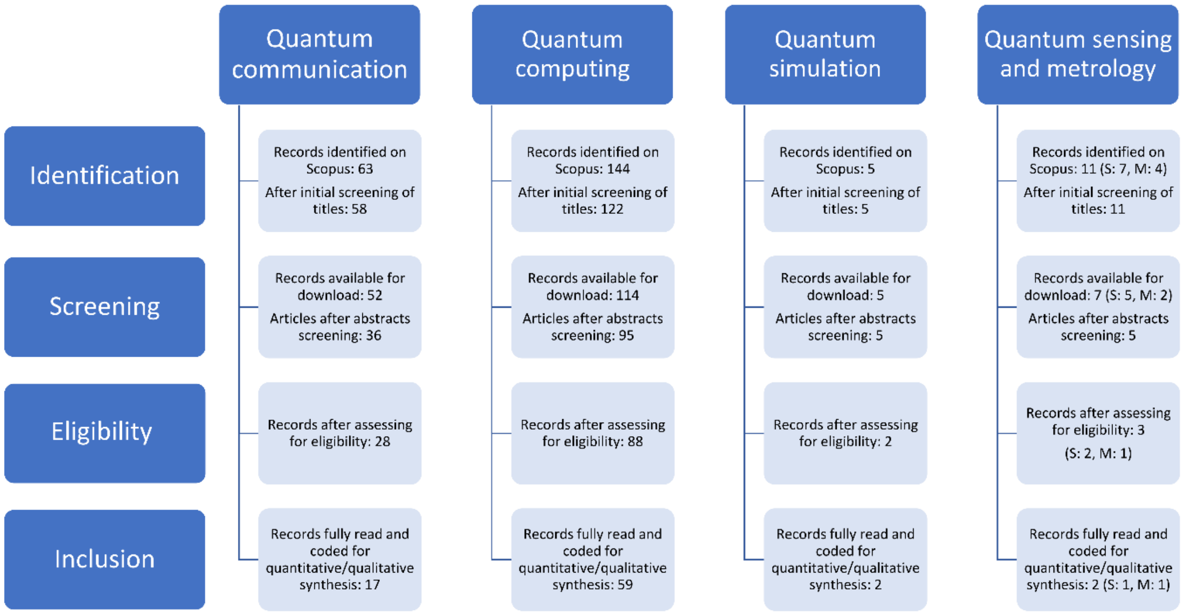
The choice of Scopus is in line with the suggestion of Gusenbauer and Haddaway (2020). According to the authors, Scopus is a suitable search engine for systematic and semi-systematic literature reviews in different social science fields (Gusenbauer & Haddaway, 2020). We also performed similar searches on Web of Science, ProQuest, ScienceDirect, and Wiley Online libraries (Gusenbauer & Haddaway, 2020). However, as the identified articles largely overlapped, only the results from Scopus were considered. No forward or backward searches were carried on. Therefore, to ensure that all the key articles were included, we performed a complementary set of searches on Google Scholar (Gusenbauer & Haddaway, 2020). However, as the additional academic articles identified on Google Scholar were of dubious quality, we excluded them from the final analysis. In total, we identified 196 articles.

We then assessed the abstracts, collegially discussing the inclusion of the related articles in the review. We preferred a semi-systematic literature review to a systematic one, as our primary goal was not a comprehensive assessment of the totality of the literature on a narrow topic but a derivation of a taxonomy of urban QTs based on academic articles of heterogeneous nature and from different sub-fields of social science (Snyder, 2019). We also gave urban-related contributions more weight in evaluating articles for inclusion to ensure that the qualitative coding results were trustworthy.

Although we opted for a semi-systematic literature review, we closely followed the Preferred Reporting Items for Systematic Review (PRISMA 2020) flow diagram to identify, screen, and include articles in order to ensure a higher degree of replicability (Liberati et al., 2009; Brennan & Munn, 2021; Page et al., 2021). Figure 1 shows the four selection stages in line with the PRISMA 2020 framework. Overall, eighty articles were included in the review.

As our primary goal was not to assess the totality of academic literature on the topic but to derive a taxonomy of urban QTs through a semi-systematic review, we do not exclude that some articles on the application of QTs in cities could have been omitted. However, we considered the eighty papers included in the review sufficient to achieve theoretical saturation, as the two relevant types of quantum technologies emerged early on, and no additional category was added to the taxonomy in the later stages of the coding process (Low, 2019).

Figure 1. Identification and selection of articles on quantum technologies



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We imported the downloaded articles into qualitative data analysis software (MAXQDA) and performed their qualitative open coding. We then collegially reviewed and discussed the initial code structures (St. Pierre & Jackson, 2014). As a result, two categories of urban-related quantum technologies emerged: quantum computing (QC) and quantum communication (QCM). Lower-level codes denoting the usage of quantum technologies in urban contexts were also analyzed and aggregated for both QC and QCM categories. Conversely, quantum simulation, sensing, and metrology (Acín et al., 2018) did not emerge as separate categories during coding.

What follows is a brief thematic synthesis of potential contributions of quantum communication and quantum computing to smart cities as derived from the coded literature. We report a more detailed thematic analysis of the contributions of the two types of quantum technologies to individual types of conventional smart city solutions in the later section of the article.

Table 1. Quantum communication and computing in quantum cities. A thematic synthesis

Quantum technology	Main themes and topics	Contributions
Quantum communication	Quantum communication in cities involves securely transferring and exchanging quantum information between distant urban communication nodes connected via quantum channels through qubits (units of quantum data).	(Y. Liu et al., 2010; Sauge et al., 2007)
	One prominent feature of quantum communication is quantum teleportation. The purpose of quantum teleportation is to send an arbitrary quantum state to a distant location (e.g., to another communication node across the city) without sending the physical object that carries the state. Conventional communication technology makes such a task impossible. Conversely, quantum physics provides a viable solution.	(Aspelmeyer, M et al., 2006; Chehimi & Saad, 2021; Lele, 2021)
	Quantum communication includes high-quality long-distance quantum channels that can accommodate the growing complexity of urban infrastructure. The defining feature of quantum communication networks in cities is the capacity to use and connect heterogeneous technologies in a modular and dependable manner. As a result, technologies as different as shopping systems, 6G networks, IoT, blockchain, financial modeling, traffic optimization, weather forecasting, medical systems, AI, and solar capture systems can benefit from the effective deployment of urban quantum communication.	(Al-Mohammed & Yaacoub, 2021; Aspelmeyer, M et al., 2006; Carvacho et al., 2021; Chehimi & Saad, 2021; T.-Y. Chen et al., 2010; Chou et al., 2014; Lele, 2021; Nema & Nene, 2020; Resch et al., 2005)
	Quantum Internet is a QCM system in which sensing, communication, and computing work simultaneously to exchange information between sensors, computers, and networks. Such technology can substantially increase the efficiency and security of urban communication infrastructure. However, establishing a broad physical entanglement distribution is necessary to improve the quantum internet's robustness and channel capacity. As a result, city managers, administrators, and planners should be ready to upgrade current communication systems to implement the first viable quantum internet solutions.	(Lele, 2021)
	One of the most critical issues in quantum communication is security. Today, information security is an important goal for smart city managers, administrators, and planners. On the other hand, fully working quantum computers can break conventional cryptosystems. As a result, traditional communication protocols are potentially no longer safe, prompting researchers to design more secure cryptographic systems.	(Lele, 2021; Malluh et al., 2014; Monz et al., 2016; Tsai et al., 2005; Wei & Zhang, 2019)
	Quantum key distribution is a promising quantum security method. It allows two legitimate remote users (for example, users in different parts of a city) to establish a shared secret key via photon transmission and use it to encrypt or decrypt messages. Post-quantum cryptography (also known as quantum-safe, quantum-proof, or quantum-resistant cryptography) refers to cryptographic methods that rely on public-key algorithms and are secured against a quantum computer attack. Post-quantum cryptography is concerned with improving existing algorithms and standards to prepare current systems for the era of quantum vulnerability. An efficient post-quantum cryptography system	(Aspelmeyer, M et al., 2006; Bennett & Brassard, 1984; Chou et al., 2014, 2014; Malluh et al., 2014; Piacentini et al., 2015; Tsai et al., 2005; X. Zhang et al., 2015)

	implemented in an urban context should withstand quantum computer attacks on the city's infrastructure while securing properties such as variability, unforgeability, identifiability, and confidentiality.	
Quantum computing	Quantum computers are the next-generation technology that has the potential to alter the economic, industrial, academic, and social landscapes of contemporary cities. Quantum computing relies on the fundamental principles of quantum physics, such as entanglement and quantum superposition, and thus transcends conventional von Neumann architecture.	(Elhaddad & Mohammed, 2016; Inglesant et al., 2021; Meng, 2020; Salehi et al., 2021; Taha, 2016; Ten Holter et al., 2021; Trabesinger, 2017; Uhlig et al., 2019)
	Modern-day computers store information in bits—either 0 (false) or 1 (true)—one at a time. As a result, they rely on Boolean algebra. Conversely, quantum computers work with quantum bits (or qubits). In contrast to traditional bits, a single qubit can stand for a one, a zero, or a mixed state that is both 0 and 1. In other words, a quantum computer operates on a probabilistic rather than a deterministic basis.	(Amiri, 2003; Cuffaro, 2015; Elhaddad & Mohammed, 2016; Sotelo, 2019; You et al., 2009)
	Quantum computers' most significant advantage is their capacity to solve computationally demanding problems, which require time, effort, and money or are impossible to perform on conventional computers. However, this does not imply that quantum architectures would completely replace the current computing paradigm. Instead, quantum computers can integrate and assist conventional computers, including in many city-related tasks and computations.	(DeBenedictis, 2020; Mosteanu & Faccia, 2021; Raisinghani & Emerson, 2001; Yetis & Karakoes, 2021)
	Artificial intelligence is one of the areas in which the synergistic effect of quantum computing can be most relevant. On the one hand, the automation of computer systems and the minimization of human intervention are two of AI's most important contributions to quantum computing. On the other hand, quantum algorithms can significantly improve unsupervised machine learning.	(Bhatia et al., 2020; Palmieri et al., 2020; Torlai et al., 2018)
	According to the analyzed literature, the most frequently mentioned areas potentially benefitting from the integration with quantum computing include 5G and 6G communications, power grid management, smart factory optimization, drug discovery, cryptography, database search improvement, blockchain, banking, finance and business, economics, simulation and modeling, weather forecasting, market prediction, disease prediction, strategic management, AI, big data, education, law, the aircraft industry, the military, IoT, and art. Integrating quantum computers into urban infrastructure may also increase inter-regional inequality due to a lack of knowledge or financial resources to acquire innovative technology. Openness and accessibility are the best ways to ensure that quantum computers' benefits outweigh their negative urban impacts. Accordingly, pertinent scientific knowledge should be made available through public campaigns and initiatives, and quantum computing capacity should be accessible via the cloud.	(Aderman, 2019; Alaminos et al., 2021; Atik & Jeutner, 2021; Bhatt & Gautam, 2019; Casati, 2020; Chambers-Jones, 2021; de Wolf, 2017; Gutiérrez-Salcedo et al., 2018; Heaney, 2019; Inglesant et al., 2021; Krendelev & Sazonova, 2018; Kumar Sharma & Ghunawat, 2019; Majot & Yampolskiy, 2015; Möller & Vuik, 2017; Shubham et al., 2019; Singh & Singh, 2016; Swarna et al., 2021; Uhlig et al., 2019; Weder et al., 2020)

	Overall, three distinct visions of QC's future can be identified. According to the first, we are on the verge of a new computing era leading to widespread consequences in all aspects of urban life. For the second, we need to focus on determining the short-term practical implications of quantum computing while avoiding futuristic speculations. The third one is a gloomier vision of "quantum supremacy," concerned with the negative consequences of the technological advantage that a quantum computer has over a conventional computer.	(Elhaddad & Mohammed, 2016; Gutiérrez-Salcedo et al., 2018; Inglesant et al., 2021; Paraoanu, 2011)
	One of the most significant threats QC poses is that it would "break the internet," making existing data encryption methods insecure. Accordingly, a substantial increase in cryptographic vulnerabilities can undermine security in financial and other critical systems in cities. The adverse effects of quantum computing on urban security highlight the need for regulations that encourage the responsible use of quantum computers in future smart cities.	(Covers & Doeland, 2020; Inglesant et al., 2021; Majot & Yampolskiy, 2015; Sotelo, 2021; F. Zhang, 2020)

Source: own elaboration

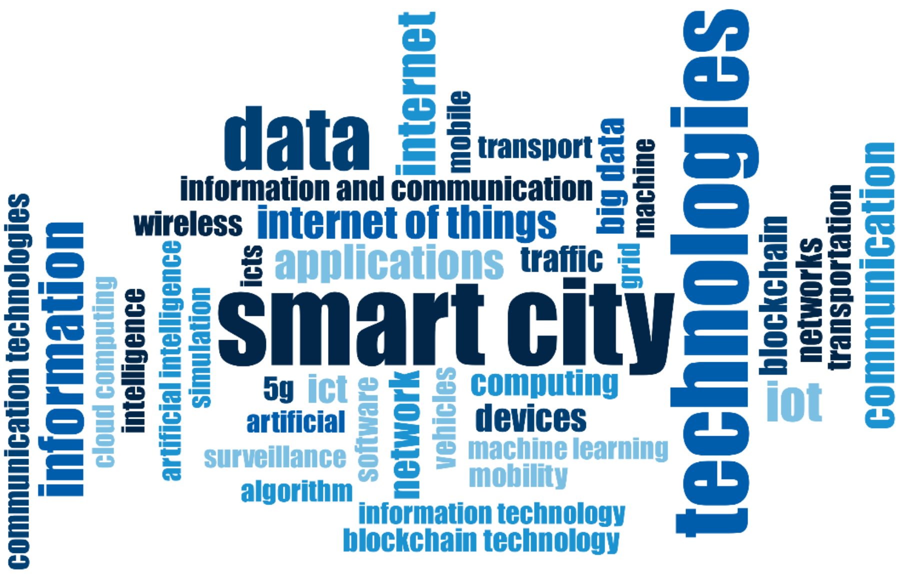
3. Investigating the relationship between quantum technologies and conventional smart city technologies

3.1 Classifying smart city technologies

Before analyzing the contributions of the two classes of quantum technologies to a smart city, we sought to derive a less speculative definition of the latter. 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 we had done in the case of quantum technologies (Acín et al., 2018), we derived the taxonomy of smart city solutions based on the automated content analysis of the abstracts of academic literature on the topic.

We used the keywords "smart city" and "technology" (linked by the AND operator) on Scopus to search and retrieve all academic records having the two keywords in their titles. Moreover, we imposed no restrictions on the academic field or type of publication. As a result, we identified 567 smart city-related academic articles (as of January 9, 2022). We downloaded and analyzed 576 abstracts in qualitative data analysis software (MAXQDA, release 22.0.1). We applied lemmatization to control for different spellings and inflected forms and then calculated the absolute frequency of all meaningful words and word combinations in the abstracts. Finally, we manually assessed the frequency table, selecting the most frequent words and word combinations related to smart city technologies. Each researcher performed the selection separately, and then we collegially decided on which words and word combinations to select in order to increase the results' trustworthiness. In total, we identified forty smart city-related keywords (Figure 2).

Figure 2. Most frequent words and word combinations related to smart city technologies



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Next, with the help of MAXQDA, we assessed how authors use those selected keywords in the abstracts. As a result, we identified seven major categories of smart city technologies: *artificial intelligence* (*AI*), *Internet of Things* (*IoT*), *information and communication technologies* (*ICTs*), *big data*, *blockchain*, *cloud computing*, and *smart transportation technologies*.

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

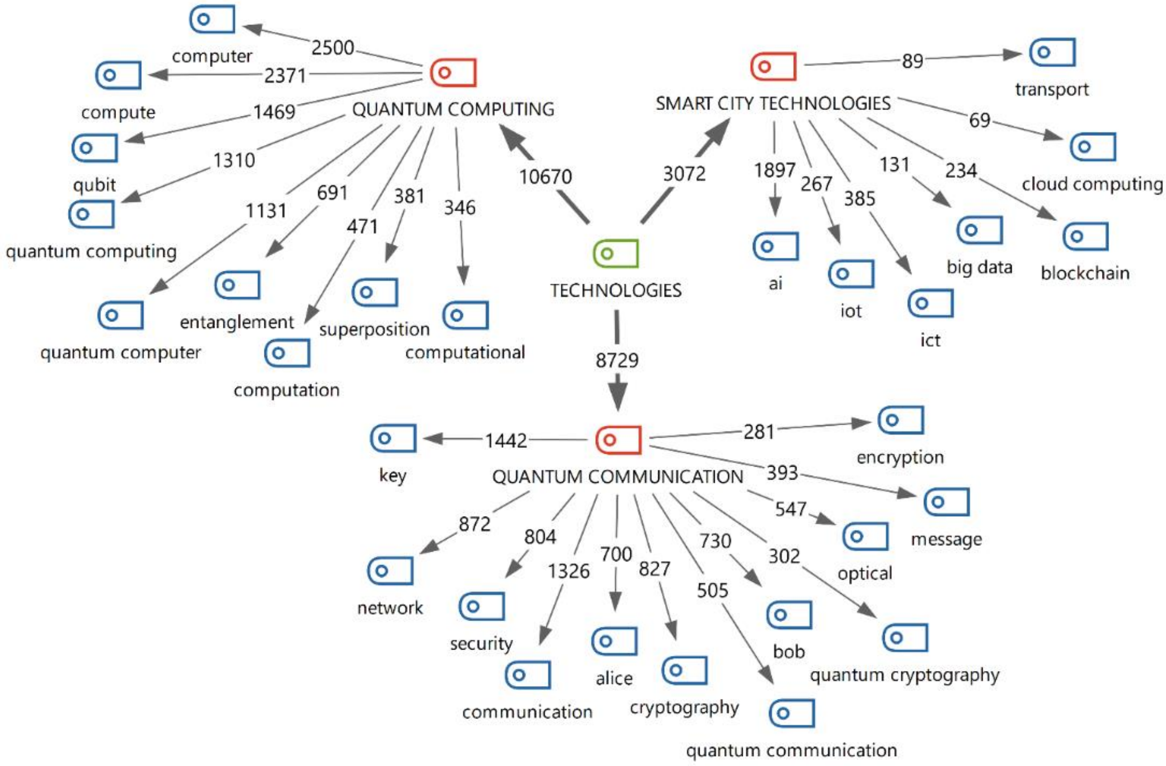
To study the potential connections between the two types of urban quantum technologies and the seven common types of smart city solutions (as determined in the previous sub-section), we analyzed how the eighty papers on quantum technologies (Figure 1) relate semantically according to the three categories of keywords (quantum communication keywords, quantum computing keywords, and smart city keywords). We performed the initial qualitative assessment in MAXQDA (release 22.0.1). We searched and automatically coded all sentences containing keywords pertinent to the seven categories of smart city technologies (see the previous sub-section). We performed similar searches and automatic coding for the quantum computing and quantum communication categories. We derived the keywords for the two categories through the thematic synthesis of QC and QCM literature (Table 1).

Figure 3 shows the hierarchical code structure resulting from the automatic coding. The numbers denote the absolute frequencies of codes across eighty articles. In all cases, we also considered the lemmatized variations of keywords (e.g., “ai” and “artificial intelligence,” “computer” and “computers”). We then transformed the absolute frequencies of twenty-eight lower-level codes into relative frequencies to account for the different lengths of the articles. We used the following formula for the calculation:

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

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).

Figure 3. Conventional and quantum urban technologies. Main themes and categories



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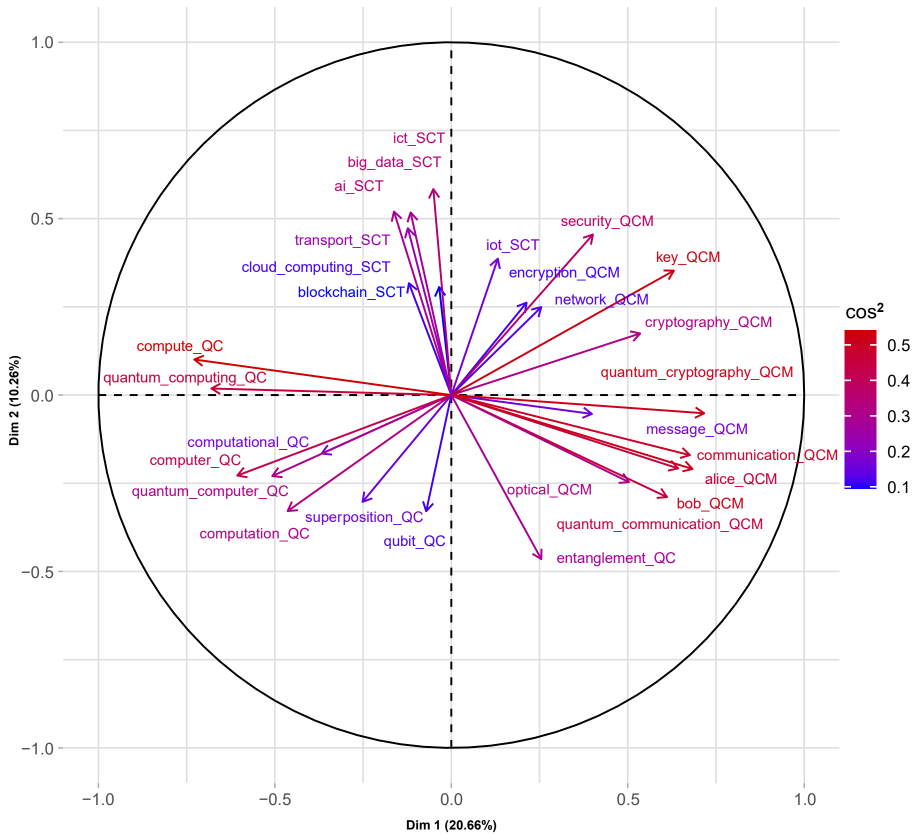
We imported the data into RStudio (version 1.4.1717) and performed a principal component analysis (PCA). Twenty-eight lower-level codes entered the analysis as active variables, yielding an equal number of uncorrelated dimensions. This implies that the twenty-eight keywords (Figure 3) are mostly uncorrelated between the retrieved articles. However, the first two dimensions stood out, accounting for approximately 31% of the total inertia, which, in turn, indicated the presence of commonalities and thematic clusters within the analyzed literature. As the remaining principal components did not noticeably contribute to the overall variability, we analyzed only the first two PCA dimensions. Figure 4 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.

Figure 4. PCA. Relationships between QC, QCM, and SCT keywords



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As shown in Figure 4, the horizontal dimension reflects the distinction between two classes of articles—on quantum computing to the left and quantum communication to the right. Additionally, the vertical axis captures the relevance of seven types of conventional smart city technologies (SCTs) 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, we can hypothetically distinguish four clusters of urban-related articles on quantum technologies. These are articles on QC or QCM with an emphasis on conventional smart city technologies and articles on QC or QCM without an emphasis on conventional smart city technologies.

As for relationships between QCM, QC, and SCTs, little can be inferred from the results of the principal component analysis. Indeed, as seen in Figure 4, the QCM, QC, and SCT variables are mostly orthogonal to one another. However, a closer observation reveals that articles on quantum communication are slightly more likely to contain keywords related to the Internet of Things. At the same time, the remaining SCT keywords are more likely to appear in articles on quantum computing.

We performed agglomerative hierarchical clustering to confirm our interpretation of PCA results. We used the Euclidean distance to compare the similarity between pairs of records. We also chose Ward's method as a measure of group proximity. Figure 5 shows the resulting cluster dendrogram. In addition, Figure 6 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.

Figure 5. Cluster analysis. Hierarchical tree

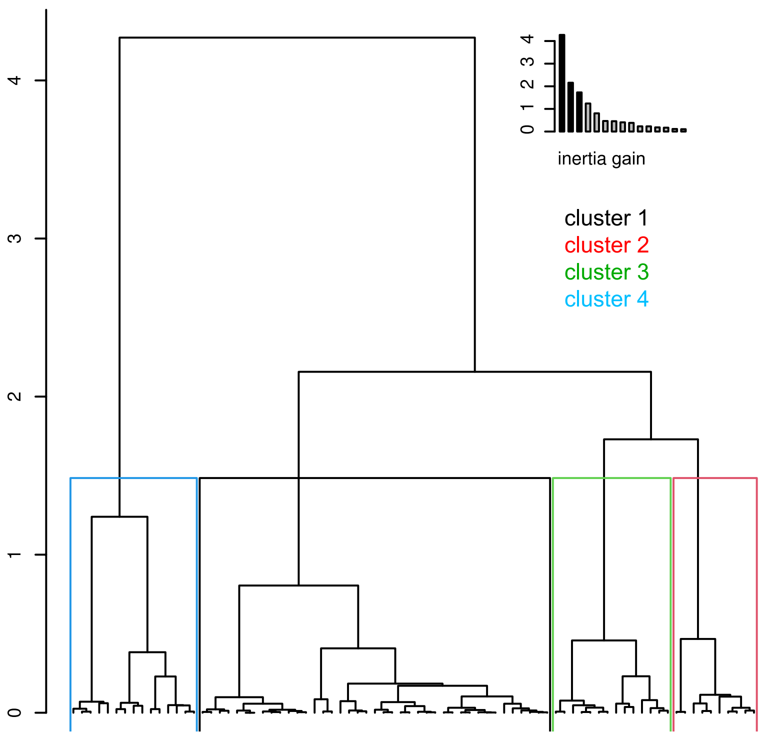

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Figure 6. Cluster analysis. The hierarchical tree projected on the factor map

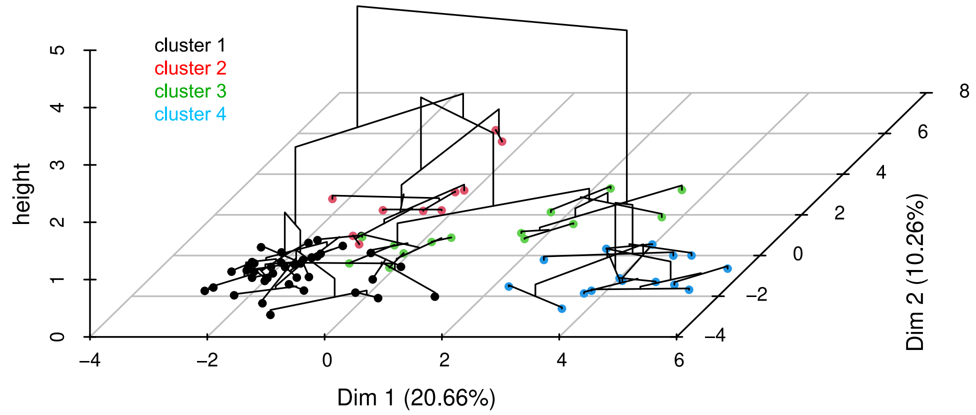

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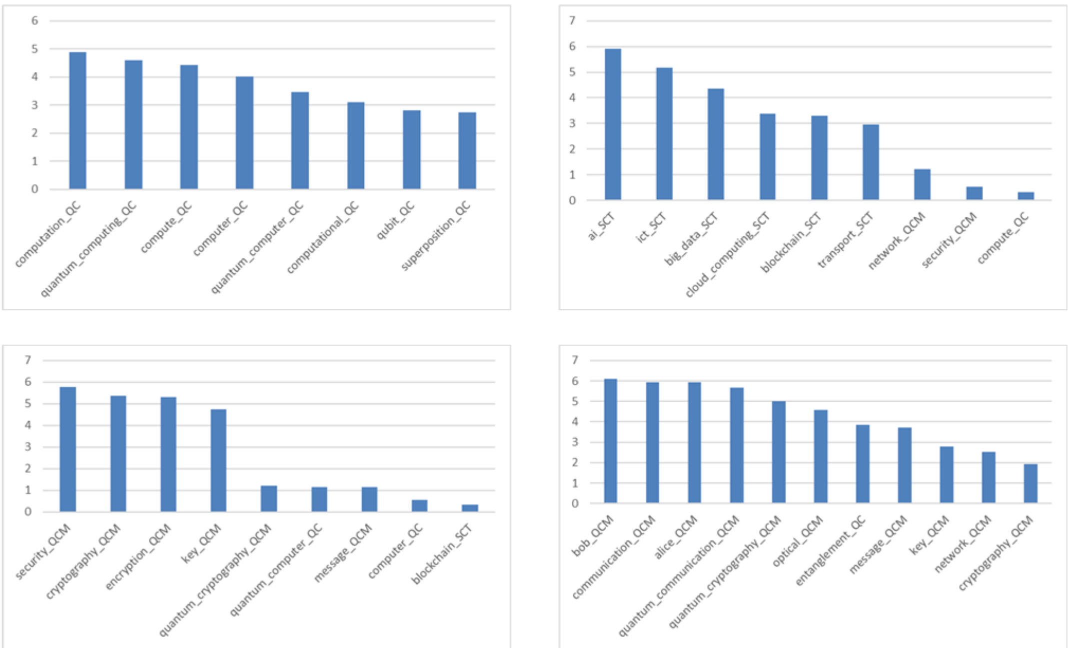
Figure 7 shows all the most significant semantic categories that (positively) contributed to the definition of clusters.

Figure 7. Most significant (p-value less or equal to 0.05) positive contributions to each cluster



N.B. top left – Cluster 1; top right – Cluster 2; down-left – Cluster 3; down-right – Cluster 4

Source: own elaboration

Cluster analysis partially confirmed the interpretation of PCA results. In particular, clusters 1 and 4 reflect the categorization of articles according to their belonging to the quantum computing (all contributing variables are QC variables) or quantum communication (QCM variables predominate) categories. On the other hand, cluster 2 contains articles that primarily deal with conventional smart city technologies but also mention quantum technologies (all three classes of variables are present, and SCT variables are predominant). By analyzing the variables contributing to the definition of cluster 2, we may conclude that AI is the most discussed topic in the literature of that 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 (i.e., the “blockchain” variable).

As a final step, we used structural equation modeling (SEM) to understand how SCTs, QC, and QCM are semantically related within the literature. While it is uncommon to use the SEM framework for purely exploratory purposes, partial least squares structural equation modeling (PLS-SEM) has been recommended as appropriate if the research is exploratory or with the goal of identifying key “driver” constructs (Hair et al., 2011). In particular, we preferred the PLS-SEM because it is less strict regarding the assumptions about the underlying data distribution and is often considered superior to other SEM frameworks when the sample size is relatively small (Ravand & Baghaei, 2019).

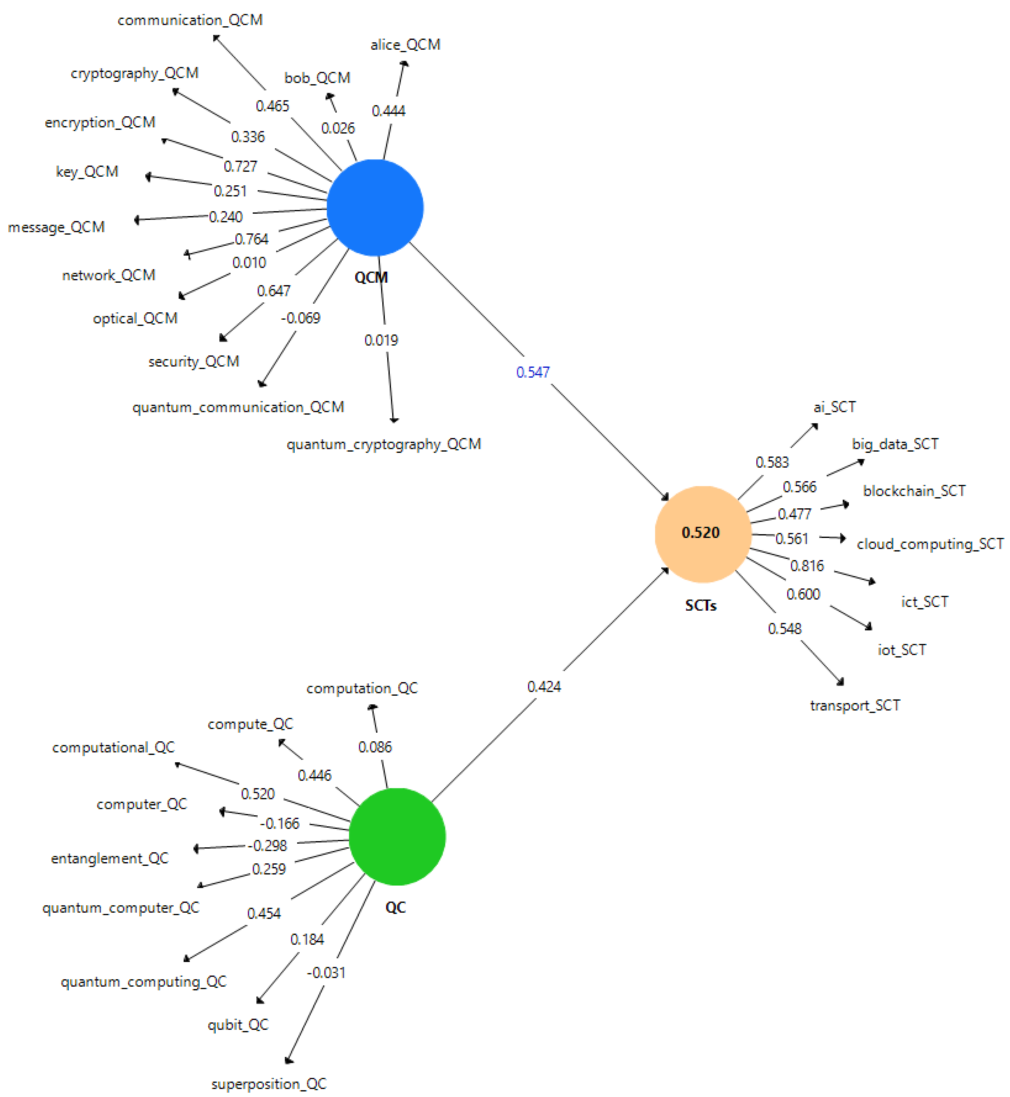
We treated twenty-eight lower-level categories (Figure 3) as observed variables. We used these to define three latent variables (SCTs, QC, and QCM, corresponding to the three upper-level categories in Figure 3). Contrary to the previous analyses, we did not treat the twenty-eight variables as relative frequencies but instead as occurrences. Consequently, they were coded as "0" or "1," depending on whether they were present in the articles. The discretization was crucial as it allowed for better interpretability of the results, even if some variability was lost in the process. Moreover, according to Kupek (2006), using binary variables within the SEM framework is legitimate, and the classification performance is broadly similar to that of logistic regression.

We analyzed the two models. We run both using the path weighting scheme, with the maximum number of iterations set to three hundred. First, we studied the relevance of quantum communication and quantum computing topics for conventional smart city technologies (Figure 8). Then, by reversing the logic, we looked at the relevance of seven categories of conventional smart city technologies within the retrieved quantum communication and quantum computing literature (Figure 9). In both cases, we assumed the reflective measurement model. Accordingly, we applied a consistent PLS algorithm (PLSc-SEM) to correct reflective constructs' correlations (Dijkstra, 2010).

According to the resulting path coefficients of the first model (Figure 8), quantum communication is more likely than quantum computing to be discussed in conjunction with smart city-related topics (path coefficient 0.547 > 0.424). The closer conceptual connection between quantum communication and conventional smart city technologies was also confirmed by a thematic synthesis of the retrieved papers (see the following section). Conversely, bootstrapping revealed that both path coefficients are statistically insignificant at the 5% level. The model's fit was 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, we deemed it acceptable for exploratory purposes. On the other hand, the fit was better when the formative model was estimated (standardized root mean square residual equal to 0.107). However, a precaution is needed in interpreting fit statistics for the PLS-PM framework, as they are still in the early stages of development (Hair et al., 2017).

In terms of construct reliability and validity, the three latent variables were appropriately 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 (Figure 8). Given the exploratory purpose of the analysis, we decided to keep them in the model.

Figure 8. PLSc-PM. Model 1



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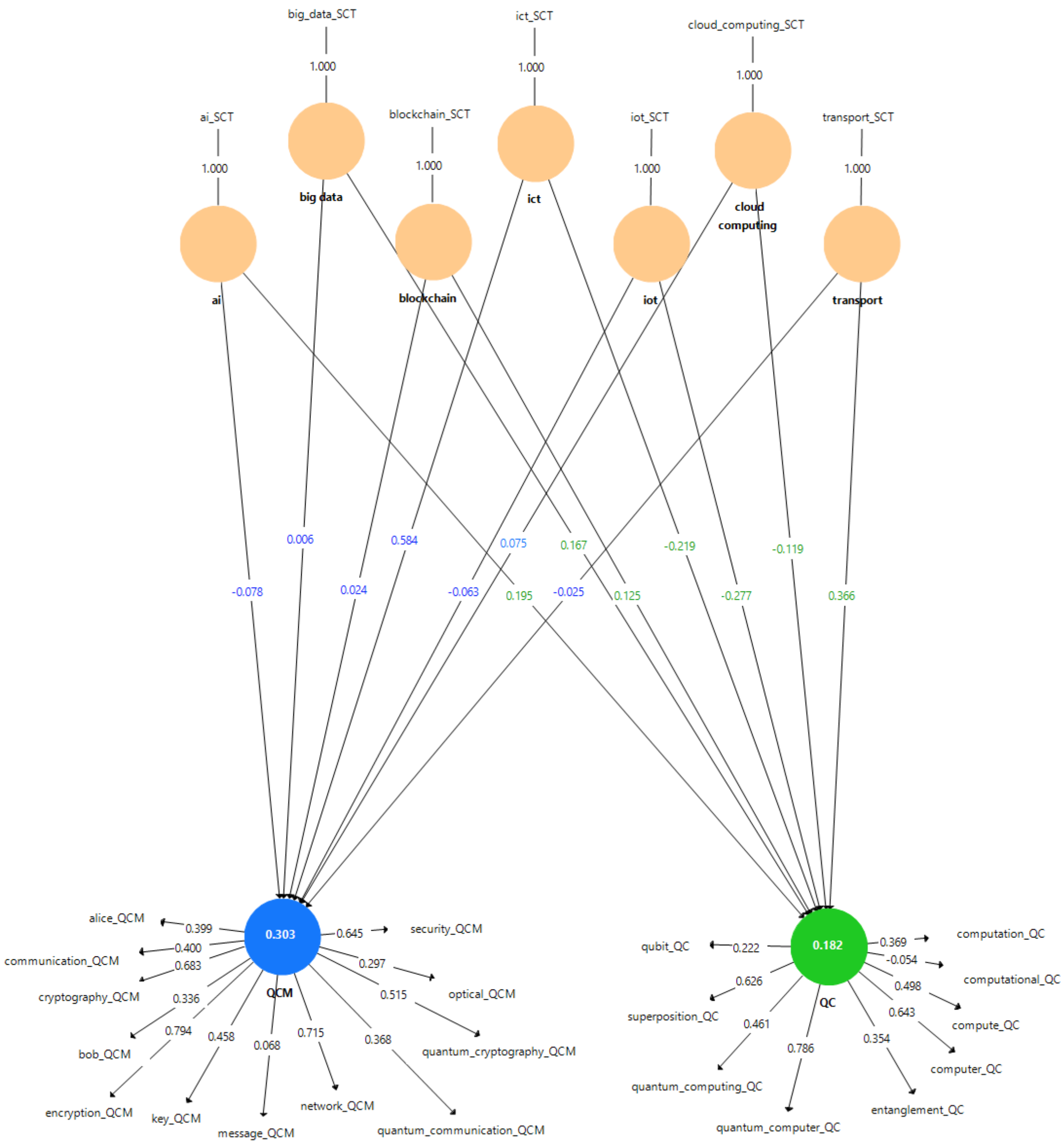
Similarly, by looking at relationships between smart city technologies and both QC and QCM keywords (Figure 9), we may observe that quantum communication is semantically more related than quantum computing to conventional smart city technologies (R squared = 0.303 for quantum communication compared to R squared = 0.182 for quantum computing).

Figure 9. PLSc-PM. Model 2



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As for individual conventional smart city technologies, ICT has the strongest semantic relationship with quantum communication topics (path coefficient = 0.584, the only statistically significant after bootstrapping at the 0.05 significance level). Conversely, the smart city technology topic most related 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 second model's fit was higher than in the case of the first model (standardized root mean square residual equal to 0.140). As in the first model, not all outer weights for QCM and QC latent variables exceeded the cutoff value of 0.7. Moreover, in the case of the second model, latent variables denoting conventional smart city technologies were defined directly by the observed variables.

To sum up, we conclude that quantum communication is currently the most important topic concerning quantum technologies for smart cities (Figure 8). ICT is the type of conventional smart city technology for which quantum communication is most relevant (Figure 9). On the contrary, the semantic relationships between quantum communication and the remaining types of conventional smart city technologies are weaker (Figure 9). The role of quantum computing is more diverse, as it is important for several conventional smart city technologies (AI, big data, blockchain, and smart transportation). However, its overall relevance within the assessed literature is lower than that of quantum communication.

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

We integrate the findings of the quantitative analyses with a qualitative thematic analysis of the eighty retrieved articles. We proceed by describing each identified category of conventional smart city technologies in terms of their potential synergies with both types of quantum technologies (quantum computing and communication). Given our difficulties separating the big data and cloud computing-related themes and topics on mere qualitative bases, we summarize both categories in a single sub-section.

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 (A. 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 (S. Kumari et al., 2021). The threat of post-quantum vulnerability calls for greater integration of blockchain and quantum technologies (S. Kumari et al., 2021).

According to the results of PLSc-SEM analysis (Figure 9), the topic of blockchain relates to both quantum computing and quantum communication. However, 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 (S. 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 (J. Chen et al., 2021; Moorman & Stricklen, 2020; Vivekanadam B, 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., 2021; Allam & Jones, 2020; Azzaoui & Park, 2020; J. Chen et al., 2021; Chiang et al., 2020; Guo et al., 2021; Gupta et al., 2021; A. Kumari et al., 2021; McKee et al., 2017; Toapanta et al., 2020; Xie et al., 2019; Zhu et al., 2019).

4.2 Internet of Things and quantum technologies

As Figure 9 shows, the Internet of Things is semantically negatively related to the topic of quantum computing. Regarding quantum communication, the effect size was too small to draw meaningful conclusions about the direction and strength of the relationship. On the contrary, the qualitative thematic analysis revealed that quantum communication could significantly boost IoT efficiency and security.

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; Park et al., 2021).

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; S. Kumari et al., 2021; Nieto-Chaupis, 2018; Ning & Liu, 2015; Routray et al., 2019; 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).

4.3 ICT and quantum technologies

Information and communication technologies, as a broader set of smart city solutions, are the most discussed in the context of quantum communication topics (Figure 9). On the contrary, according to the PLSc-SEM analysis, its semantic relationship to quantum computing themes and topics is negative.

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 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 (Park et al., 2021; 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 (Park et al., 2021; 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).

4.4 Big data, cloud computing, and quantum technologies

According to the PLSc-SEM analysis, big data is more semantically related to quantum computing, and cloud computing is semantically closer to quantum communication. However, we discuss both in the same sub-paragraph because, according to thematic analysis, the two classes of conventional smart city solutions are closely interrelated.

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, Cao, Dong, et al., 2021; Qian, Cao, Lu, et al., 2021).

As the data volumes 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).

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 PLSc-SEM analysis (Figure 9), artificial intelligence is most related to the topic of quantum computing. Indeed, 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, 2022; 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 (Wallnöfer 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; Wallnöfer et al., 2020).

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; Z. Liu et al., 2020; Manna et al., 2021; Manzalini, 2020; Santos, 2021; F. Zhang et al., 2020).

5. Discussion and managerial implications

To emphasize the managerial relevance of the application of quantum technologies in smart cities, we categorized the impact of quantum technologies' integration into smart city infrastructures considering the following observations:

- when addressing a problem, QTs 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, QTs allow for more exact predictions and forecasts (Kim et al., 2021; Proctor et al., 2022);
- QTs can sustain complex communication networks (Bassoli et al., 2021);
- QTs 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);
- QTs can significantly affect privacy and security standards and procedures in different smart city subsystems (S. 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, we may identify numerous benefits of such integration. For example:

- more precise urban-related forecasting made possible by QTs 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 (S. Kumari et al., 2021; Portmann & Renner, 2021; 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.

Openness and accessibility are some of the ways to ensure that QTs' benefits outweigh their negative impacts. Therefore, the related scientific knowledge should be made publicly available and actively communicated, and if possible, QTs' higher computational capacity should be made accessible via the cloud (de Wolf, 2017). Moreover, to reinforce the positive impacts of QTs in smart cities, the crucial step is to ensure that urban residents start thinking in new ways compatible with quantum technolgies (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 QTs (DeBenedictis, 2020; Gordon & Gordon, 2012; Mykhailova & Svore, 2020; Uhlig et al., 2019).

If quantum technologies reach widespread usage, radical social changes might follow (Berezin, 2007). For this reason, we advise urban decision-makers to start strategizing QT's 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, 2021). 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).

6. Conclusion and limits of the research

The analysis of academic literature revealed that quantum communication and quantum computing are the most important 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.

In evaluating the impact of quantum technologies on conventional smart city technologies, we observed that many researchers (over-) emphasize the security dangers posed by quantum computers and the related solutions proposed by quantum communication. However, we argue that such a view on QTs could aliment 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, we advise city managers, administrators, and planners to start incorporating the calculation of the potential benefits quantum technologies could bring to urban infrastructure while planning and allocating the resources for future smart city initiatives.

We also encourage researchers to investigate practical everyday applications of quantum technologies in smart cities in addition to a frequently studied topic of quantum defensive strategies (mainly associated with digital warfare). Indeed, as the quantitative analyses of semantic relationships between the retrieved articles revealed, thematic connections among quantum computing, quantum communication, and seven facets of smart city technology (AI, ICT, IoT, blockchain, big data, cloud computing, and transportation) are present but not yet strong, indicating an important research gap.

Quantum technologies rely on quantum mechanics' counterintuitive and, sometimes, abstract principles. Adopting QTs for everyday use in cities makes it necessary for urban managers, administrators, and planners to effectively communicate the benefits and drawbacks of urban QTs and the fundamental principles of their operation, which, in turn, requires increasing people's "quantum literacy." To reach a conceptual shift from quantum defense strategies to everyday QTs' applications in cities, a novel form of education and training should orient future generations to perceive the world in safer, although equivocal terms in line with the urban quantum development. As a result, in addition to investing in quantum technology development, educational investments are also critical (Bashirpour Bonab, Fedele, et al., 2023).

To conclude, our study has several limitations. First, we hypothesized the relationships between quantum technologies and conventional smart city technologies based on the frequency of corresponding keywords in the retrieved academic papers on QTs within the broader social science domain. As such, the related variables should not be considered exact operational definitions of quantum or smart city technologies. What we 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. Such a study would require advanced and ubiquitous QTs, which, for now, are only in the nascent phases of development. Second, we only used simple Boolean queries for the literature search. We do not exclude that several relevant papers could have been omitted from the analyses. However, given the high number of analyzed documents (eighty for the content and thematic analyses and 567 for the derivation of the conventional smart city technologies taxonomy), we consider the theoretical saturation appropriately reached. Therefore, it is unlikely that additional insights could have emerged from the omitted academic literature. Indeed, as we noticed early on, most articles were variations on the few fundamental themes and topics continually re-emerging during the qualitative coding.

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