NEW DIRECTIONS IN QUANTUM COMPUTING TECHNOLOGY

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Abstract

Quantum computing has increased steeply since the early 1990s advancing quantum information, communication, sensing, quantum cryptography, entanglement, quantum algorithms, etc. The investigation of evolutionary patterns can support technological and economic change. Using patent data, logistic modelling here suggests that topics in quantum computing technology (Quantum Gates, Quantum Information, and Quantum Dots) have exponential growth. Moreover, entity linking method clarifies evolving interconnections in quantum computing topics over time that are categorized in emerging, declining, dominant, and saturated groups. The findings here have main implications of technological forecasting to support strategic management and innovation policy towards main industrial transformation.

Keywords: Quantum computing; Quantum revolution; Quantum information science; quantum information processing; patent analysis; topic modeling; entity linking; S-curve analysis; logistic model; technometrics; technological change; innovation management; knowledge economy

JEL codes: O31, O32

1. **Introduction**

Quantum computing research plays a pivotal role in advancing information processing and communication technologies (Kozlowski and Wehner, 2019). Quantum computing is an emerging technology having main potential aspects to foster innovations in communication, cryptography, optics, and other areas that support knowledge economy of nations (Atik and Jeutner, 2021; Carberry et al., 2021; Dahlberg et al., 2019, 2022; Möller and Vuik, 2017). Acín et al. (2018) categorize quantum technology into key research fields: quantum computation and quantum sensing systems. In particular, quantum computation is directed to the development of computers and software using science advances in quantum theory. Although the vast literature in quantum computing, the evolution of technological trajectories that drives groundbreaking innovations remains insufficiently explored. The study here endeavors to address this gap and clarify evolutionary patterns of quantum computing to show technological directions and potential applications in communication, cryptography, and optics. The research strategy here applies a logistic model and entity linking method, using patent data, to identify and analyze key topics underlying technological trajectories that are categorized in emerging, declining, saturated, and dominant groups to support technological forecasting and innovation management. The evolution of quantum computing is vital for guiding R&D investments and supporting technological advancements having industrial, economic, and societal impact in current knowledge and digital economies. This study is also basic to clarify future trends of quantum computing technologies to design and develop a complete and functional quantum ecosystem based on effective technological networks, reliable physical infrastructures, skilled human resources, etc. to support technological, economic and social change also driven by new institutions (cf., Batra et al., 2021; Coccia, 2019c; Coccia et al., 2023; Hou and Shi, 2021; Pande and Mulay, 2020; Rao et al., 2020).

In the following sections, we critically analyze the current literature about studies on the evolution of quantum computing technologies. The Methodology is based on an integrated approach of logistic model, entity linking method and co-occurrence network analysis. Results clarify scientific and technological trajectories in quantum computing and categorize key topics into emerging, declining, saturated, and dominant phases to support technological forecasting for theoretical and managerial implications that are discussed with a perspective of induction for other quantum technologies. Finally, concluding remarks synthetize and systematize the findings that can encourage further research in the presence of the evolving quantum computing landscape.

2. Theoretical background

Studies on the evolution of new technologies and research topics have basic aspects to detect emerging technological trajectories for improving technological forecasting that guides R&D investments towards innovations having industrial, economic and social impact (Coccia, 2017, 2019a, 2019b, 2021, 2020; Kott, 2019). Researchers emphasize that the evolution of technologies is increasingly shaped by the dynamic interaction among various technological components, leading to the co-evolution of new technological trajectories (Ardito et al., 2021; Jovanovic et al., 2021, Coccia, 2018, 2019; Coccia and Watts, 2020). In a broader context, technological evolution is often driven by scientific advancements, perceived as a self-organizing system with numerous scientific changes and interactions (Sun and Kaur et al., 2013). The exploration of scientific development, which underlies technological change, is typically conducted through the analysis of publications, serving as a primary unit of investigation to illustrate science maps depicting the evolution of scientific fields and technologies over time (Boyack et al., 2009; Liang et al., 2021). The evolution of new technology and research field is affected by many factors, such as the accumulation of knowledge in specific research fields, technological choice of leading firms and nations, application of new materials, social, economic and political factors, etc. (Coccia, 2017a, 2017b, 2018, 2018a, 2020; Magee, 2009; Vespignani, 2009; Sahal, 1981). Scholars analyze the advances of new technologies and path-breaking innovations with different approaches to clarify technological progress. Faust (1990, p. 473) applies patent analysis and new indicators to detect the emergence and development of high-tech products. Wang et al. (2016, p. 537ff) use the classification and re-classification of patents to analyze the evolution of many technologies. Patent analysis also underpins appropriate models of S-curves to explain the evolution and diffusion of technologies and innovations (Altuntas et al., 2015; Ernst, 1997; Sahal, 1981; Trappey et al., 2011). Savov et al. (2020) propose a citation-based approach to identify breakthrough scientific papers, showcasing the importance of citation networks in understanding the advancement of scientific knowledge. Pahlavan and Krishnamurthy (2021) offer a historical perspective on the evolution and impact of Wi-Fi technology, demonstrating how technological trajectories can unfold and become integral to various applications. Similarly, Casella et al. (2022) conduct a systematic literature review on Radio Frequency Identification technological evolution, shedding light on the trends and applications of this technology. These studies about the evolution of technologies underscore their dynamic nature in innovation ecosystems having rapid changes driven by a continuous interplay between scientific advancements, converging technologies and practical applications.

In order to consider this aspect, some studies apply different methodologies, including topic models, S-shaped models, patent data analysis, path analysis, etc. to map the evolution of various technologies such as some studies have done in artificial intelligence, internal combustion engines, 5G wireless technology, and blockchain (Liu et al., 2020; Sinigaglia et al., 2022; Han et al., 2023; Bhatt et al., 2023; Huang et al., 2022). Aharonson and Schilling (2016) to analyze complex technologies introduce different measures to characterize technological capabilities, providing alternative perspective for assessing technological evolution over time. In this context, technology analysis with S-shaped curves, based on patent data, can show the technology life cycle that sustain reliable technology forecasting for guiding best-practices of innovation management (Altuntas and Aba, 2022; Coccia, 2020). Ernst (1997) assumes that technological evolution has four phases that in a S-shaped curve are: a) the emerging stage; b) the growth stage that generates some radical innovations (Coccia, 2016, 2020a); c) the maturity phase that generates incremental innovations; and d) finally, the phase of saturation in which an established technology and/or innovation is going to be substituted by new technology/innovation (Sahal, 1981; Gao et al., 2013). A main observation here is that technologies in a stage of growth or maturity can have a substantial patenting activity, but they cannot be ready to be implemented in markets with promising innovations because the economies have not a functional innovation ecosystem to support the creation and diffusion of new technologies (Coccia, 2022; Coccia et al, 2023). Other quantitative approaches based on bibliometric data of journals and patents can capture information of emerging innovations (Cozzens et al., 2010; Ren and Zhao, 2021). These approaches not only detect specific technological trajectories but also show the complex dynamics of technology evolution in turbulent environments. In this perspective, Deshmukh and Mulay (2021) suggest that the maximum numbers of publications in the field of quantum computing in physics, astronomy and computer science can support main technological trajectories. Jiang and Chen (2021) explore the landscapes of quantum technology using patent network analysis and show the significance of quantum ecosystem, based on interconnected relations, essential elements, basic infrastructure and networks in facilitating emergence of technological trajectories and transformative changes in society. Coccia (2022, 2022b), using publication and patent data, shows main technological trajectories in quantum computing and computer and their rates of growth that suggest path-breaking directions in quantum technology, such as quantum optics, quantum information, quantum algorithms, quantum entanglement, quantum communication and quantum cryptography.

However, studies of the evolution of new technologies in quantum computing based on patents and research topics to show scientific and technological development are scarce in literature, also considering that rapid changes affect continuously the dynamics of technological trajectories. Moreover, studies that apply different approaches integrated to clarify the complex evolutionary dynamics of quantum technologies are lacking, though they can support technological forecasting and main implications of management for fruitful innovations in modern knowledge economies. This study endeavors to cover this gap and analyzes patenting activity and research topics in quantum computing to clarify scientific and technological development considering different evolutionary stages of emerging technological trajectories. Next section describes data and methodology of this study for a technology analysis that extends theoretical and managerial perspectives for clarifying and supporting pathways of quantum computing technologies in environment with rapid changes.

3. Study design

In line with the aim of providing a comprehensive overview of the technology landscape in quantum computing patents, this study draws inspiration from the systematic mapping study (SMS) methodology proposed by Kitchenham and Charters (2007) and Petersen et al. (2015). SMS is recognized for its ability to conduct a broad review of a research field, systematically identifying the quantity and types of research available within it (Mastropetrou et al., 2019). In adopting this methodology, our research questions endeavor to clarify the broader trends and patterns of technological development in quantum computing (cf., Petersen et al., 2015). The mapping of publication frequencies over time enhances our understanding of the evolving research landscape in quantum computing.

3.1 Research design

Figure 1 shows primary five stages of our research methodology commonly associated with SMS approach (Petersen et al., 2008).

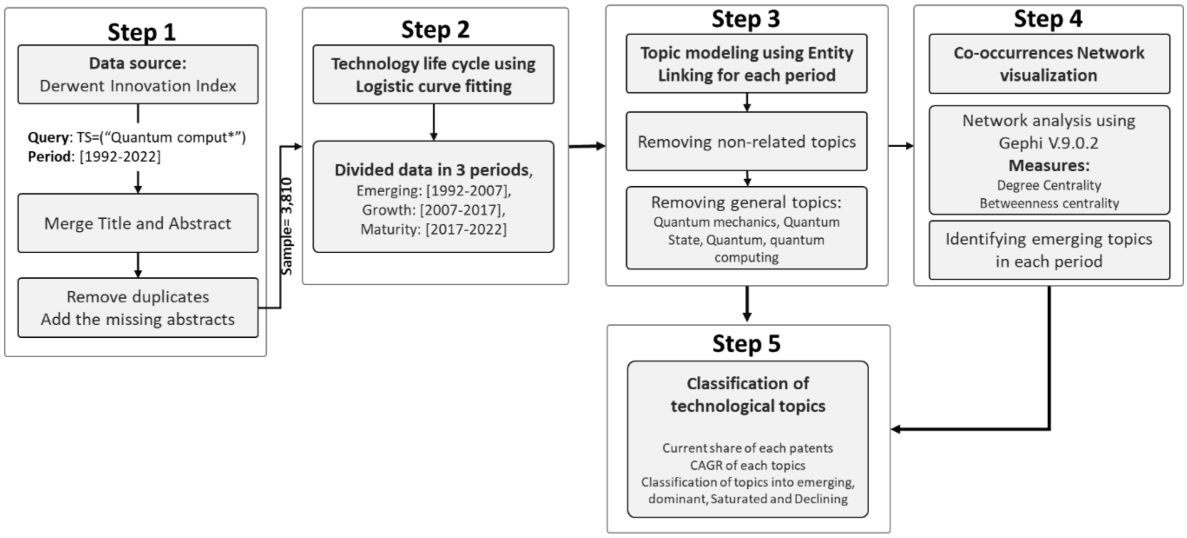


Figure 1. The high-level conceptual flow of the research methodology

In general,

- First, in the Data Collection stage, we carefully search for patents using the Derwent Innovation Index-DII dataset from the Web of Science database.
- In the second stage, Technology Life-Cycle Analysis is based on a logistic model to identify different stages in quantum computing technology, and then SMS categorizes research trends.
- The third stage focuses on Topic Modeling using Entity Linking to find central themes of research.
- The fourth stage is a structured Network Analysis of Topics that examines how themes evolve in the course of time.
- Finally, we suggest a classification of technological topics based on patent share and growth rate considering the format and principles of SMS to ensure a systematic and thorough exploration of patenting activity in quantum computing technology.

In particular,

- *Step 1: data collection*

We used the Thomson Reuters Derwent Innovation Index (DII) from the Web of Science database to retrieve the most relevant patents in the field of quantum computing (Web of science, 2022). The database of Derwent Innovations Index has more than over 14.3 million of basic inventions from nearly 60 global patent-issuing authorities. It collects patent documents worldwide since 1963 and updates weekly with around 25,000 new patent documents from 40 patent offices, along with 45,000 patent citation documents from six key offices (Yuan and Li, 2020). To extract the most relevant patents related to quantum computing technologies, we searched for 'Quantum comput*' in the topics (Abstract and Title) of patents. The initial results include 3,834 patents spanning from 1992 to 2022. In the process of refining the dataset, patents without abstracts were excluded by a systematic cleaning procedure. Notably, the "PI tag" represents the Priority Application Information and Date and is utilized for logistic model analysis. Following this refinement, our final sample was 3,810 patents. We downloaded all of the data as plain text files and further cleaned for analyses.

- *Step 2: Technology life cycle analysis*

A technology life cycle analysis determines growth stages of quantum computing technology. According to Ernst (1997), technological evolution can be modelled with S-shaped curves based on cumulative R&D expenditures. Based on patent data, S-shaped curves can provide a clear picture of the evolution of technology life cycles for technology forecasting and analysis (Altuntas and Aba, 2022; Lin et al., 2021; Ye et al., 2021). Gompertz and Logistic functions are the most widely models used for fitting S-curves (Dhar & Bhattachrya, 2018). In our investigation, we explored the potential suitability of Gompertz and Logistic functions as models for shaping S-curves of the technological life cycle based on patent growth in quantum computing. A comparison between the Logistic and Gompertz models was carried out, and the findings are detailed in Appendix A (Table 1A). The process of selection also involved a careful examination of metrics, such as the coefficient R^2, root mean square value (RMSE), and mean absolute percentage error (MAPE) (Chu et al., 2009; Nagula, 2016). The comparison in Table 1A indicates the superiority of the Logistic model across critical measures. As a consequence, we opt for the logistic curve because of its ability to better fit data and effectively capture symmetric patterns of evolution, a quality considered fitting for representing the development of quantum computing technology. This higher level of fit, supported by metrics just mentioned, underpins the reliability and precision of our chosen logistic model in forecasting the growth stages of the quantum computing technology life cycle. The preference for the Logistic curve over the Gompertz model in examining the development of quantum computing technology holds important implications. The Logistic model's lower RMSE implies improved precision in predicting patent growth, and its higher R^2 suggests an overall better fit to scatter data. While the MAPE values are closely matched, the slightly higher MAPE of the Logistic model implies a minor compromise in percentage accuracy, traded for an enhanced fit and predictive capability. In practical terms, these outcomes underscore the Logistic curve's effectiveness in portraying the life cycle of quantum computing technology. Researchers, technology analysts, policymakers and R&D managers can obtain from the Logistic model for more precise predictions, offering valuable insights into the developmental stages of quantum computing technology to support R&D investment towards potential innovations.

The logistic model can be described by the following equation (Aduba and Asgari, 2022; Meyer et al., 1999; Sinigaglia et al., 2022):

$$P(t) = \frac{k}{1+e^{-\alpha(t-\beta)}} \qquad (1)$$

Where:

P (t) = number of patents over time t;

k = the saturation level of growth

α = the growth rate and the "steepness" of the sigmoidal curve

β = the inflection point of growth or midpoint of the curve

In addition, we can transform the equation (1) for computational purposes as follows:

$$P(t) = \frac{k}{1+exp\left[-\frac{ln(81)}{\Delta t}(t-t_m)\right]} \qquad (2)$$

Where:

$\Delta t = \frac{\ln 81}{\alpha}$ and indicates the time variation [1]; it takes the trajectory to increase from 10% to 90% of the limit *k*; This parameter is a critical component in the logistic model, offering valuable information about the characteristic duration of technology growth. Its value influences the shape and speed of the growth trajectory. If Δ is small, it suggests that the patent growth trajectory experiences a relatively rapid rise, swiftly reaching the 10% to 90% range. Moreover, t_m = the midpoint of the growth trajectory at P (t_m) = k/2, which is specified by the β parameter. The parameter k is the asymptotic limit of growth curve and estimates the future population of P (Meyer et al., 1999). The midpoint parameter acts as a time indicator, assisting analysts and researchers in assessing the stage of development in quantum computing technology. Grasping this midpoint, along with related factors, such as characteristic duration, enhances the predictive ability of the logistic curve. The symmetrical pattern of the

[1] For details on this equation, see Meyer et al. (1999), pp. 250ff.

logistic curve, directed by the parameters α and β, reflects the evolutionary path of the technology. The parameter *k* serves as a crucial indicator of the saturation level, marking the stage where patent accumulation approaches its maximum limit. Using this equation, our analysis harmonizes mathematical accuracy with observed patenting trends, aiding in a detailed understanding of the technological life cycle in quantum computing.

The cumulative number of patents and Loglet Lab software were used to identify the growth stage of quantum computing (Yung et al., 1999). Loglet Lab determines key parameters, such as the growth rate, inflection point, and saturation level, basic for characterizing the technology's evolution. The cumulative patent data serves as the basis for constructing the logistic curve, allowing for a comprehensive analysis of the emerging, growth, maturity, and saturation phases. The software not only quantifies the duration of each phase but also provides visual representation, enhancing the understanding of quantum computing's developmental trajectory (Yung et al., 1999). The results of logistic model using Loglet Lab software are shown in Table 1.

Table 1: Duration of phases in quantum computing technology based on patents

	Emerging period	Growth period	Maturity period	Saturation period	Stage in 2022
Quantum Comput*	1992-2008	2008-2017	2017-2027	2027-2036	Maturity

Logistic curve fitting indicates that quantum computing, based on patent data, is in a maturity stage. To better align the data analysis with the different phases of the technology life cycle, we divided our dataset into three periods based on the publication years of the patents: from 1992 to 2008, 2008 to 2017, and from 2017 to 2022. The first period, from 1992 to 2008, represents the early emergence of quantum computing, when the technology was in its nascent stage, and research and development efforts were gaining momentum. The second period, from 2008 to 2017, corresponds to the phase of growth and advancement in quantum computing. The last period, from 2017 to 2022, represents the maturity phase of quantum computing technology. These time periods capture significant milestones and shifts in the development of quantum computing technology. Data analysis in these three corresponding periods shows the most relevant topics and relationships in quantum computing technology.

- *Step 3: Topic modeling using Entity linking method*

Entity linking was used to identify the most relevant topics in quantum computing. In order to accomplish this step, it is necessary to select relevant keywords and determine the underlying topics that generate this technology. There are a number of approaches available for extracting general topics from documents using Natural Language

Processing (NLP). In recent years, a variety of topic modeling techniques have been applied to identify different subjects in a field of study, including Latent Dirichlet Allocation (Blei et al., 2003), Latent Semantic Analysis (Landauer et al., 1998), and Probabilistic Latent Semantic Analysis (PLSA) (Hofmann, 1999). A topic model is a statistical algorithm that identifies main themes and topics within large collections of unstructured documents (Blei, 2012). Based on the words appearing in a document, their relationships, and how they change over time, the topic modelling algorithm reveals its topic (Blei, 2012). Document collections can be organized chronologically so that different topics and topic frequencies can be observed over time. To capture this dynamic behavior, researchers use topic models with time-stamped data (Chen et al., 2017). In the context of our study, time-stamped data allows us to capture the evolving nature of quantum computing technology and related research topics. Quantum computing is a rapidly advancing field, with science advances, innovations, breakthroughs, and shifts in research focus on distinct time periods. Time-stamped data enables us to organize patent information chronologically, facilitating the identification of topics that gain prominence, decline, or undergo transformation across different stages of the technology's development. Moreover, there are a number of algorithms developed for mining documents chronologically (Blei and Lafferty, 2006; Wang et al., 2012; Gohr et al., 2009). The entity linking approach introduced by Cornolti et al. (2013) was employed here to identify the evolution of topics in quantum computing. The entity linking approach differs significantly from traditional topic modeling methods like Latent Dirichlet Allocation (LDA) and Latent Semantic Analysis (LSA) in several key aspects. Unlike LDA and LSA, which face challenges in naming unlabeled topics and rely on manual identification and labeling of term groups, entity linking operates at a more granular level, linking individual mentions to specific entities (Lee and Kang, 2018). Other approaches like LDA and LSA generate broader topics based on word co-occurrence patterns; instead, entity linking is particularly useful for connecting terms to a structured knowledge base, enhancing specificity. In addition, entity linking method identifies meaningful sequences (mentions) and can be associated with specific identifiers (entities) obtained from a catalog, rather than using a bag of words concept. Entity linking eliminates the arbitrary nature of selecting the number of topics, a challenge faced by LDA, where researchers are often left without specific rules to determine the number of topics and must justify their choices (Marrone, 2020). As said, entity linking relies on a structured knowledge base, such as Wikipedia, for linking, while other approaches generate topics without direct reference to external knowledge bases. This study utilized Wikipedia as one of the most popular catalogs for entity linking.

In the context of quantum computing, the significance of employing the entity linking approach extends to its unique capabilities in tracing the evolution of topics over time, a dimension not explicitly addressed by traditional bag-of-words-based methods. Hence, unlike methods like Latent Dirichlet Allocation (LDA) and Latent Semantic Analysis (LSA), which might overlook the temporal dynamics of emerging topics, entity linking excels in capturing the chronological development of specific themes. We used TAGME software to perform entity linking for quantum computing patents. The tool is capable of extracting meaningful short phrases from an unstructured text and linking them to Wikipedia entities (Ferragina and Scaiella, 2010). In particular, we utilized TagMe's API version 0.1.3, interfacing with it using the Python programming language version 3.9.7 within a Jupyter notebook environment (version 4.6). The choice of TAGME software for entity linking in our methodology was driven by its ability to provide a specific, contextually relevant, and structured linkage of mentions to entities from a well-established knowledge base. The parameters and efficiency of TAGME align well with the requirements of our research, contributing to the accuracy and effectiveness of the entity linking process in the context of quantum computing patents.

For comprehensive topic identification in Quantum Computing, we combined the abstract and title of each patent. We chose to analyze both the abstract and title of each patent to gain a complete understanding of quantum computing technologies. This approach helps to ensure that our method captures not just the technical details of each invention but also the broader themes and applications in the inter-related fields. The parameters for the entity linking process were set according to the methodology outlined by Marrone et al. (2022). Specifically, the long_text parameter was set to 10, indicating the number of surrounding codes used for annotating a particular mention in the text. A higher value provides a broader context, enhancing the quality of annotations. The 'epsilon' parameter (set at 0.427) establishes a balance between favoring context and common surrounding words, influencing the weighting of different contextual elements. Finally, the rho (ϱ) parameter was set to 0.16, defining the confidence score threshold for appropriate annotations given their context in the input text. These confidence scores, assigned by TagMe, represent the likelihood that the annotations are contextually suitable. NVIDIA GPU Tesla P100 with 60GB memory was used due to the high volume of documents being analyzed. As a result of this process, each record contains a column called "annotations" containing topics derived from the Entity Linking algorithm. At the final step, we removed topics that did not contain a word concerning quantum after implementing TAGME. In selecting keywords for entity linking in our study on quantum computing, we aimed to capture basic elements of the technology. We chose specific keywords relevant to quantum computing, ensuring they accurately represented distinct themes in the field under study. Our criteria considered the terms' relevance to quantum computing, their contribution to understanding the technology, and alignment with existing literature and terminology. Overall, then, this approach is directed to enhance the precision of topic identification by choosing keywords reflecting the breadth and uniqueness of quantum computing research.

- *Step 4: Network analysis of topics in patents over time*

After implementing entity linking, each patent contains a column that has several topics related to its content. We used these topics in order to create the co-occurrences network over the three periods mentioned before: i.e., from 1992 to 2008, 2008 to 2017, and from 2017 to 2022. Our focus was on topics that are strongly related to quantum computing technologies, and we removed any other topics in each patent. Using Python, we created a co-occurrence network between topics in each period and visualized it using Gephi version 0.9.2 (Bastian et al., 2009). The node indicates the topics related to quantum computing, and a link makes a connection between two topics whenever they appear in at least one patent. The thickness of each edge represents the weight of co-occurrences. If more than two topics appear in the same patents, the connected edge will be thicker. Additionally, we used degree centrality, betweenness centrality, and closeness centrality measures to analyze the most important topics in each period.

- Degree centrality (DC) is the number of edges a node has (Sharma and Suolia, 2013). In the topic co-occurrence networks, degree stands for the total number of topics that appear with the node in the same patents.
- Betweenness centrality (BC) shows how much a node is essential to create connections with other nodes in the shortest path. Nodes with the highest score of BC, they have a position to be a bridge for connections among the other network nodes (Kashani and Roshani, 2019). The Betweenness Centrality of node v is calculated using the following formula (Freeman, 1977; Wasserman et al., 1994):

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where:

BC= Betweenness Centrality measure of node v

σst = Total number of shortest paths from nodes s to node t

σst (v) = Number of shortest paths from s to t going through v

- Finally, a node's closeness centrality is an indicator of network centrality, defined as the number of links needed to connect each node in the network with all the other nodes in the network or the average number of links required to reach all other nodes in the network from a node in the network (Goldstein and Vitevitch, 2017):

$$C_v = \frac{1}{\sum_{u \in V} d(v,u)}$$

Where:

d(v, u) = the shortest path between nodes v and u

Σ = sum of the path lengths from node v to all other nodes in the network

The betweenness centrality and closeness centrality measures provide a quantitative measure of the influence and connectivity of topics within the quantum computing research network. These metrics help to identify key topics that act as bridges, facilitating collaboration and information flow, as well as topics strategically positioned for efficient knowledge transfer. By integrating these centrality measures into our analysis, we aim to offer a more nuanced and comprehensive understanding of the evolving relationships and structural dynamics within the quantum computing patent landscape.

- *Step 5: Classification of technological topics in patents*

In order to capture patenting activity trends at the topic level, we applied the method introduced by Choi and Song (2018). In particular, we examine the current share of each topic in all quantum computing-related patents, as well as the change in the patent share over time. By dividing the number of patent applications in a topic by the total number of patent applications, we are able to calculate the current patent share of the topic. To quantify the change in patent share over time, a compound annual growth rate (CAGR) is used. Based on these two indexes, a classification framework is proposed for trends of patenting activity. Our focus is on the top 20 topics that have the highest degree centrality rank following the previous step. Using these criteria, we can measure both the current status and the growth rate of patenting activity. As a result, the proposed framework identifies four different types of technological topics. Dominant topics have large patent shares and a positive patent growth rate. Emerging topics have small patent shares and negative patent growth rates. Saturated topics have a large patent share and a negative patent growth rate. In contrast, declining topics have a small patent share and a positive patent growth rate.

In brief, topics are categorized as follows:

- Emerging topics: when CAGR is positive, but patent share is less than the average
- Declining topics: when CAGR is negative, but patent share is less than the average
- Saturated topics: when CAGR is negative, but patent share is greater than the average
- Dominant topics: when CAGR is positive, but patent share is less than the average

4. Results

Figure 2 shows the number of quantum computing-related patents published from 1992 to 2022. Results show that patents have increased significantly since 2016. To put it differently, quantum computing development is mainly concentrated from 2016 onwards.

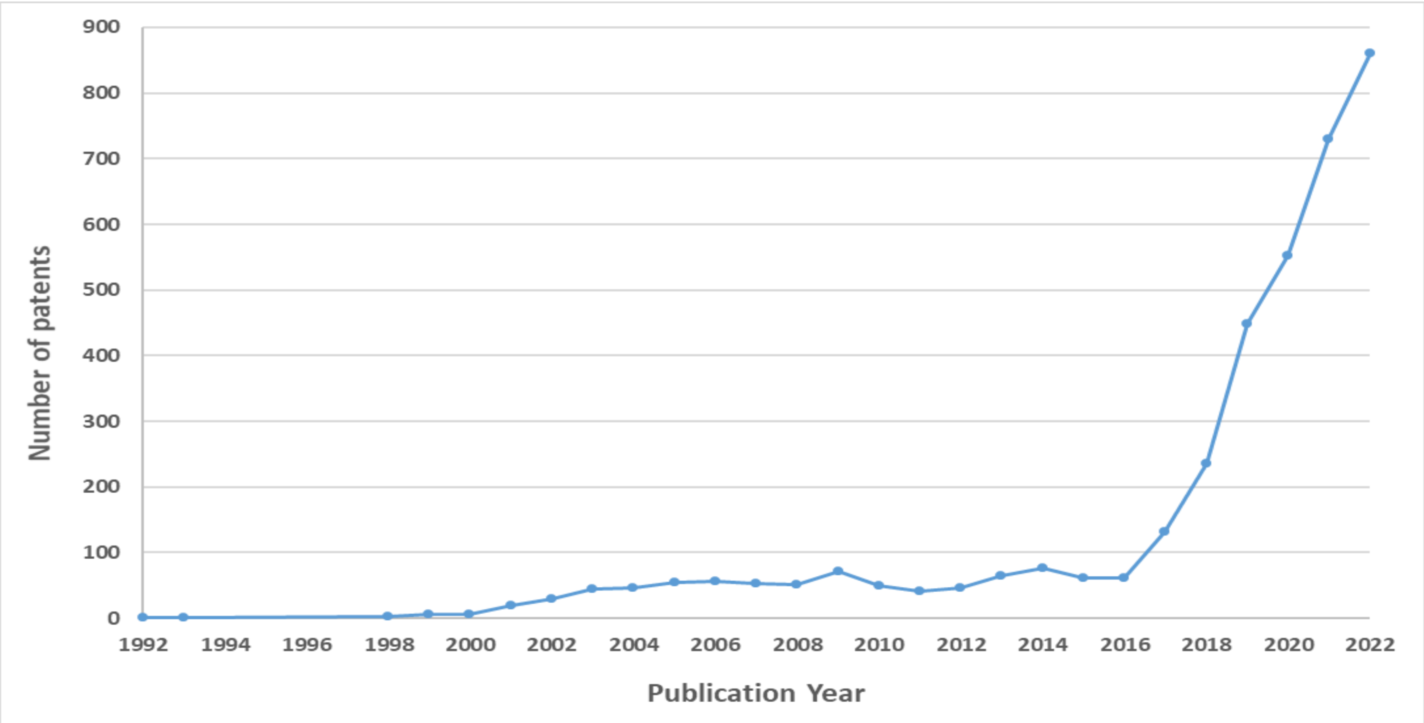


Figure 2. Distribution of the patent publication over years in quantum computing, 1992-2022

As we discussed in the method section, we used logistic model in order to find the stages in quantum computing-related patents. Table 2 shows results of logistic model using LogLet Lab software.

Table 2. Parameters and accuracy of the logistic model in quantum computing

	Midpoint (t_m), year				Growth time (Δt), number				Saturation (k), number				R^2
	Value	Min	Max	Med	Value	Min	Max	Med	Value	Min	Max	Med	
Quantum computing	2027	2020	2027	2025	2027	2020	2027	2025	14,402	5,176	14,410	10,883	0.91

*Note***.** Values of the t_m, Δt and k estimated by logistic growth method. With confidence levels of 95%, the bootstrap method estimates the minimum and maximum parameter values and shows the confidence region. R^2 is a coefficient of determination that indicates how well a logistic model fits. A growth stage of technology occurs when technology reaches 10%, a maturity stage at 50%, and a saturation stage at 90%. Loglet Lab software is used to estimate all of these parameters.

These results divide the data into three periods:

- Emerging period from 1992 to 2007
- Growth period from 2007 to 2017
- Maturity period from 2017 to 2022

To identify the most relevant topics in each period, we performed topic modeling at this stage. Using the TagMe tool and the Python programming language, this study applied entity linking method to identify quantum computing-related patent topics. A column called annotation is included in each patent after topic modeling based on entity-linking method. We used these topics to determine the co-occurrence network between quantum computing-related topics.

Table 3 shows the comparison of networks in three periods in terms of network's measures.

- In the emerging period, total number of patents are 269, and total number of topics (nodes) are 48. The network density is 0.119, which respectively shows a considerable integration within the network
- In the growth stage, based on the 576 published patents, the number of nodes increased by 1.39 times, and the number of edges increased by 1.78 times, with also a reduction in network density, which is 0.108 in this second period under study
- In the maturity stage, 2017-2022, the number of topics increased by 1.59 times compared to the growth stage. This graph has a density of 0.094, which is less than the graph density in growth network.

Table 3. Comparison of network measures and indicators in quantum computing topics over three periods

	Emerging [1992-2008]	Growth [2008-2017]	Maturity [2017-2027]
Total Number. of Patents	269	576	2958
Number of Nodes	48	67	107
Number of Links	134	239	506
Network Density	0.119	0.108	0.094
Avg. Path length	2.195	2.147	2.075

Note. Nodes represent vertices in a graph; links (or edges) are connections between nodes (or vertices) of the network. Network Density is the maximum number of existed edges divided by the number of possible edges; Avg. Path Length is the number of steps in average, through the shortest routes between all possible joints of network nodes. The stages (Emerging, Growth, Maturity) are determined through S-curve analysis.

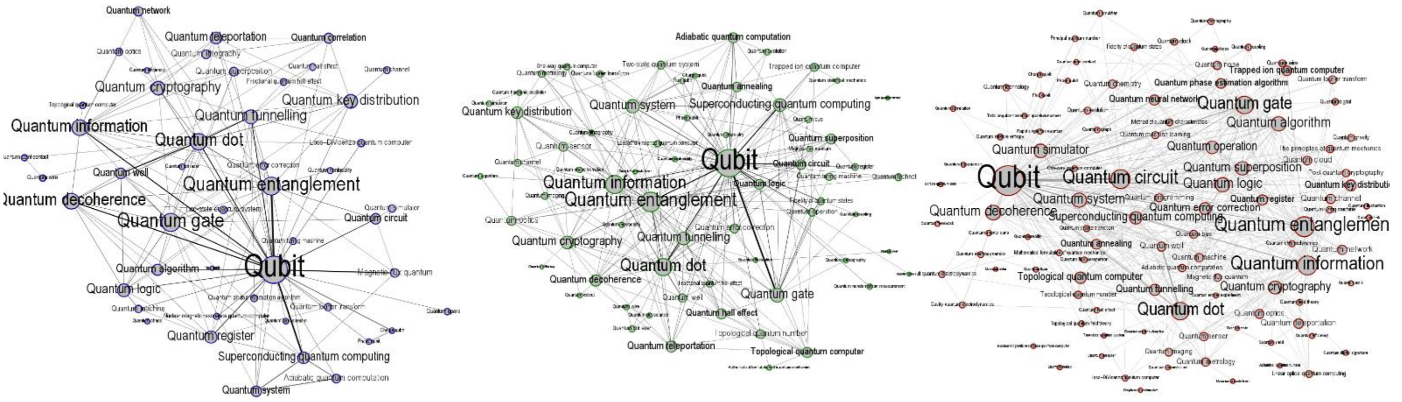
Table 4 shows the measures related to evolution of patent topics over time.

Table 4. Comparison of network measures in patent topics of quantum computing over three periods

Emerging				Growth				Maturity			
Topic	DC	BC	CC	Topic	DC	BC	CC	Topic	DC	BC	CC
Qubit	37	0.505	0.793	Qubit	50	0.442	0.802	Qubit	87	0.413	0.859
Quantum gate	20	0.049	0.597	Quantum entanglement	32	0.132	0.643	Quantum entanglement	51	0.06	0.653
Quantum entanglement	20	0.079	0.582	Quantum information	29	0.097	0.631	Quantum information	48	0.066	0.640
Quantum dot	17	0.137	0.589	Quantum dot	27	0.148	0.607	Quantum circuit	47	0.040	0.620
Quantum decoherence	16	0.017	0.554	Quantum gate	19	0.026	0.550	Quantum dot	43	0.085	0.628
Quantum information	16	0.1	0.575	Quantum system	18	0.030	0.532	Quantum gate	43	0.031	0.608
Quantum tunnelling	13	0.093	0.560	Superconducting quantum computing	17	0.015	0.541	Quantum decoherence	33	0.013	0.566
Quantum cryptography	12	0.066	0.541	Quantum tunnelling	17	0.022	0.541	Quantum system	32	0.024	0.569
Quantum key distribution	12	0.058	0.547	Quantum cryptography	17	0.057	0.562	Quantum algorithm	32	0.017	0.569
Quantum logic	11	0.006	0.505	Quantum key distribution	16	0.068	0.537	Quantum logic	31	0.009	0.569
Quantum register	11	0.009	0.5	Quantum decoherence	13	0.016	0.532	Quantum superposition	29	0.008	0.556
Quantum teleportation	9	0.01	0.510	Quantum teleportation	13	0.005	0.532	Quantum simulator	29	0.011	0.566
Superconducting quantum computing	9	0.003	0.484	Quantum superposition	12	0.006	0.52	Quantum cryptography	27	0.046	0.573
Quantum well	8	0.003	0.505	Quantum hall effect	11	0.002	0.503	Quantum operation	26	0.005	0.550
Quantum algorithm	8	0.001	0.474	Adiabatic quantum computation	11	0.006	0.511	Superconducting quantum computing	25	0.005	0.550
Quantum correlation	7	0.005	0.489	Topological quantum computer	11	0.020	0.52	Quantum error correction	23	0.006	0.550
Quantum system	7	0.003	0.484	Quantum optics	10	0.01	0.528	Topological quantum computer	21	0.01	0.535
Quantum circuit	7	0.043	0.494	Quantum logic	10	0.002	0.503	Quantum tunnelling	20	0.002	0.529
Quantum network	6	0.001	0.505	Quantum circuit	10	0.003	0.485	Quantum key distribution	19	0.012	0.529
Quantum superposition	5	0.0007	0.469	Quantum annealing	10	0.002	0.5	Quantum register	17	0.001	0.5
Average value	**12.55**	**0.06**	**0.54**		**17.65**	**0.06**	**0.55**		**34.15**	**0.04**	**0.59**

***Note*:** degree centrality (DC) indicates number of connections (connectivity); Betweenness centrality (BC) indicates the amount of influence or control a node has over the flow between nodes in network (similar to a bridge); closeness centrality (CC) indicates the easiest access to all other nodes in a network or sub-network (shortest distance from nodes).

Figure 3 shows the co-occurrence network in quantum computing-related topics over the three periods. Additionally, table 2A (in Appendix A) illustrates the topics that emerge from emerging to growth phases and from growth to maturity phases in patent topics of quantum computing.



EMERGING **GROWTH** **MATURITY**

Figure 3. A comparison of the interconnection of major topics in quantum computing at different stages of development: emerging, growth, and maturity. Emerging phase is from 1992 to 2007; Growth phase is from 2008 to 2017; Maturity phase is from 2018 to 2027.

Based on the results of table 4 and figure 3, “Qubit” has the highest DC and BC score in all three periods. This means that this topic has a main role in structuring the network and establishing new linkages with different topics in all stages of evolution in quantum computing technology, which caused the highest-level connection score.

- In the emerging stage, after qubits, quantum gates and quantum entanglement with a DC score of 20 are the most important topics. In addition, based on the bridging role in the network (BC), "Qubit" with a BC score of 0.50, "Quantum dot" with a BC score of 0.137, and "Quantum information" with a BC score of 0.10 are the most influential topics. Moreover, Figure 3 and table 4 show that quantum gates are interconnected with quantum information, quantum decoherence, quantum algorithms, and quantum logic. Quantum entanglement is closely related to quantum key distribution, quantum tunneling, and quantum teleportation. During this stage of the quantum computing evolution, topic of quantum gates has a degree centrality (DC) of 20, topic of quantum dots has a degree centrality of 17, quantum cryptography has a degree centrality of 12, quantum key distribution has a degree centrality of 12, and quantum registers have a degree centrality of 11.

- During the growth stage, the network expands rapidly (see, figure 3): quantum entanglement and quantum information are in the top of rank considering the degree centrality, after qubits. In terms of betweenness centrality (BC), topic of quantum dots with a value of 0.148 has an important role in bridging the network. The third rank is by quantum entanglement with a value of 0.132. Table 4 shows that topic of quantum information has increased to the second rank during the growth stage and has built strong connections with quantum entanglement, quantum dot, quantum cryptography, quantum system, quantum key distribution, quantum gate, and quantum sensor. As the growth stage continues, quantum information becomes increasingly significant in linking other topics together. On the basis of the degree centrality (DC) measure, the following technologies are the most significant at this stage: "quantum information" with a value of 29, "quantum dot" with 27, "Superconducting quantum computing" with 17, quantum cryptography with 17, and quantum key distribution with a value of 16.
- In the maturity stage, figure 3 and table 4 show a remarkably high growth in the number of links between patent topics in quantum computing. Topics of Quantum information and quantum entanglement have been experiencing a considerable growth in the DC measure. Moreover, DC of quantum circuit increased to 47 and ranked fourth in the list. The highest scores among other topics are for quantum dot and quantum information based on BC measure. As a result of this stage of evolution, topic of quantum entanglement has increased its connections with 46 other nodes. It is now ranked second in terms of connections with other topics. The quantum circuit also has grown significantly during this period and developed strong connections with 42 other topics (see table 2A in Appendix A). Moreover, based on DC value, the most prominent topics emerged at this stage are quantum neural network with a value of 17, quantum cloud with a value of 13, quantum noise with a value of 11, and quantum programming with a value of 11. During this stage of evolution, "quantum information" with a degree centrality (DC) of 48, "quantum circuit" with a DC of 47, "quantum dot" with a DC of 43, "quantum gate" with a DC of 43, and "quantum simulator" with a DC of 29 are the most significant technologies.

In order to illustrate the pathways of relevant technologies at each stage, we illustrate the dynamics of the top five technologies in our dataset by counting the frequency of their occurrences in patents (Figure 4).

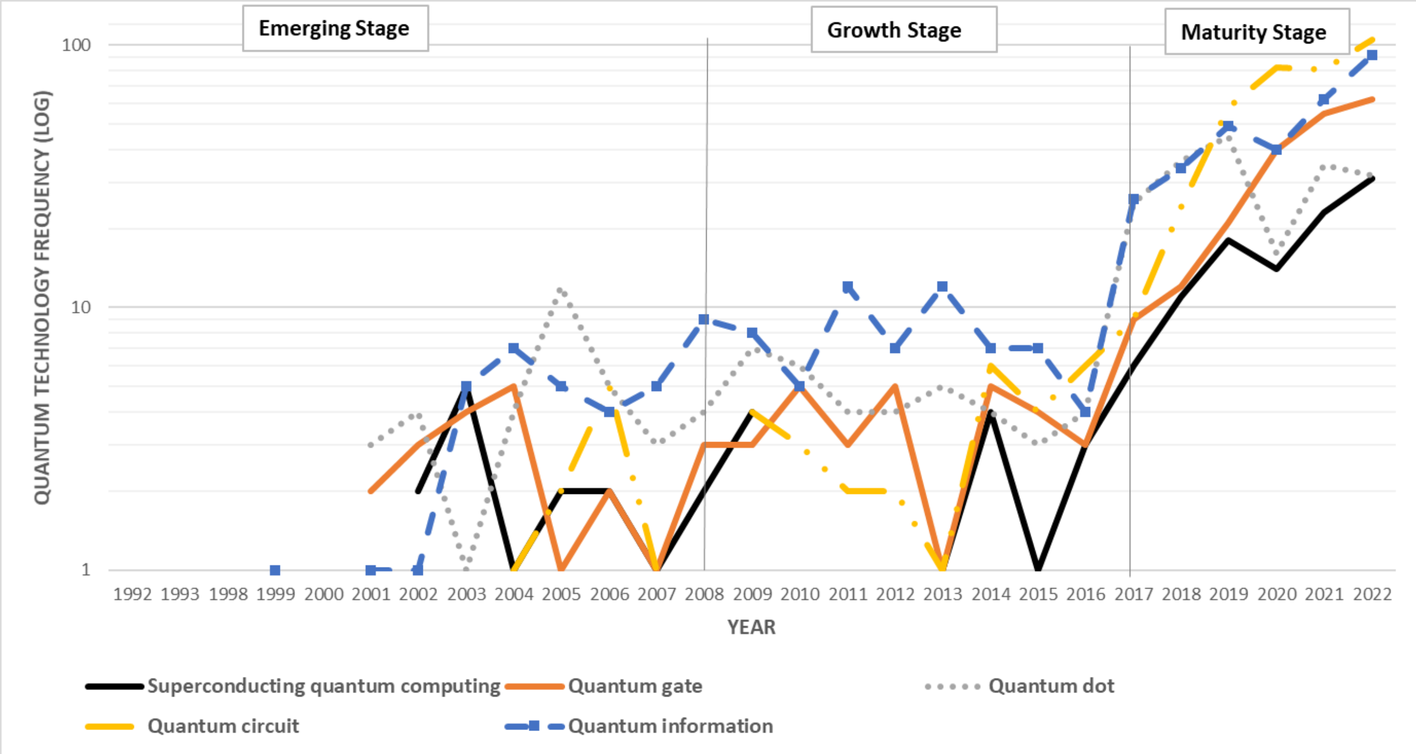


Figure 4. Top 5 technologies related to quantum computing topics in patents ranked by their frequencies

Note: The *x*-axis indicates the year of publication of the patent; The *y*-axis indicates the frequency of occurrences of technological topics in patents (LOG); S-curve analysis determines the stages of evolution: emerging stage is from 1992 to 2007, Growth stage is from 2008 to 2017 and Maturity stage is from 2018 to 2027. Quantum entanglement, quantum superposition, qubit, etc., are topics associated with properties of quantum computing that were removed.

Figure 4 shows that the top five topics in quantum computing are experiencing an exponential growth in maturity phase. This aspect indicates that these topics are more often in patents under study after 2017. As a result of our analysis in the evolution of topics over time, we have classified them into four main categories, considering patent share and the CAGR of patent share (figure 5): i.e., dominant, emerging, saturated, and declining. Based on data of the year 2022, the average patent share by topic was 0.268, which was used to determine whether a particular topic has a small or large patent share. The reference value of the CAGR in patent share was set as 0. Figure 5 shows the spatial geography of 50 patent topics in quantum computing.

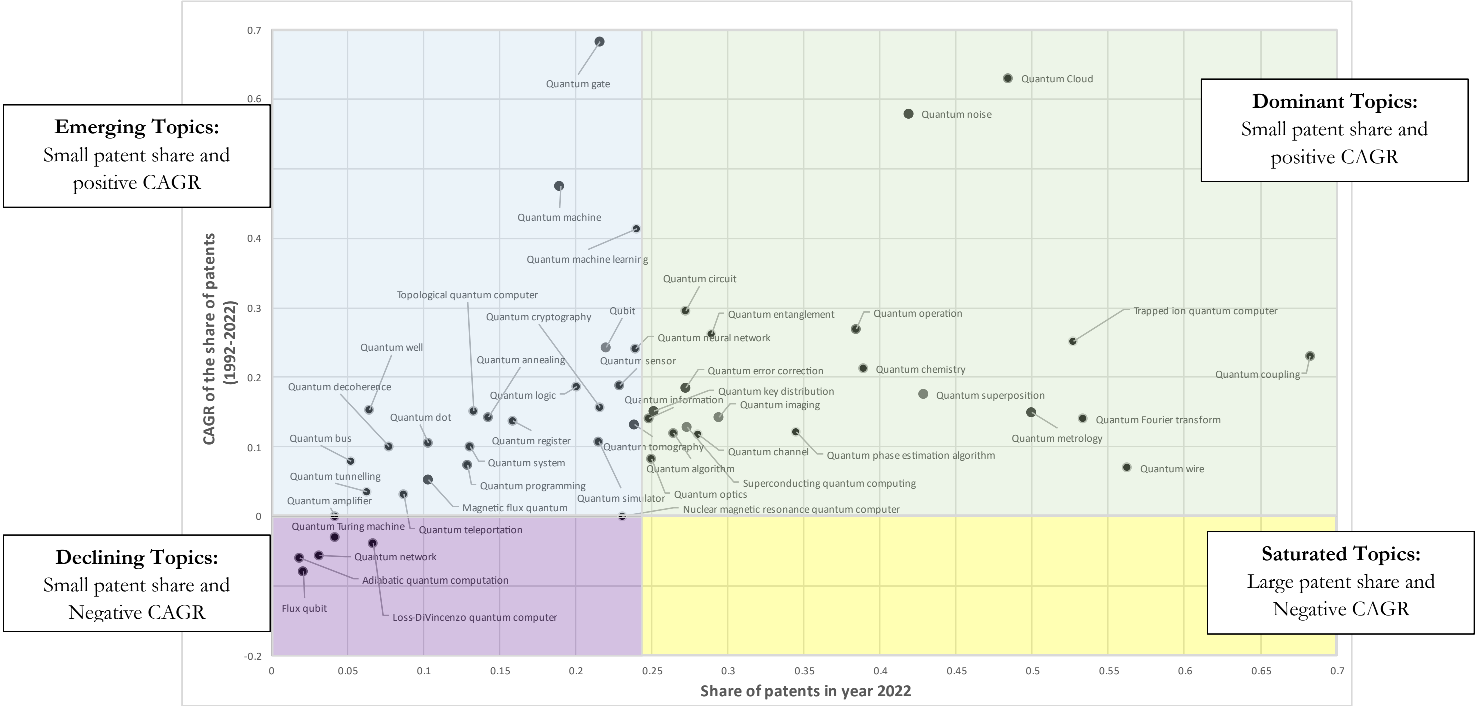


Figure 5: Classification of topics in Quantum computing patents over three periods

Note: *x*-axis indicates share of patents in year of 2022; *y*-axis indicates Compound Annual Growth Rate (CAGR) of the share of patents from 1992 to 2022; Average share of patents in 2022 by topic is 0.268; Purple area indicates Declining topic with small patent share and negative CAGR of patent share; Yellow area indicates saturated topic with large patent share and negative CAGR of patent share; Blue Area indicates emerging topics with small patent share and positive CAGR of patent share; Green area indicates dominant topics with small patent share and positive CAGR of patent share.

In Figure 5 and Table 5, we present a comprehensive classification of various quantum-related topics based on their current patent shares and Compound Annual Growth Rates (CAGRs) over the last 30 years. This analysis provides valuable insights into the emerging, declining, and dominant areas within the realm of quantum technologies.

Figure 5 and Table 5 highlight a set of topics classified as emerging, including "Quantum gate," "Quantum machine," etc. These topics exhibit a current patent share below the average, coupled with a positive CAGR in patent share over the last three decades. The increasing pace of patenting activity suggests potential future growth in these areas. Conversely, certain topics such as "Quantum Turing Machine," "Quantum teleportation," and other topics fall into the declining category. Notably, these topics demonstrate a negative CAGR and a current patent share below the average, indicating a waning interest in recent years. A group of topics, including "Quantum cloud," "Quantum noise," and several other ones, emerges as dominant. In these areas, active technological development is evident, and a robust future growth trajectory can be anticipated. The dominance is characterized by both a substantial current patent share and ongoing technological advancement. Remarkably, Figure 5 reveals the absence of topics in the saturated area, typically associated with negative CAGR and large patent shares. Two intriguing topics, "Nuclear magnetic resonance quantum computer" and "Quantum amplifier," lie on the boundary between declining and emerging areas. These cases warrant further investigation to understand their unique dynamics and potential technological shifts in interest.

Table 5. Categorization of topics related to the quantum computing technology

Saturated topics CAGR < 0	**Declining topics CAGR < 0**	**Emerging Topics CAGR > 0**	**Dominant Topics CAGR > 0**
------------	"Quantum Turing Machine", "Quantum teleportation", "Quantum network", "Adiabatic quantum computation", "Flux Qubit", "Loss-DiVincenzo quantum computer"	"Quantum gate", "Quantum machine", "Quantum well", "Quantum decoherence", "Quantum sensor", "Quantum dot", "Quantum register", "Quantum system", "Quantum programming", Quantum tunnelling", "Quantum bus", "Topological quantum computer", "Magnetic flux quantum", "Quantum simulator", "Quantum logic", "Quantum annealing", "Quantum tomography", "Qubit", "Quantum Neural Network", "Quantum Machine learning", "Quantum cryptography"	"Quantum cloud", "Quantum noise", "Quantum circuit", "Quantum entanglement", "Quantum operation", "Quantum operation", "Trapped ion quantum computer", "Quantum coupling", "Quantum error correction", "Quantum information", "Quantum key distribution", "Quantum imaging", "Quantum Chanell", "Quantum chemistry", "Quantum algorithm", "Quantum optics", "Superconducting quantum computing", "Quantum phase estimation algorithm", "Quantum Furrier transform", "Quantum superposition"

Note. CAGR represents Compound Annual Growth Rate

5. Main discussion

5.1 References with previous research.

The evolution of quantum computing over the last three decades has exhibited unparalleled (Scheidsteger et al., 2021). Scholars have analyzed quantum research and suggested main pathways, that of course are not exhaustive (cf., Dowling and Milburn, 2003; Jaeger, 2018; Long et., 2019). This study shows that technologies in quantum computing are in continuous evolution with changes in the dynamics and structure of technological cycle. The findings reveal that the evolutionary dynamics of quantum computing co-evolves with endogenous processes that support interaction with manifold topics increasing the extension and density of networks with increasingly inter-related technologies (Coccia et al., 2024; Sun et al., 2013). These observed dynamics enrich our theoretical understanding of how scientific technological fields evolve, especially the role of interconnections and cumulative knowledge over time. Moreover, they results here provide a practical roadmap for understanding the future development in quantum computing. For instance, Figure 4 illustrates that the top five quantum computing technologies are experiencing exponential growth during the maturity phase, indicating the rapid advancement in this domain. This finding suggests a main technological change in quantum computing that is driven by accumulation of patents in specific research topics that increase scientific development and technological interactions with related technologies (Coccia et al., 2024). Results also suggest that technologies in quantum computing co-evolve with complex interactions driven by three evolutionary characteristics: a high connectivity between nodes of research fields and technologies (growth of DC from 12.55 in emerging phase to 34.15 in maturity phase); stable values of the average influence or control of nodes on the flow between nodes within quantum computing ecosystem (betweenness centrality is a measure of centrality in a graph based on shortest paths, here is in the range of 0.06-0.04); finally a moderate increase of the closeness centrality (a measure of access efficiency or of independence from potential control by intermediaries) from 0.54 in emerging phase to 0.59 in maturity phase. A main aspect of the ecosystem in quantum computing, represented here with networks of patent topics is a morphological evolution during the transition from emerging to maturity phases, from a spheroid shape of network (having a symmetric shape, is a scientific and technological network in the initial phase of evolution with nodes and mutual interconnexions sparse) to irregular shape (has an asymmetric shape and is a scientific and technological network in the growing phase of evolution with dense nodes, mutual interconnexions and high connectivity).

5.2 Managerial and policy implications

The findings of this study have significant practical implications for various stakeholders, including policymakers, R&D managers, technology analysts, etc. in the field of quantum computing. By understanding the evolutionary dynamics and co-evolutionary patterns in this rapidly advancing technology, decision-makers can leverage these insights to drive progress and innovation effectively.

- Strategic Resource Allocation: R&D investments are crucial drivers of scientific and technological development. Our study highlights critical research topics and technologies in quantum computing that exhibit higher degrees of centrality. Policymakers and R&D managers can strategically allocate economic resources towards these research fields to accelerate scientific and technological advancements. Funding directed to cutting-edge research encourages collaboration and strategic alliances among firms to design and foster the development of breakthrough innovations. For instance, by identifying "Quantum

Information" as a dominant technology with a high degree centrality, R&D managers can prioritize funding for projects related to quantum information processing, enabling advancements in quantum algorithms and cryptographic systems having a lot of practical applications. Also, with the classification of "Quantum gate", "Quantum machine", "Quantum well", "Quantum decoherence", "Quantum sensor", "Quantum dot", and many others as emerging topics, these areas might be identified as potential target for strategic resource allocation to further stimulate the field's rapid growth.

- Strategic collaboration: the co-evolutionary dynamics and network structures of quantum computing topics reveal potential opportunities for cross-fertilization of ideas and projects. Interconnected technologies offer a fertile ground for collaborative initiatives among researchers, academic institutions, and industry players . Partnerships of firms and academic institutions across different fields can lead to the emergence of disruptive innovations and accelerate the technology's commercialization (Coccia, 2017b, 2017c, 2020, 2020a, 2020b). Based on the high betweenness centrality of "Quantum Dot," leader firms can initiate collaborative research projects between vital players to develop new quantum dot-based technologies with enhanced performance. For example, emerging topics like "Quantum Neural Network" and "Quantum Machine learning" offer opportunities for cross-disciplinary collaboration, potentially leading to groundbreaking advancements.
- Technology Transfer and Market Opportunities: The co-evolutionary nature of quantum computing technologies provides valuable insights into the emergence of market opportunities. Identifying technologies that are transitioning from the growth phase to the maturity phase can help stakeholders anticipate market demand and prepare for technology transfer in markets. Understanding the dynamics of patent topics can guide in management of technology licensing decisions and facilitate the commercialization of quantum technologies. For instance, "Quantum Circuit" is experiencing an exponential growth and transitioning to maturity, firms can explore licensing opportunities of this technology to capitalize on the rising demand for advanced quantum circuits having various applications, such as in quantum simulation and optimization. Simultaneously, dominant topics like "Quantum cloud", "Quantum noise", "Quantum circuit", etc., provide indicators of current market demand and areas ripe for R&D investments and technology transfer.

- Competitiveness and Market Positioning: By analyzing the morphological changes in the patent topics network, industrial players can assess their competitiveness and market positioning in the quantum computing ecosystem. Monitoring the evolution of dominant technologies can help organizations to align their R&D efforts and strategic planning to stay at the forefront of the rapidly evolving quantum market. A firm having a competitive advantage in "Quantum Entanglement" can leverage its expertise and existing patents to solidify its position as a key player in the quantum communication and quantum cryptography markets. Furthermore, acknowledging the classification of declining topics like "Quantum Turing Machine", "Quantum teleportation", "Quantum network", and others, firms could strategically refocus their efforts towards more promising or dominant areas to maintain or enhance their market positioning and related competitive advantage, avoiding innovation failure (Coccia, 2023).

Table 6 systematize the managerial implications of the study.

Table 6. Managerial and strategic implications of the technology analysis in quantum computing research fields.

Management Implications	Tactical Recommendation	Evidence from results	Key stakeholders
Strategic Resource Allocation	Allocate a substantial share of R&D investments to Quantum Information Prioritize projects advancing quantum algorithms and cryptographic systems Cross-disciplinary teams for technological development Leverage public-private partnerships for sustained funding	- Significant growth in the number of links and connections related to Quantum Information and Quantum Algorithm during the Maturity stage (2017-2022). - Quantum Information with the highest degree centrality (48) and strong connections with various topics in the Maturity stage -Logistic model predicts a continued increase in quantum computing patents, emphasizing the need for sustained funding	Policymakers, R&D Managers, Technology analysts, Funding Agencies
Strategic Collaboration	Harness Quantum Dot's pivotal role in the network for collaborative endeavors. Facilitate joint projects involving firms in the emerging industry of quantum computing. Establish an industry-wide consortium for shared research and resources Promote knowledge exchange between firms and academic institutions with workshops and forums.	- Quantum Dot identified as a pivotal topic with high betweenness centrality (0.137) in the Emerging period. - Network analysis shows increased collaboration opportunities in the Growth and Maturity stages	Industry Consortiums, Leading firms, industrial association, Universities and research labs
Technology Transfer and Market Opportunities	Explore strategic technology transfer avenues for Quantum Circuit from university to industry Investigate licensing opportunities to meet growing market demand in quantum computing. Identify application areas (e.g., quantum simulation, optimization) and tailor marketing strategies. Foster partnerships with industry players for market penetration in different areas.	-Quantum Circuit is a dominant topic with significant growth in connections (degree centrality of 47) during the Maturity stage. - Top 5 technologies, including Quantum Circuit, experiencing exponential growth in maturity phase.	Technology Transfer Offices, Licensing Agencies, Marketing Teams, Industry Partnerships
Competitive advantage and Market Positioning	Capitalize the Quantum Entanglement expertise for market leadership Regularly assess the competitive landscape and refine R&D strategies to maintain dominance. Industry collaborations for standardization and adoption of Quantum Entanglement in communication and cryptography markets.	- Quantum Entanglement has high degree centrality and betweenness centrality across all stages. - Network measures highlight its pivotal role in connecting with other topics. - Quantum Entanglement's increased connections in the Maturity stage indicating growing expertise and influence.	R&D Strategy Teams, Marketing Teams, Industry Collaborators, Standardization Bodies
Future-Proofing Investments	Allocate resources to explore emerging technologies (e.g., Quantum Neural Network, Quantum Cloud, Quantum Noise) with potential growth. Establish task force teams for continuous monitoring and adaptation in markets Foster an agile R&D environment to respond to evolving technological landscapes.	- Identified emerging topics include Quantum Neural Network, Quantum Cloud, and Quantum Noise. - Exponential growth in technological topics in the maturity phase, indicating potential aspects for future developments.	R&D Managers, Strategic Planners, Training and Development Teams

	Invest in training and development to stay ahead in emerging fields.		
Adaptive Innovation Strategies	Develop adaptive innovation strategies based on learning processes in organization Invest in flexible R&D frameworks to respond to emerging trends Encourage a culture of collaboration and knowledge sharing to adapt quickly to changing dynamics. Regularly review and adjust innovation roadmaps based on evolving patent landscapes.	- Co-evolutionary patterns observed in the dynamics of the top five technologies in quantum science - Flexible R&D frameworks and a culture of collaboration supported by the observed network measures.	Innovation Managers, Researchers, Technology Strategists
Organizational Adjustments	Make structural adjustments in the organization to align with morphological changes, creating new units. Establish specialized teams or units for technologies experiencing significant growth. Foster inter-departmental collaboration to maximize knowledge flow and creation. Regularly evaluate and optimize the organizational structure with human and economic flexibility	Morphological Changes in Patent Topics between networks over time	Organizational Leaders, Department Heads, Innovation Teams
Portfolio Diversification	Diversify R&D portfolios based on the categorized types (Dominant, Emerging, Saturated, Declining). Balance investments of both established technologies and emerging ones. Establish monitoring mechanisms for saturated and declining topics to avoid potential resource drains. Explore partnerships or acquisitions to strengthen the portfolio.	- Classification of topics into Dominant, Emerging, Saturated, and Declining categories based on patent share and CAGR. - Recommendation supported by the need to balance investments and avoid potential resource drains.	R&D Portfolio Managers, Partnership Teams, Acquisition Teams, Monitoring Teams
Regulatory and Ethical Considerations	Proactively engage with policymakers to address regulatory aspects in quantum computing. Stay informed about evolving frameworks for responsible development.	Proactive Engagement for regulatory aspects in quantum science to avoid social and economic problems. Engaging with policymakers for a responsible quantum computing development.	Policymakers, Planners. Quantum Technology Developers
Investment in Quantum Education	Address the demand for skilled human resources in quantum computing by investing in educational initiatives. Collaborate with academic institutions to develop specialized programs for building a skilled talent pool.	- Recommendation supported by the identified emerging technologies and the need for skilled human resources in organization and public institutions. Collaboration with academic institutions facilitated by observed network measures.	Education and Training Teams, Academic Collaborations

6. Conclusions

The insights of this study significantly contribute to our understanding of the evolutionary patterns in quantum computing. The innovative categorization of various quantum computing topics into emerging, declining, dominant, and saturated groups (based on their respective patent shares and Compound Annual Growth Rates-CAGR), provides a detailed perspective of the developmental trajectories of assorted topics in quantum computing. This approach offers crucial insights into the future direction of this field. Further, the revelations of co-evolutionary dynamics and morphological changes in patent topics illuminate the intricate interactions and structural evolution within quantum computing research. These findings accentuate the role of diverse technologies and research fields in shaping the future trajectories of quantum computing and offer practical implications for strategic resource allocation, collaborative initiatives, technology transfer, and competitiveness in this rapidly advancing field. Moreover, evolutionary pathways in quantum computing, described here, have main implications for management of technologies and innovations to support decisions of R&D investments. In fact, policymakers and R&D managers know that financial resources can be an accelerator factor of progress and diffusion of science and technology to support the scientific and technological development (Roshani et al., 2021). This study shows critical research topics and technologies in quantum computing that are growing with a higher degree centrality; R&D management can allocate economic resources towards these research fields and technologies in quantum computing to accelerate the development of science and technology and foster technology transfer having fruitful effects for industrial and corporate change in knowledge economies.

6.1 Limitations and ideas for future research

These conclusions are, of course, tentative. Although this study has provided some interesting, albeit preliminary results, it has several limitations. First, the precision of the search queries is affected by ambivalent meanings in quantum computing, such as information, computing, computer, etc. Second limitation is that sources understudy may only capture certain aspects of the ongoing evolutionary dynamics in quantum research and technology. In fact, patent analysis can only detect certain aspects of the ongoing dynamics in quantum computing and next study should apply complementary analysis based on publications for improving the technological foresight; third, there are multiple confounding factors that could have an important role in the dynamics of quantum research to be further investigated, such as multiple discoveries (Coccia, 2022a), high R&D investments, scientific institutions, collaboration intensity, intellectual property rights, etc. (Coccia and Wang, 2016; Coccia, 2008, 2017, 2019; Mosleh et al., 2022) Fourth, this study shows technologies in a growth and/or maturity phase for patenting activity. However, many technologies in quantum computing need a long incubation period and R&D investments before to be implemented in markets as innovations that guide technological change. Another limitation is the potential bias introduced by using Wikipedia as a catalog for the entity linking process. While Wikipedia is a rich resource, its nature of being collaboratively edited can lead to potential inaccuracies or biases. Moreover, the sensitivity of parameter settings, such as those determining context and confidence scores, poses a challenge. Nevertheless, we addressed this by fine-tuning parameters for their specificity. Additionally, the computational intensity of entity linking, especially with a large volume of documents, requires substantial resources. Yet, we efficiently managed resources using TAGME's API and a high-performance GPU. In short, the exclusion of topics without the word 'quantum' and the dependency on Wikipedia introduce potential biases, limiting the neutrality and comprehensiveness of topic representation. Future research could consider additional databases to mitigate this limitation and enhance the robustness of the entity linking process.

Hence, the study here, based on patents, provides proxies of future innovations in quantum computing and has to be refined to improve implications of technological forecasting. In conclusion, future research should consider new data when available and apply new approaches to reinforce proposed results. Despite these limitations, the results presented here clearly illustrate the main evolutionary paths in quantum computing that are increasingly based on a growing connectivity between technologies and research fields that need a further detailed examination for explaining driving factors and designing alternative strategies of innovation management that support competitive advantage of firms in current knowledge economies .

Appendix A

Table 1A: Testing results of the Gompertz and Logistic curve

	RMSE	MAPE	R^2
Logistic	213	0.365	0.914
Gompertz	290	0.362	0.878

Note. RMSE=Root Mean Square Value; MAPE= Mean Absolute Percentage Error; R^2 is a coefficient of determination that indicates how well a model fits. The presented table compares the testing results of the Logistic and Gompertz curve fitting models in predicting the patent growth of quantum computing technology. The R-squared value (R^2) serves as a measure of how well each model fits the data, with higher values indicating a better fit. In our analysis, the Logistic curve demonstrates superior performance with an R^2 of 0.914, signifying a high level of explanatory power. Additionally, the lower values of Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) for the Logistic curve (213 and 0.365, respectively) compared to the Gompertz model underscore its better accuracy in predicting patent growth dynamics.

Table 2A. Top 20 emerging quantum-computing related topics from emerging to growth, and growth to maturity stages based on the degree centrality.

Emerging → Growth			**Growth → Maturity**		
Rank	**Topic**	**DC**	**Rank**	**Topic**	**DC**
1	Quantum annealing	10	**1**	Quantum neural network	17
2	Quantum sensor	9	**2**	Quantum cloud	13
3	Topological quantum number	8	**3**	Quantum noise	11
4	Trapped ion quantum computer	7	**4**	Quantum programming	11
5	Quantum metrology	7	**5**	Post-quantum cryptography	9
6	Quantum operation	6	**6**	Quantum machine learning	8
7	Quantum imaging	6	**7**	Linear optical quantum computing	6
8	Fidelity of quantum states	6	**8**	Method of quantum characteristics	6
9	One-way quantum computer	6	**9**	Quantum gravity	6
10	Quantum bus	5	**10**	Quantum field theory	5
11	Flux qubit	5	**11**	Quantumdigital	5
12	Quantum evolution	4	**12**	Circuit quantum electrodynamics	5
13	Quantum technology	4	**13**	Quantum clock	5
14	Quantum dot solar cell	3	**14**	Quantum fluid	4
15	Quantum nondemolition measurement	2	**15**	Cavity quantum electrodynamics	4
16	Quantum phase transition	2	**16**	Quantum electrodynamics	4
17	Quantum defect	2	**17**	Quantum chromodynamics	4
18	Quantum coupling	2	**18**	Quantum flux parametron	4
19	Quantum harmonic oscillator	2	**19**	Topological quantum field theory	4
20	Quantum efficiency	1	**20**	Quantum graph	4

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Bibliography

Acín, A.; Bloch, I.; Buhrman, H.; Calarco, T.; Eichler, C. et al. 2018. The quantum technologies roadmap: A European community view. In: New Journal of Physics 20, Nr. 8, 80201. DOI: https://doi.org/10.1088/1367-2630/aad1ea

Aduba, J. J., & Asgari, B. (2022). Analysing and forecasting the diffusion of electronic payments system in Nigeria. Technology Analysis & Strategic Management, 34(10), 1215-1233.

Aharonson, B. S., & Schilling, M. A. (2016). Mapping the technological landscape: Measuring technology distance, technological footprints, and technology evolution. Research Policy, 45(1), 81-96.

Altuntas S., Aba S. 2022. Technology Forecasting of Unmanned Aerial Vehicle Technologies through Hierarchical S-Curves¸ Defence Science Journal, Vol. 72, No. 1, January 2022, pp. 18-29, DOI : 10.14429/dsj.72.16823

Altuntas, F., Gök, M.Ş. 2021. Analysis of patent documents with utility mining: A case study of wind energy technology. Kybernetes, 50(9), 2548-2582. doi: 10.1108/K-06-2020-0365.

Altuntas, S.; Dereli, T. & Kusiak, A. 2015. Forecasting technology success based on patent data. Technol. Forecast. Soc. Change., 2015, 96 (July), 202–214.doi: 10.1016/j.techfore.2015.03.011.

Anastopoulos I., Bontempi E., Coccia M., Quina M., Shaaban M. 2023. Sustainable strategic materials recovery, what's next? Next Sustainability, VSI: Sustainable strategic materials recovery_Editorial, n. 100006, https://doi.org/10.1016/j.nxsust.2023.100006

Ardito, L., Coccia, M., & Messeni Petruzzelli, A. (2021). Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. R&D Management, 51(4), 381–392.

Atik J. & Jeutner V. 2021. Quantum computing and computational law, Law, Innovation and Technology, 13:2, 302-324, DOI: 10.1080/17579961.2021.1977216

Bastian, M., Heymann, S., & Jacomy, M. (2009, March). Gephi: an open source software for exploring and manipulating networks. In Proceedings of the international AAAI conference on web and social media (Vol. 3, No. 1, pp. 361-362).

Batra, K., Zorn, K.M., Foil, D.H., (...), Lane, T.R., Ekins, S. 2021. Quantum Machine Learning Algorithms for Drug Discovery Applications, Journal of Chemical Information and Modeling, 61(6), pp. 2641-2647

Bhatt, P. C., Lai, K. K., Drave, V. A., Lu, T. C., & Kumar, V. (2023). Patent analysis based technology innovation assessment with the lens of disruptive innovation theory: A case of blockchain technological trajectories. Technological Forecasting and Social Change, 196, 122864.

Blei, D. M. (2012). Probabilistic topic models. Communications of the ACM,55(4), 77–84. https://doi.org/10.1145/2133806.2133826.

Blei, D. M., & Lafferty, J. D. (2006). Dynamic topic models. In Proceedings of the 23rd international conference on machine learning (pp. 113–120). https://doi.org/10.1145/1143844.1143859.

Blei, D. M., Ng, A. Y., & Jordan, M. I. (2003). Latent Dirichlet allocation. the Journal of machine Learning research, 3, 993-1022.

Boyack, K., Börner, K., & Klavans, R. (2009). Mapping the structure and evolution of chemistry research. Scientometrics, 79(1), 45–60.

Carberry, D., Nourbakhsh, A., Karon, J., (...), Andersson, M.P., Mansouri, S.S.2021. Building Knowledge Capacity for Quantum Computing in Engineering Education, Computer Aided Chemical Engineering 50, pp. 2065-2070

Casella, G., Bigliardi, B., & Bottani, E. (2022). The evolution of RFID technology in the logistics field: A review. Procedia Computer Science, 200, 1582-1592.

Cavallo, E., Ferrari E., Bollani, L., Coccia M. 2014. Attitudes and behaviour of adopters of technological innovations in agricultural tractors: A case study in Italian agricultural system, Agricultural Systems, vol. 130, pp. 44-54, DOI: 10.1016/j.agsy.2014.05.012

Chen, B., Tsutsui, S., Ding, Y., & Ma, F. (2017). Understanding the topic evolution in a scientific domain: An exploratory study for the field of information retrieval. Journal of Informetrics,11(4), 1175–1189. https://doi.org/10.1016/j.joi.2017.10.003.

Choi, D., & Song, B. (2018). Exploring technological trends in logistics: Topic modeling-based patent analysis. Sustainability, 10(8), 2810.

Chu, W. L., Wu, F. S., Kao, K. S., & Yen, D. C. (2009). Diffusion of mobile telephony: An empirical study in Taiwan. Telecommunications policy, 33(9), 506-520.

Coccia M. 2004. Spatial metrics of the technological transfer: analysis and strategic management, Technology Analysis & Strategic Management, vol. 16, n. 1, pp. 31-52. https://doi.org/10.1080/0953732032000175490

Coccia M. 2005. Measuring Intensity of technological change: The seismic approach, Technological Forecasting & Social Change, vol. 72, n. 2, pp. 117-144. https://doi.org/10.1016/j.techfore.2004.01.004

Coccia M. 2005. Metrics to measure the technology transfer absorption: analysis of the relationship between institutes and adopters in northern Italy. International Journal of Technology Transfer and Commercialization, vol. 4, n. 4, pp. 462-486. https://doi.org/10.1504/IJTTC.2005.006699

Coccia M. 2005. Technometrics: Origins, historical evolution and new direction, Technological Forecasting & Social Change, vol. 72, n. 8, pp. 944-979. https://doi.org/10.1016/j.techfore.2005.05.011

Coccia M. 2008. New organizational behaviour of public research institutions: Lessons learned from Italian case study. International Journal of Business Innovation and Research, vol. 2, n. 4, pp. 402–419. https://doi.org/10.1504/IJBIR.2008.018589

Coccia M. 2008. Spatial mobility of knowledge transfer and absorptive capacity: analysis and measurement of the impact within the geoeconomic space, The Journal of Technology Transfer, vol. 33, n. 1, pp. 105-122. https://doi.org/10.1007/s10961-007-9032-4

Coccia M. 2010. Foresight of technological determinants and primary energy resources of future economic long waves. International Journal of Foresight and Innovation Policy, vol. 6, n. 4, pp. 225–232, https://doi.org/10.1504/IJFIP.2010.037468

Coccia M. 2010. Public and private R&D investments as complementary inputs for productivity growth. International Journal of Technology, Policy and Management, vol. 10, n. 1/2, pp. 73-91. DOI: 10.1504/IJTPM.2010.032855

Coccia M. 2010. Spatial patterns of technology transfer and measurement of its friction in the geo-economic space. International Journal of Technology Transfer and Commercialisation, vol. 9, n. 3, pp. 255-267. https://doi.org/10.1504/IJTTC.2010.030214

Coccia M. 2012. Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine. Int. J. Healthcare Technology and Management, vol. 13, n. 4, pp. 184-197. https://doi.org/10.1504/IJHTM.2012.050616

Coccia M. 2012. Driving forces of technological change in medicine: Radical innovations induced by side effects and their impact on society and healthcare, Technology in Society, vol. 34, n. 4, pp. 271-283, https://doi.org/10.1016/j.techsoc.2012.06.002

Coccia M. 2012. Evolutionary growth of knowledge in path-breaking targeted therapies for lung cancer: radical innovations and structure of the new technological paradigm. International Journal of Behavioural and Healthcare Research, vol. 3, nos. 3-4, pp. 273-290. https://doi.org/10.1504/IJBHR.2012.051406

Coccia M. 2012. Evolutionary trajectories of the nanotechnology research across worldwide economic players, Technology Analysis & Strategic Management, vol. 24, n.10, pp. 1029-1050, https://doi.org/10.1080/09537325.2012.705117

Coccia M. 2014. Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change, Technology Analysis & Strategic Management, vol. 26, n. 7, pp. 733-749, https://doi.org/10.1080/09537325.2014.882501

Coccia M. 2014. Emerging technological trajectories of tissue engineering and the critical directions in cartilage regenerative medicine. Int. J. Healthcare Technology and Management, vol. 14, n. 3, pp. 194-208. http://dx.doi.org/10.1504/IJHTM.2014.064247

Coccia M. 2015. Spatial relation between geo-climate zones and technological outputs to explain the evolution of technology. Int. J. Transitions and Innovation Systems, vol. 4, nos. 1-2, pp. 5-21, http://dx.doi.org/10.1504/IJTIS.2015.074642

Coccia M. 2015. Technological paradigms and trajectories as determinants of the R&D corporate change in drug discovery industry. Int. J. Knowledge and Learning, vol. 10, n. 1, pp. 29–43. http://dx.doi.org/10.1504/IJKL.2015.071052

Coccia M. 2016. Problem-driven innovations in drug discovery: co-evolution of the patterns of radical innovation with the evolution of problems, Health Policy and Technology, vol. 5, n. 2, pp. 143-155. https://doi.org/10.1016/j.hlpt.2016.02.003

Coccia M. 2016. Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organizational performance in the discovery process of R&D labs, Technology Analysis & Strategic Management, vol. 28, n. 4, pp. 381-395, https://doi.org/10.1080/09537325.2015.1095287

Coccia M. 2017. Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. Technology Analysis & Strategic Management, vol. 29, n. 9, pp. 1048-1061, https://doi.org/10.1080/09537325.2016.1268682

Coccia M. 2017a. Sources of disruptive technologies for industrial change. L'industria –rivista di economia e politica industriale, vol. 38, n. 1, pp. 97-120, DOI: 10.1430/87140

Coccia M. 2017b. Disruptive firms and industrial change, Journal of Economic and Social Thought, vol. 4, n. 4, pp. 437-450, http://dx.doi.org/10.1453/jest.v4i4.1511

Coccia M. 2017c. The Fishbone diagram to identify, systematize and analyze the sources of general purpose technologies. Journal of Social and Administrative Sciences, vol. 4, n. 4, pp. 291-303, http://dx.doi.org/10.1453/jsas.v4i4.1518

Coccia M. 2018. A Theory of the General Causes of Long Waves: War, General Purpose Technologies, and Economic Change. Technological Forecasting & Social Change, vol. 128, March, pp. 287-295 (S0040-1625(16)30652-7), https://doi.org/10.1016/j.techfore.2017.11.013

Coccia M. 2018. An introduction to the methods of inquiry in social sciences, Journal of Social and Administrative Sciences, vol. 5, n. 2, pp. 116-126, http://dx.doi.org/10.1453/jsas.v5i2.1651

Coccia M. 2018. An introduction to the theories of institutional change, Journal of Economics Library, vol. 5, n. 4, pp. 337-344, http://dx.doi.org/10.1453/jel.v5i4.1788

Coccia M. 2018. Classification of innovation considering technological interaction, Journal of Economics Bibliography, vol. 5, n. 2, pp. 76-93, http://dx.doi.org/10.1453/jeb.v5i2.1650

Coccia M. 2018. Competition between basic and applied research in the organizational behaviour of public research labs, Journal of Economics Library vol. 5, n. 2, pp. 118-133, http://dx.doi.org/10.1453/jel.v5i2.1652

Coccia M. 2018. Functionality development of product innovation: An empirical analysis of the technological trajectories of smartphone. Journal of Economics Library, vol. 5, n. 3, pp. 241-258, http://dx.doi.org/10.1453/jel.v5i3.1741

Coccia M. 2018. Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations, The Journal of Technology Transfer, vol. 43, n. 3, pp. 792-814, https://doi.org/10.1007/s10961-017-9572-1

Coccia M. 2018. Theorem of not independence of any technological innovation, Journal of Economics Bibliography, vol. 5, n. 1, pp. 29-35, http://dx.doi.org/10.1453/jeb.v5i1.1578

Coccia M. 2018. What are the characteristics of revolution and evolution? Journal of Economic and Social Thought, vol. 5, n. 4, pp. 288-294, http://dx.doi.org/10.1453/jest.v5i4.1789

Coccia M. 2018a. Disruptive firms and technological change, Quaderni IRCrES-CNR, vol., 3, n. 1, pp. 3-18, http://dx.doi.org/10.23760/2499-6661.2018.001

Coccia M. 2019. A Theory of classification and evolution of technologies within a Generalized Darwinism, Technology Analysis & Strategic Management, vol. 31, n. 5, pp. 517-531, http://dx.doi.org/10.1080/09537325.2018.1523385

Coccia M. 2019. Intrinsic and extrinsic incentives to support motivation and performance of public organizations, Journal of Economics Bibliography, vol. 6, no. 1, pp. 20-29, http://dx.doi.org/10.1453/jeb.v6i1.1795

Coccia M. 2019. The theory of technological parasitism for the measurement of the evolution of technology and technological forecasting, Technological Forecasting and Social Change, vol. 141, pp. 289-304, https://doi.org/10.1016/j.techfore.2018.12.012

Coccia M. 2019. Theories of the evolution of technology based on processes of competitive substitution and multi-mode interaction between technologies. Journal of Economics Bibliography, vol. 6, n. 2, pp. 99-109, http://dx.doi.org/10.1453/jeb.v6i2.1889

Coccia M. 2019. Why do nations produce science advances and new technology? Technology in society, vol. 59, November, n. 101124, pp. 1-9, https://doi.org/10.1016/j.techsoc.2019.03.007

Coccia M. 2019a. What is technology and technology change? A new conception with systemic-purposeful perspective for technology analysis, Journal of Social and Administrative Sciences, vol. 6, no. 3, pp. 145-169, http://dx.doi.org/10.1453/jsas.v6i3.1957

Coccia M. 2019b. New Patterns of Technological Evolution: Theory and Practice, ©KSP Books, ISBN: 978-605-7602-88-6, Published July 30, 2019

Coccia M. 2019c. Comparative Institutional Changes. A. Farazmand (ed.), Global Encyclopedia of Public Administration, Public Policy, and Governance, Springer Nature Switzerland AG, Ihttps://doi.org/10.1007/978-3-319-31816-5_1277-1

Coccia M. 2020. Destructive Technologies for Industrial and Corporate Change. In: Farazmand A. (eds), Global Encyclopedia of Public Administration, Public Policy, and Governance. Springer, Cham. https://doi.org/10.1007/978-3-319-31816-5_3972-1

Coccia M. 2020. How does science advance? Theories of the evolution of science. Journal of Economic and Social Thought, vol. 7, n. 3, pp. 153-180. http://dx.doi.org/10.1453/jest.v7i3.2111

Coccia M. 2020. Multiple working hypotheses for technology analysis, Journal of Economics Bibliography - J. Econ. Bib., JEB - vol. 7., n. 2, pp. 111-126, http://dx.doi.org/10.1453/jeb.v7i2.2050

Coccia M. 2020a. Asymmetry of the technological cycle of disruptive innovations. Technology Analysis & Strategic Management, vol. 32, n. 12, p. 1462-1477. https://doi.org/10.1080/09537325.2020.1785415

Coccia M. 2020b. Fishbone diagram for technological analysis and foresight. Int. J. Foresight and Innovation Policy, Vol. 14, Nos. 2/3/4, pp. 225-247. DOI: 10.1504/IJFIP.2020.111221

Coccia M. 2021. Evolution of technology in replacement of heart valves: Transcatheter aortic valves, a revolution for management of valvular heart diseases, Health Policy and Technology, vol. 10, n. 2, n. 100512, https://doi.org/10.1016/j.hlpt.2021.100512

Coccia M. 2021. Technological Innovation. The Blackwell Encyclopedia of Sociology. Edited by George Ritzer and Chris Rojek. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781405165518.wbeost011.pub2

Coccia M. 2022. Technological trajectories in quantum computing to design a quantum ecosystem for industrial change, Technology Analysis & Strategic Management. Technology Analysis & Strategic Management, 36(8), 1733–1748. https://doi.org/10.1080/09537325.2022.2110056

Coccia M. 2022a. Probability of discoveries between research fields to explain scientific and technological change. Technology in Society, vol. 68, February, n. 101874, https://doi.org/10.1016/j.techsoc.2022.101874

Coccia M. 2022b. Disruptive innovations in quantum technologies for social change. Journal of Economics Bibliography, vol. 9, n.1, pp. 21-39. http://dx.doi.org/10.1453/jeb.v9i1.2287

Coccia M. 2023. High potential of technology to face new respiratory viruses: mechanical ventilation devices for effective healthcare to next pandemic emergencies, Technology in Society, vol. 73, May 2023, n. 102233, https://doi.org/10.1016/j.techsoc.2023.102233

Coccia M. 2023. New Perspectives in Innovation Failure Analysis: A taxonomy of general errors and strategic management for reducing risks. Technology in Society, vol. 75, n. 102384, https://doi.org/10.1016/j.techsoc.2023.102384

Coccia M. 2024. Digital Pathology Ecosystem: Basic Elements to Revolutionize the Diagnosis and Monitoring of Diseases in Health Sector. In: Faghih, N. (eds) Digital Entrepreneurship. Contributions to Management Science. pp. 111-134, Springer, Cham. https://doi.org/10.1007/978-3-031-58359-9_5

Coccia M. 2024. The General Theory of Scientific Variability for Technological Evolution, Sci 6, no. 2: 31. https://doi.org/10.3390/sci6020031

Coccia M., Falavigna G., Manello A. 2015. The impact of hybrid public and market-oriented financing mechanisms on scientific portfolio and performances of public research labs: a scientometric analysis, Scientometrics, vol. 102, n. 1, pp. 151-168, https://doi.org/10.1007/s11192-014-1427-z

Coccia M., Finardi U., Margon D. 2012. Current trends in nanotechnology research across worldwide geo-economic players, The Journal of Technology Transfer, vol. 37, n. 5, pp. 777-787, DOI: 10.1007/s10961-011-9219-6

Coccia M., Ghazinoori S., Roshani S. 2023. Evolutionary Pathways of Ecosystem Literature in Organization and Management Studies. Research Square. https://doi.org/10.21203/rs.3.rs-2499460/v1

Coccia M., Mosleh M., Roshani S., 2024. Evolution of quantum computing: Theoretical and innovation management implications for emerging quantum industry. IEEE Transactions on Engineering Management, vol. 71, pp. 2270-2280, DOI (identifier) 10.1109/TEM.2022.3175633

Coccia M., Roshani S. 2024. Evolutionary Phases in Emerging Technologies: Theoretical and Managerial Implications from Quantum Technologies, in IEEE Transactions on Engineering Management, vol. 71, pp. 8323-8338, doi: 10.1109/TEM.2024.3385116

Coccia M., Roshani S. 2024. General laws of funding for scientific citations: how citations change in funded and unfunded research between basic and applied sciences. Journal of Data and Information Science, 9(1), 1–18. https://doi.org/10.2478/jdis-2024-0005

Coccia M., Roshani S. 2024. Path-Breaking Directions in Quantum Computing Technology: A Patent Analysis with Multiple Techniques. J Knowl Econ (2024). https://doi.org/10.1007/s13132-024-01977-y

Coccia M., Roshani S., Mosleh M. 2021. Scientific Developments and New Technological Trajectories in Sensor Research. Sensors, vol. 21, no. 23: art. n. 7803. https://doi.org/10.3390/s21237803

Coccia M., Watts J. 2020. A theory of the evolution of technology: technological parasitism and the implications for innovation management, Journal of Engineering and Technology Management, vol. 55, n. 101552, https://doi.org/10.1016/j.jengtecman.2019.11.003

Coccia Mario 2024. Foundations of Science in Invasive Technologies. Qeios. doi:10.32388/NR1YME, https://doi.org/10.32388/NR1YM

Coccia, M., Roshani, S. 2024. Research funding and citations in papers of Nobel Laureates in Physics, Chemistry and Medicine, 2019-2020. Journal of Data and Information Science, 9(2), 1–25. https://doi.org/10.2478/jdis-2024-0006, https://sciendo.com/article/10.2478/jdis-2024-0006

Coccia, M.; Roshani, S.; Mosleh, M. 2022. Evolution of Sensor Research for Clarifying the Dynamics and Properties of Future Directions. Sensors, 22(23), 9419; https://doi.org/10.3390/s22239419

Coccia, Mario. 2024. "Converging Artificial Intelligence and Quantum Technologies: Accelerated Growth Effects in Technological Evolution", Technologies 12, no. 5: 66. https://doi.org/10.3390/technologies12050066

Cornolti, M., Ferragina, P., & Ciaramita, M. (2013, May). A framework for benchmarking entity-annotation systems. In Proceedings of the 22nd international conference on World Wide Web (pp. 249-260).

Cozzens S., Gatchair S., Kang J. , Kyung-Sup Kim , Lee H. J., Ordóñez G., Porter A. 2010. Emerging technologies: quantitative identification and measurement, Technology Analysis & Strategic Management, 22:3, 361-376, DOI: 10.1080/09537321003647396

Dahlberg A., Matthew Skrzypczyk, Tim Coopmans, Leon Wubben, Filip Rozpędek, Matteo Pompili, Arian Stolk, Przemysław Pawełczak, Robert Knegjens, Julio de Oliveira Filho, Ronald Hanson, and Stephanie Wehner. 2019. A link layer protocol for quantum networks. In Proceedings of the ACM Special Interest Group on Data Communication (SIGCOMM '19). Association for Computing Machinery, New York, NY, USA, 159–173. https://doi.org/10.1145/3341302.3342070

Dahlberg, E. A., van der Vecht, B., Delle Donne, C., Skrzypczyk, M. D., te Raa, I., Kozlowski, W., & Wehner, S. D. C. (2022). NetQASM—a low-level instruction set architecture for hybrid quantum–classical programs in a quantum internet. Quantum Science and Technology, 7, n. 035023, DOI: 10.1088/2058-9565/ac753f

Deshmukh, S., Mulay, P. 2021. Quantum clustering drives innovations: A bibliometric and patentometric analysis, Library Philosophy and Practice 2021, pp. 1-27

Dhar, M., & Bhattacharya, P. (2018). Comparison of the logistic and the Gompertz curve under different constraints. Journal of Statistics and Management Systems, 21(7), 1189-1210.

Dowling, J.P.; Milburn, G.J. 2003. Quantum technology: The second quantum revolution. Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci. 2003, 361, 1655–1674.

Engineering, Tech. rep., Technical report, EBSE Technical Report EBSE-2007-01.

Ernst, H. 1997. The use of patent data for technological forecasting: the diffusion of CNC-technology in the machine tool industry. Small business economics, 9(4), 361-381. https://doi.org/10.1023/A:1007921808138

Faust K. 1990. Early identification of technological advances on the basis of patent data, Scientometrics, vol. 19, nos.5-6, pp. 473-480. https://doi.org/10.1007/BF02020708

Ferragina, P., & Scaiella, U. (2010). Tagme: on-the-fly annotation of short text fragments (by wikipedia entities). In Proceedings of the 19th ACM international conference on Information and knowledge management (pp. 1625-1628).

Freeman, L.C. A 1977. Set of Measures of Centrality Based on Betweenness. Sociometry 1977, 40, 35, doi:10.2307/3033543.

Gao, L., Porter, A.L., Wang, J., Fang, S., Zhang, X., Ma, T., Wang, W. and Huang, L., 2013. Technology life cycle analysis method based on patent documents. Technological Forecasting and Social Change, 80(3), pp.398-407

Gohr, A., Hinneburg, A., Schult, R., & Spiliopoulou, M. (2009). Topic evolution in a stream of documents. In Proceedings of the 2009 SIAM international conference on data mining (Vols. 1–0, pp. 859–870). https://doi.org/10.1137/1.9781611972795.74.

Goldstein, R., & Vitevitch, M. S. (2017). The influence of closeness centrality on lexical processing. Frontiers in psychology, 8, 1683.

Han, B., Zhang, J., Cai, H., Xia, M., Tu, Y., & Wu, J. (2023). 5G wireless technology evolution: Identifying evolution pathways of core technologies based on patent networks. Wireless Networks, 1-12.

Hofmann, T. (1999) Probabilistic Latent Semantic Indexing. Proceedings of the 22nd Annual International ACM SIGIR Conference on Research and Development in Information Retrieval, Berkeley, 15-19 August 1999, 50-57. http://dx.doi.org/10.1145/312624.312649

Hou, H., & Shi, Y. (2021). Ecosystem-as-structure and ecosystem-as-coevolution: A constructive examination. Technovation, 100, 102193.doi.org/10.1016/j.technovation.2020.102193Get

Huang, Y., Li, R., Zou, F., Jiang, L., Porter, A. L., & Zhang, L. (2022). Technology life cycle analysis: From the dynamic perspective of patent citation networks. Technological Forecasting and Social Change, 181, 121760.

Jaeger, L. 2018. The Second Quantum Revolution: From Entanglement to Quantum Computing and Other Super-Technologies; Springer: Berlin/Heidelberg, Germany

Jiang, S. Y., & Chen, S. L. (2021). Exploring landscapes of quantum technology with Patent Network Analysis. Technology Analysis & Strategic Management, 33(11), 1317-1331.

Jovanovic, M., Sjödin, D., & Parida, V. (2021). Co-evolution of platform architecture, platform services, and platform governance: Expanding the platform value of industrial digital platforms. Technovation, 102218.

Kashani, E. S., & Roshani, S. (2019). Evolution of innovation system literature: Intellectual bases and emerging trends. Technological Forecasting and Social Change, 146, 68-80.

Kitchenham B. and Charters S. (2007) Guidelines for Performing Systematic Literature Reviews in Software

Kott A. 2019. Toward universal laws of technology evolution: modeling multi-century advances in mobile direct-fire systems. Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, pp. 1–16, DOI: 10.1177/1548512919875523

Kozlowski, W., & Wehner, S. 2019. Towards large-scale quantum networks. In C. Contag, & T. Melodia (Eds.), Proceedings of the 6th ACM International Conference on Nanoscale Computing and Communication, NANOCOM 2019 [3345497] (Proceedings of the 6th ACM International Conference on Nanoscale Computing and Communication, NANOCOM 2019). https://doi.org/10.1145/3345312.3345497

Landauer, T. K., Foltz, P. W., & Laham, D. (1998). An introduction to latent semantic analysis. Discourse processes, 25(2-3), 259-284.

Lee, H., & Kang, P. (2018). Identifying core topics in technology and innovation management studies: A topic model approach. The Journal of Technology Transfer, 43, 1291-1317.

Liang, Z., Mao, J., Lu, K., Ba, Z., & Li, G. (2021). Combining deep neural network and bibliometric indicator for emerging research topic prediction. Information Processing & Management, 58(5), 102611.

Lin, D., Liu, W., Guo, Y., Meyer, M. (2021). Using technological entropy to identify technology life cycle, Journal of Informetrics, 15(2),101137.

Liu, H., Chen, Z., Tang, J., Zhou, Y., & Liu, S. (2020). Mapping the technology evolution path: A novel model for dynamic topic detection and tracking. Scientometrics, 125, 2043-2090.

Long, G.L.; Mueller, P.; Patterson, J. Introducing Quantum Engineering. Quantum Eng. 2019, 1, e6.

M. Coccia 2018. General properties of the evolution of research fields: a scientometric study of human microbiome, evolutionary robotics and astrobiology, Scientometrics, vol. 117, n. 2, pp. 1265-1283, https://doi.org/10.1007/s11192-018-2902-8

M. Coccia 2020. The evolution of scientific disciplines in applied sciences: dynamics and empirical properties of experimental physics, Scientometrics, n. 124, pp. 451-487. https://doi.org/10.1007/s11192-020-03464-y

Magee C. L., Basnet, S., Funk, J. L., Benson, C. L. 2016 Quantitative empirical trends in technical performance. Technological Forecasting & Social Change, vol. 104, March, pp. 237-246. http://doi.org/10.1016/j.techfore.2015.12.011.

Marrone, M. (2020). Application of entity linking to identify research fronts and trends. Scientometrics, 122(1), 357-379.

Marrone, M., Lemke, S., & Kolbe, L. M. (2022). Entity linking systems for literature reviews. Scientometrics, 127(7), 3857-3878.

Mastropetrou, M., Bithas, G., & Kutsikos, K. (2019, September). Digital Transformation in the Luxury Industry-a Systematic Mapping Study. In 12th Annual Conference of the EuroMed Academy of Business.

Meyer, P. S., Yung, J. W., & Ausubel, J. H. 1999. A primer on logistic growth and substitution: the mathematics of the Loglet Lab software. Technological forecasting and social change, 61(3), 247-271.

Möller, M., Vuik, C. 2017. On the impact of quantum computing technology on future developments in high-performance scientific computing. Ethics Inf Technol 19, 253–269. https://doi.org/10.1007/s10676-017-9438-0

Mosleh M., Roshani S., Coccia M. 2022. Scientific laws of research funding to support citations and diffusion of knowledge in life science. Scientometrics 127, 1931–1951. https://doi.org/10.1007/s11192-022-04300-1

Nagula, M. (2016). Forecasting of fuel cell technology in hybrid and electric vehicles using Gompertz growth curve. Journal of Statistics and Management Systems, 19(1), 73-88

Pahlavan, K., & Krishnamurthy, P. (2021). Evolution and impact of Wi-Fi technology and applications: A historical perspective. International Journal of Wireless Information Networks, 28, 3-19.

Pande, M., Mulay, P. 2020. Bibliometric Survey of Quantum Machine Learning. Science and Technology Libraries 39(4), pp. 369-382

Petersen, K., Feldt, R., Mujtaba, S., & Mattsson, M. (2008, June). Systematic mapping studies in software engineering. In 12th International Conference on Evaluation and Assessment in Software Engineering (EASE) 12 (pp. 1-10).

Petersen, K., Vakkalanka, S., & Kuzniarz, L. (2015). Guidelines for conducting systematic mapping studies in software engineering: An update. Information and software technology, 64, 1-18.

Rao, P., Yu, K., Lim, H., Jin, D., Choi, D.2020. Quantum amplitude estimation algorithms on IBM quantum devices. Proceedings of SPIE - The International Society for Optical Engineering 11507,115070O

Ren H., Zhao Y. 2021. Technology opportunity discovery based on constructing, evaluating, and searching knowledge networks. Technovation, vol. 101, n. 102196, https://doi.org/10.1016/j.technovation.2020.102196

Roshani S., Bagheri R., Mosleh M., Coccia M. 2021. What is the relationship between research funding and citation-based performance? A comparative analysis between critical disciplines. Scientometrics 126, 7859–7874. https://doi.org/10.1007/s11192-021-04077-9

Roshani S., Coccia M., Mosleh M. 2022. Sensor Technology for Opening New Pathways in Diagnosis and Therapeutics of Breast, Lung, Colorectal and Prostate Cancer. HighTech and Innovation Journal, vol.3, n.3, September, pp. 356-375. http://dx.doi.org/10.28991/HIJ-2022-03-03-010

Sahal D. 1981. Patterns of Technological Innovation. Addison-Wesley Publishing Company, Inc., Reading, MA.

Savov, P., Jatowt, A., & Nielek, R. (2020). Identifying breakthrough scientific papers. Information Processing & Management, 57(2), 102168.

Scheidsteger T., Haunschild R., Bornmann L., Ettl C. 2021. Bibliometric analysis in the field of quantum technology, Quantum Reports 3(3), pp. 549-575

Sharma, D.; Surolia, A. Degree Centrality. In Encyclopedia of Systems Biology; Dubitzky, W., Wolkenhauer, O., Cho, K.-H., Yokota, H., Eds.; Springer New York: New York, NY, 2013; pp. 558–558 ISBN 9781441998620.

Sinigaglia, T., Martins, M. E. S., & Siluk, J. C. M. (2022). Technological evolution of internal combustion engine vehicle: A patent data analysis. Applied Energy, 306, 118003.

Sinigaglia, T., Martins, M. E. S., & Siluk, J. C. M. 2022. Technological evolution of internal combustion engine vehicle: A patent data analysis. Applied Energy, 306, 118003.

Sun X., Kaur, J., Milojevic' S., Flammini A., Menczer F. 2013. Social Dynamics of Science. Scientific Reports, vol. 3, n. 1069, pp. 1-6, doi:10.1038/srep01069.

Sun, X., Kaur, J., Milojević, C. S., Flammini, A., & Menczer, F. (2013). Social dynamics of science. Scientific Reports, 3, 1069.

Trappey, C. V.; Wu, H.Y.; Taghaboni-Dutta, F. & Trappey, A.J.C. 2011. Using patent data for technology forecasting: China RFID patent analysis. Adv. Eng. Informatics., 2011, 25(1),53–64. doi: 10.1016/j.aei.2010.05.007.

Vespignani A. 2009. Predicting the behavior of techno-social systems. Science, vol. 325, pp. 425–428. DOI: 10.1126/science.1171990

Wang C.C., Sung H.Y., Huang MH. 2016. Technological evolution seen from the USPC reclassifications, Scientometrics, vol. 107, n. 2, pp. 537-553. https://doi.org/10.1007/s11192-016-1851-3

Wang, Y., Agichtein, E., & Benzi, M. (2012). TM-LDA: Efficient online modeling of latent topic transitions in social media. In Proceedings of the 18th ACM SIGKDD international conference on knowledge discovery and data mining (pp. 123–131). https://doi.org/10.1145/2339530.2339552.

Wasserman, S.; Faust, K. Social Network Analysis: Methods and Applications; Structural analysis in the social sciences; Cambridge University Press: Cambridge ; New York, 1994; ISBN 9780521382694.

Ye, Y., Chaonan, W., Jingying, L., Yuxiang, T. (2021). Research on the development trend of China's key core technologies of artificial intelligence based on the technology life cycle. 2021 IEEE 4th International Conference on Electronic Information and Communication Technology, ICEICT 2021 pp. 814-817

Yuan, X., & Li, X. (2020). A network analytic method for measuring patent thickets: A case of FCEV technology. Technological Forecasting and Social Change, 156, 120038.

Yung, J. W., Meyer, P. S., & Ausubel, J. H. 1999. The Loglet Lab software: a tutorial. Technological Forecasting and Social Change, 61(3), 273-295.