Exploring the Innovation Path of the Digital Construction Industry Using Mixed Methods

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Abstract: To provide a theoretical basis for deepening digital reform in the construction industry and explore the innovation path of the digital construction industry, this research uses patent data for Guangdong Province to carry out explanatory sequence research. First, this research analyzes the dynamic evolution process of networks in the digital construction industry by using social network analysis. Then, grounded theory is used to conduct qualitative research to explore the innovation path of the digital construction industry. The results show that the scale of the innovation network of the digital construction industry is continually expanding and the digital carriers are becoming increasingly diverse. Influenced by the diversification of digital carriers, the research theme of the digital construction industry is beginning to develop in the direction of intelligence. The findings indicate that the use of mixed methods improves the robustness of the results and that the quantitative research results are explained by the qualitative research results. This research not only contributes to information development in the construction industry but also provides a theoretical basis for deepening digital reform in the construction industry.

1. Introduction

The application of digital technology has provided a new innovation platform for the development of the traditional construction industry, and the digital construction industry is now part of the digital economy. In the "Statistical Classification of the Digital Economy and Its Core Industries (2021)" promulgated by the National Bureau of Statistics of China, the digital construction industry is defined as the integration of digital technology and the traditional construction industry. As the digital construction industry is new, there are few studies on the topic, and there is also a lack of relevant studies on its development. Considering the digital transformation requirements of the construction industry, it is necessary to study the innovation path of the industry.

In recent years, many researchers have attached great importance to the application of digital technology in the construction industry. Benjamin Teisserenc and Samad Sepasgozar studied the adoption of blockchain technology through digital twins in the construction industry [1]. Diego Calvetti studied the future of sensored construction sites [2]. Li studied the advanced-technological UAV-based enhanced reconstruction of edges for building models [3]. The global demand for digitalization in the construction industry continues to increase. With the emergence of Industry 4.0, the rapid development of digital technology has pushed the construction industry into the digital age. In 2019, the global construction digitalization market was valued at approximately 9.8 billion US dollars, and this value is expected to exceed 29.1 billion dollars by 2027 With the increasing demand for infrastructure construction in emerging economies, such as China, Vietnam, and India, the demand for the digital construction industry in the Asia-Pacific region will soon bring the industry into the lead in the world, and infrastructure construction will bring additional opportunities for the development of the digital construction industry [4].

In the new era of digital transformation, the role of intellectual property has become increasingly prominent. Intellectual property, especially patent ownership, has become an important measure of the comprehensive strength of a region. To explore regional innovation capability, Zhuang and Wu measured the degree of association among Chinese universities, enterprises and the government in collaborative innovation with patent data [5]. Li took the number of patent applications and the number of granted patents for service invention as the Index of Innovation Output and analyzed the efficiency factors that influence differences in regional innovation ability across China [6]. These studies provide references for research on innovation in the digital construction industry with the aid of intellectual property patent data.

In this paper, patent applications in the digital construction industry are taken as the breakthrough point. First, this research explores the development of the digital construction industry using the social network method and constructs an innovation network for the industry. Based on this, we study changes in the network topology structure of the digital construction industry and determine the innovation themes. Furthermore, to explain the results obtained by the social network science method, grounded theory is used to carry out explanatory sequence research and generate an innovation theory path for the digital construction industry. This study reveals the development of digital technology innovation in the construction industry, explores the innovation path for construction industry information and provides a theoretical basis and practical experience for deepening digital reform in the construction industry.

The rest of this paper is organized as follows. Section 2 provides a literature review of the relevant research. Section 3 presents the research design and the research methodology. Section 4 presents the results and a discussion of future research directions. Section 5 concludes the paper by summarizing the main findings.

2. Literature Review

2.1. The Concept of the Digital Economy

Tapscott first proposed the concept of the digital economy in 1996 and focused on three aspects: the digital economy and its elements, the relationship between the internet and business and government, and the changing role of leaders [7].

The "G20 Digital Economy Development and Cooperation Initiative" clearly defined the digital economy as a series of economic activities. The digital economy takes digital knowledge and information as key factors of production, the modern information internet as an important carrier, and the use of information and communication technology as important driving forces [8]. The China Academy of Information and Communications Technology defined the digital economy as a new economic form in which digital knowledge and information are key factors of production, digital technology innovation is the core driver, and the modern information network is an important carrier. Through the deep integration of digital technology and the real economy, the digitalization and intelligence level of traditional industries are continuously improved and the reconstruction of economic development and government governance models is accelerated [9].

Unlike the G20 and China Academy of Information and Communications Technology, the National Bureau of Statistics of China regards data resources as a key factor of production in the digital economy. The National Bureau of Statistics of China defines the digital economy as a series of economic activities with data resources as a key production factor, modern information networks as an important carrier, and the effective use of information and communication technology as an important driving force of efficiency improvement and economic structural optimization.

2.2. Scope of the Digital Economy

Although Tapscott determined the nature of the digital economy, he did not provide a clear definition of its scope. E-commerce is at the forefront of the digital economy [10]. The U.S. Department of Commerce focused on the impact of IT and e-commerce on economic

growth in its "Emerging Digital Economy" report, and IT and e-commerce have begun to be used as a classification basis for the digital economy [11]. The U.S. Census Bureau divided the digital economy into three parts: supporting infrastructure, e-commerce processes, and e-commerce transactions [12]. The Bureau of Economic Analysis divided the digital economy into three categories: digital infrastructure, e-commerce and digital media [13]. With the widespread application of information and communications technology, the boundaries of the digital economy have changed. Ahmad and Ribarsky concluded that information and communications technology belongs to the digital economy as a type of digital empowerment [14].

The National Bureau of Statistics of China determined the scope of the digital economy industry to be digital product manufacturing, digital product service industry, digital technology application industry, digital factor-driven industry, and digital efficiency improvement industry. The digital construction industry belongs to the digital efficiency improvement industry.

2.3. The Concept of Innovation

Innovation is the driving force of economic growth and the primary driving force of development [15]. It plays an important role in the progress of society and industry, especially in the era of the digital economy. The term "innovation" was first proposed in 1912 by Schumpeter, who argued that "innovation is the 'new combination' of new production factors and production conditions in the production system" [16]. Drucker defined innovation as the act that endows resources with a new capacity to create wealth [17]. Freeman and Soete defined innovation as a management system for building new engineering, new products and new technologies [18]. Innovation is a multistage process, the measurement of which can be divided into three parts: (1) measurement of innovation inputs, such as R&D; (2) measurement of intermediate outputs, such as the number of patented inventions; and (3) direct measurement of innovation outputs [19].

2.4. Digital Economy Innovation

A high level of innovation is an important feature of the development of the digital economy. In recent years, studies on digital economy innovation have been increasing and many research results have been published, including studies on digital transformation [20–23], innovation-driven development [24,25], high-quality economic development [26–28], and new generation information technology [29–32]. However, these studies have mostly been multiangle studies on digital economy innovation and have primarily been qualitative; there has been no explanatory sequence research combining quantitative and qualitative methods. Nor has there been a clear proposal or project with the digital construction industry as the research subject.

2.5. Digitalization in the Construction Industry

Digitalization is an important change driver in the construction industry. Puolitaival and Kähkönen discussed the nature and type of digital technologies used in construction management and explored digital technology-related competences; their research as a whole took a multimethod qualitative approach relying on the constructivist paradigm, and the research design had some exploratory features but was mostly descriptive [33]. Wang et al. adopted a sequential mixed qualitative and quantitative data collection and analysis approach to systematically identify, assess, and categorize barriers to digital transformation in the engineering and construction sectors. Their findings contributed to the body of knowledge on digital transformation in the construction industry and helped construction firms and government bodies improve their understanding of these barriers to digital transformation and put forward relevant policies and incentives, thus taking advantage of digital transformation benefits as a way to enhance construction project management [34]. Khahro et al. analyzed the possible benefits of and barriers to digital transformation and e-commerce in the construction industry and found that the

maintenance of existing frameworks, stability and lack of software expertise are among the obstacles in the construction industry's use of e-business methods [35].

2.6. Patent Data Research

Patent data contain a variety of innovation information, including applicant information, patent technology classification, and citation information, which creates the possibility for multidimensional innovation research [36]. Based on patent data, international cooperation analysis [37], regional innovation capability analysis and comparative analysis [38] can be carried out. Patent data are often used as an important indicator when studying the impact of industrial policy on firms' innovation behavior. Some scholars have studied the impact of industrial policy on firms' patent output [39,40]. In addition, the citation information of patents can be used to study knowledge spillovers [41].

Patent data are widely used in the core areas of technology management [42]. From the perspective of technological innovation, patent data are an important resource for analyzing technological change and have become a measure of R&D output. Therefore, patent data are regarded as the end point of innovation. In the late 1970s, the OECD began to pay attention to patent data and developed the "Patent Handbook", which explained the relationship between patent indicators and other technological indicators, the methodological issues of using patent indicators, and the advantages of using patent indicators. It also discussed the link between patent indicators and innovation indicators.

3. Research Design and Methodology

3.1. Research Subject

According to "The Report on the Development and Employment of the Digital Economy in the Guangdong-Hong Kong-Macao Bay Area" (hereafter referred to as the Bay Area), which was released by the China Academy of Information and Communications Technology [43], the digital economy has been developing rapidly in Guangdong, totaling 4.9 trillion yuan in 2019 and accounting for 45.3 percent of Guangdong's GDP. The scale of the digital economy in Guangdong Province and the GDP of Guangdong Province are shown in Figure 1.
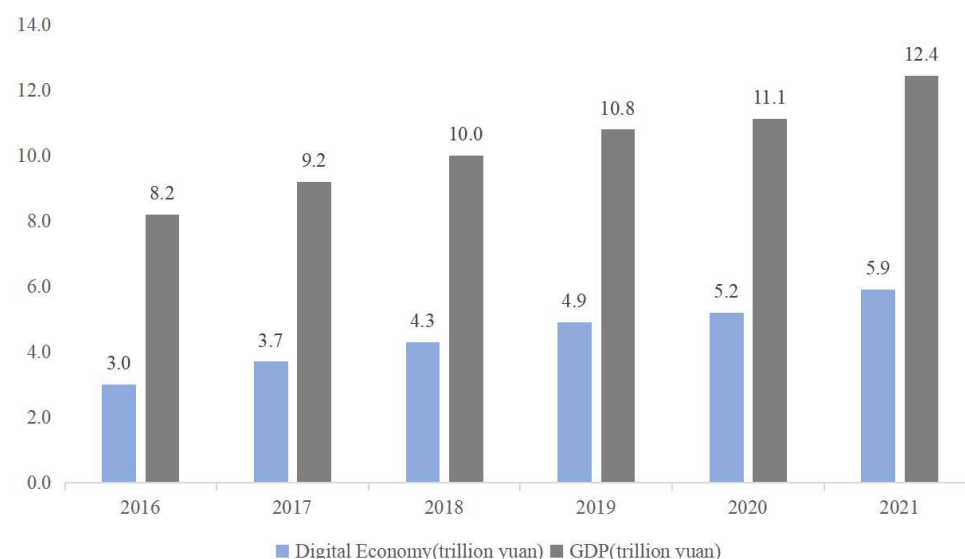
Figure 1. The scale of the digital economy in Guangdong Province and the GDP of Guangdong Province (2016–2021).

At the same time, the proportion of the digital economy to the total provincial GDP in Guangdong increased from 37% in 2016 to 45% in 2019. According to the "White Paper on the Development of China's Digital Economy (2021)" by the CAICT, the scale of the digital economy in Guangdong Province in 2020 was approximately 5.2 trillion yuan, accounting

for 46.8% of Guangdong's GDP and ranking first in China. According to the "China Digital Economy Development Report (2022)" issued by the CAICT, the scale of Guangdong's digital economy in 2021 was approximately 5.9 trillion yuan, ranking first in China and accounting for 47.5% of Guangdong's GDP. Guangdong has become the high ground of digital economy development in China, while the development of the digital construction industry and its innovation network there are both highly representative and worthy of further study.

3.2. Research Step

Step 1: Data Collection

For this research, we collected patent data for 9 cities, Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing, in the Greater Bay Area of Guangdong Province from 2016 to 2020 and obtained an original database.

Step 2: Data filtering

This research referred to the "Statistical Classification of Digital Economy and Its Core Industries (2021)", "International Patent Classification and National Economic Industry Classification Reference Table (2018)", "National Economic Industry Classification Notes (2017)", "National Economic Industry Classification" (GB/T 4754-2017) and other relevant classification standards to filter the original database. First, we retrieved all 2-digit codes of the construction industry from the "National Economic Classification"; then, we searched for keywords related to the digital construction industry and finally obtained the digital construction industry patent research sample.

Step 3: Identifying the innovative development path of the digital construction industry

Based on the patent research sample of the digital construction industry, we applied mixed methods to identify the innovative development path of the digital construction industry. We adopted an explanatory sequence design, and the specific implementation steps were as follows. First, based on the Louvain algorithm, we took the International Patent Classification (IPC) as the main basis for constructing a two-dimensional matrix of digital construction industry innovation and then created the digital construction industry innovation networks. The research themes were determined based on the identified innovative core technologies, and the breakthrough points of the technological route were determined based on the identified key technologies. Then, based on grounded theory, we used open coding for the digital construction industry patent information. Through axis coding, we explored the meaning of the initial concepts and categories, identified their logical relationships, and integrated the main categories. Through selective coding, we determined the core categories and then refined the theoretical framework to identify the innovative development path of the digital construction industry.

The research steps are shown in Figure 2.

3.3. Mixed Methods Research

In 2004, American education researchers R. Burke Johnson and Anthony J. Onwuegbuzie presented mixed methods research as a natural complement to qualitative and quantitative research, calling mixed methods research "the third research paradigm" [44].

The first international academic journal dedicated to mixed methods research defined "mixed methods research" as "a researcher's use of both qualitative and quantitative research methods in a single study or a research program to collect, analyze data, integrate research findings and inferences" [45].

Quantitative and qualitative research methods each have their own advantages. Quantitative research achieves generalization and precision of conclusions, and qualitative research realizes in-depth excavation of experience from a personal perspective. However, mixed methods use both approaches in academic research to maximize the realization of the research objectives.
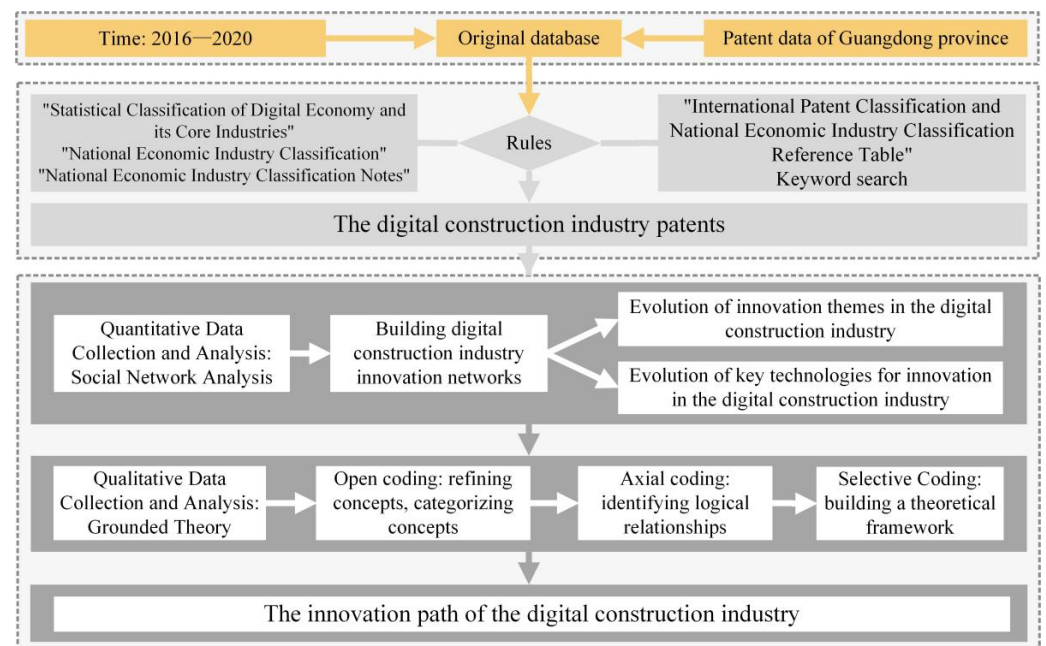
Figure 2. Research steps.

3.4. Explanatory Sequence Design

One of the three core foundational approaches in mixed methods research is explanatory sequence design, which aims to first use quantitative research to collect and analyze data and then to use qualitative research to interpret the results of the quantitative method. Statistical significance and effect sizes generated by quantitative research methods provide generalized results for the research. However, we often do not know the context in which the results were obtained. In the next stage, qualitative research can help us interpret the results of quantitative research.

This research design is called explanatory sequence design. The advantage of this design is that quantitative research is used first to analyze the research problem, and qualitative research is then used to explain the results. The two research methods support each other. Figure 3 shows a flow chart for the explanatory sequence design of this paper.
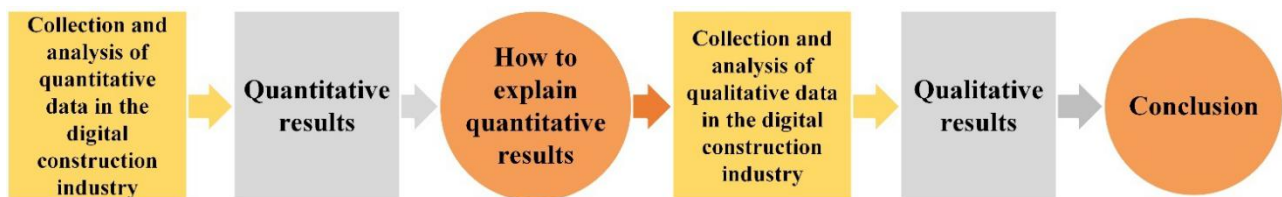
Figure 3. Flowchart of explanatory sequence design.

3.5. Social Network Analysis

The Louvain algorithm is a module-based community discovery algorithm used to discover the hierarchical community structure with the goal of maximizing the modularity Q of the whole graph attribute structure. The advantage of the Louvain algorithm is that it can identify the core node, research subject and key node of each module. By virtue of the community discovery algorithm, this research analyzes the current situation of the digital construction industry, explores the relationship and boundaries among patent subjects, constructs the knowledge atlas system for the industry, and determines the evolution of modularization themes in the industry.

(1) Modularity

The physical meaning of modularity is the difference between the number of edges in a community and the number of edges in a random situation. The range of modularity is $[-1/2, 1)$ and is defined as follows:

$$Q = \frac{1}{2m} \sum_{i,j} \left(A_{ij} - \frac{k_i * k_j}{2m} \right) * \delta(c_i, c_j) \tag{1}$$

$$\delta(u, v) = \begin{cases} 1 & when\, u == v \\ 0 & else \end{cases} \tag{2}$$

where A_{ij} represents the weight of the edges between node I and node j. When the network is not a weighted graph, the weight of all edges can be regarded as 1; $k_i = \sum_j A_{ij}$ represents the sum of the weights of all edges connected to node i; c_i represents the community to which node i belongs; $m = \frac{1}{2} \sum_{ij} A_{ij}$ is the sum of the weights of all the edges; the probability that node j is connected to any node is $\frac{k_j}{2m}$; and the edge of node i and j is $k_i \left(\frac{k_j}{2m} \right)$ in random cases.

(2) Modularity gain

When node i is assigned to its neighbor j, the change in modularity is related only to the community of nodes i and j. The modularity gain when assigning node i to community c where neighbor node j resides is

$$\Delta Q = \left[\left(\frac{\sum in + k_{i,in}}{2m} \right) - \left(\frac{\sum tot + k_i}{2m} \right)^2 \right] - \left[\frac{\sum in}{2m} - \left(\frac{\sum tot}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right] \tag{3}$$

where $k_{i,in}$ is the sum of the edge weights of the nodes in communities c and i and $k_{i,in}$ is the sum of the corresponding edge weights multiplied by 2. $\sum tot$ represents the total weight of the nodes in community c.

3.6. Grounded Theory

Grounded theory is a well-known approach in the field of qualitative research put forward by Glaser and Strauss [46]. This qualitative research method has the main purpose of establishing a theory based on empirical data [47]. Before our research began, there was no theoretical hypothesis. Therefore, this research started from actual observations, generalized the experience with original data, and then advanced to systematic theory. Grounded theory is a way of building a theory from the bottom up.

The operational process of grounded theory is as follows:

(1) Generate concepts from the data and log the data step by step;
(2) Continually compare data and concepts and systematically ask generative theoretical questions about the concepts;
(3) Develop theoretical concepts and establish connections between them;
(4) Encode the data level by level (encoding data is the most important part of grounded theory, which includes three levels of coding); and
(5) Construct theories that strive to obtain the density, variability and high degree of integration of the theoretical concepts.

Overall, the coding of information level by level, including open coding, axial coding and selective coding, is the most important part of grounded theory. First, the researcher requires an open mind to log all materials as they emerge. Second, the main task of axial coding is to discover and establish various connections between conceptual categories. Finally, selective coding is the systematic analysis of the discovered conceptual categories and the selection of a "core category".

4. Results and Discussions

To explore the theme and evolutionary trend of digital innovation in the traditional construction industry, we constructed innovation networks for the digital construction industry with IPC as the main body. Then, we divided the cluster into three levels: large-scale clusters (with 10 or more nodes), medium-scale clusters (with 5–10 nodes) and small-scale clusters (with less than 5 nodes). The modularization distribution of the digital construction industry from 2016 to 2020 is shown in Figure 4. The evolution of the scale of the largest cluster in the digital construction industry is shown in Figure 5.
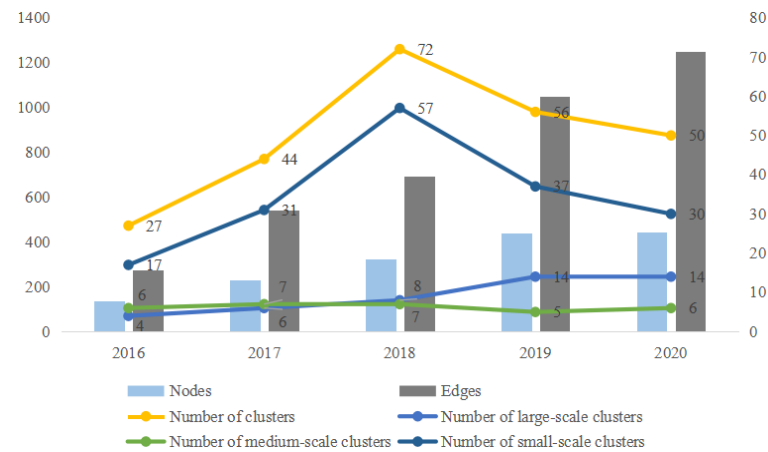

Figure 4. Modularization distribution of the digital construction industry (2016–2020).
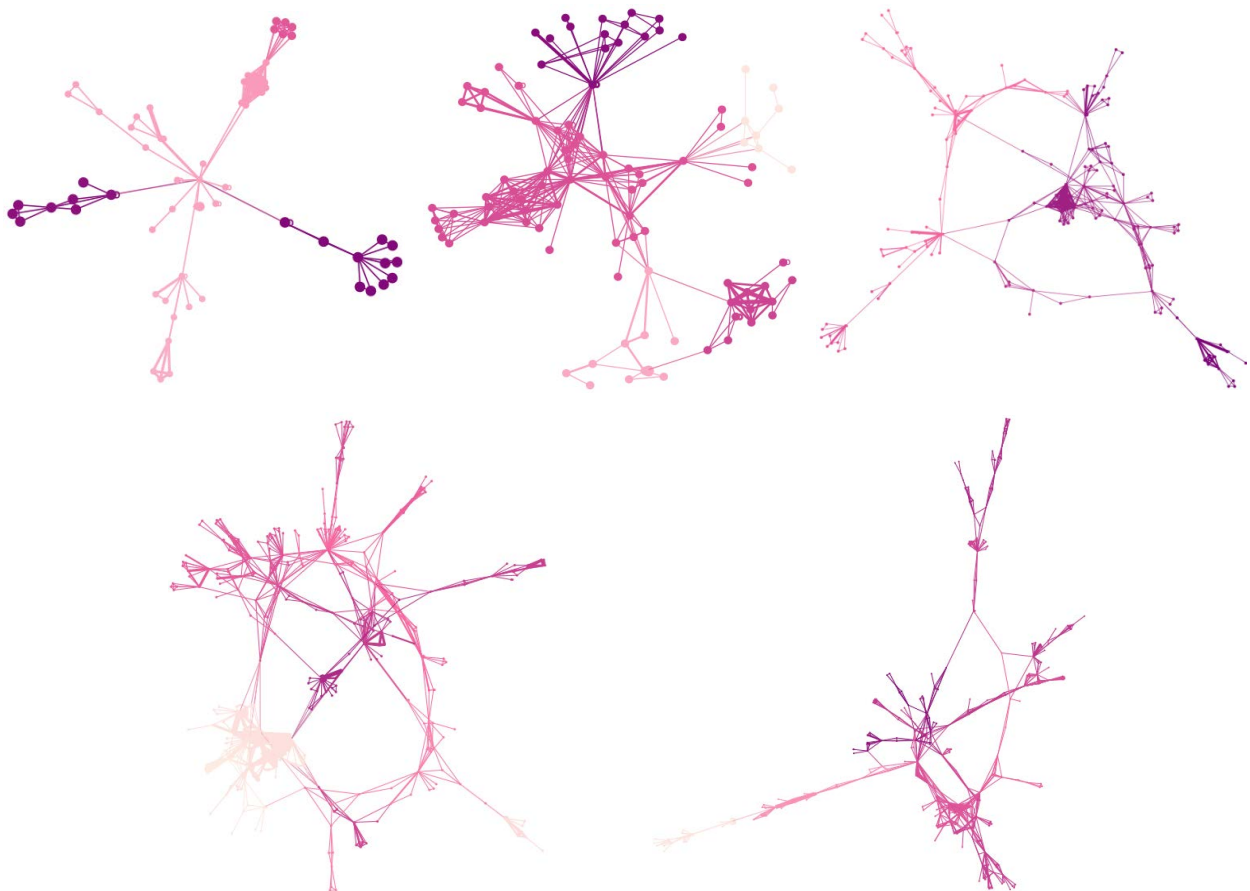

Figure 5. Evolution of the scale of the largest cluster in the digital construction industry (2016–2020).

4.1. Characteristics of Innovation Networks in the Digital Construction Industry

The number of nodes and edges both increased over the years, but the number of clusters decreased after peaking in 2018. This indicates that more nodes were integrated into the cluster, and the number of large-scale clusters increased year by year. According to statistics, from 2016 to 2020, the number of large-scale clusters increased and the numbers of medium-scale and small-scale clusters decreased, indicating an increase in network connectivity.

As shown in Figure 5, the scale of the largest cluster in the digital construction industry expanded between 2016 and 2020, and an increasing number of IPC elements were included in the cluster, indicating that technological innovation in the digital construction industry was developing. The cluster index statistics for the digital construction industry are shown in Table 1.

Table 1. Cluster Index Statistics for the Digital Construction Industry.

Year	Node	Edge	Average Degree	Average Weighting	Network Diameter	Network Density	Average Clustering Coefficient	Average Path Length
2016	135	274	4.059	4.296	6	0.03	0.855	3.609
2017	232	544	4.69	5.629	9	0.02	0.885	3.395
2018	325	695	4.277	5.902	11	0.013	0.839	4.708
2019	442	1048	4.742	6.937	12	0.011	0.831	5.072
2020	446	1249	5.601	6.534	16	0.013	0.857	6.206

Table 1 shows the following.

(1) The network scale had a gradual expansion tendency. The number of nodes and edges in the network both increased annually, which means that cooperation among subjects in various fields was gradually expanding.

(2) The network diameter increased every year, reaching 16 in 2020. Research has shown that the diameter of sci-tech innovation networks increases rapidly at the beginning of their growth [48]. The growth trend of the innovation network of the 9 cities in the Bay Area shows that these cities had entered their growth period.

(3) Compared with the number of nodes, the average path length of all clusters was very small, and the average clustering coefficient was always greater than 0.8, which are the characteristics of a small world network.

(4) The average degree and average weighted degree of the network nodes showed an increasing annual trend, indicating that the connectivity of the network also increased every year. However, the network density was much lower than 1, indicating that although the innovation subjects increased each year, they were all in small independent and modularized networks, and the overall cohesion of the network was not strong, representing unstable and weak cooperation among various fields.

4.2. Subject Identification in Innovation Network Research on the Digital Construction Industry

The digital construction innovation networks during the period 2016–2020 are shown in Figures 6–10.

In 2016, there were 4 large-scale clusters, 6 medium-scale clusters and 17 small-scale clusters. In 2017, the numbers of large- and medium-scale clusters increased, but the proportion of medium-scale independent clusters also increased, indicating a lack of connectivity among the new clusters.

In 2018, the numbers of large and small clusters both increased, but large clusters lacked connectivity to the other clusters. In 2019, the numbers of small-scale and medium-scale clusters both decreased, but the number of large-scale clusters increased significantly and no independent large-scale clusters appeared, indicating that the sizes of both small- and medium-scale clusters were expanding and that their connectivity was increasing.

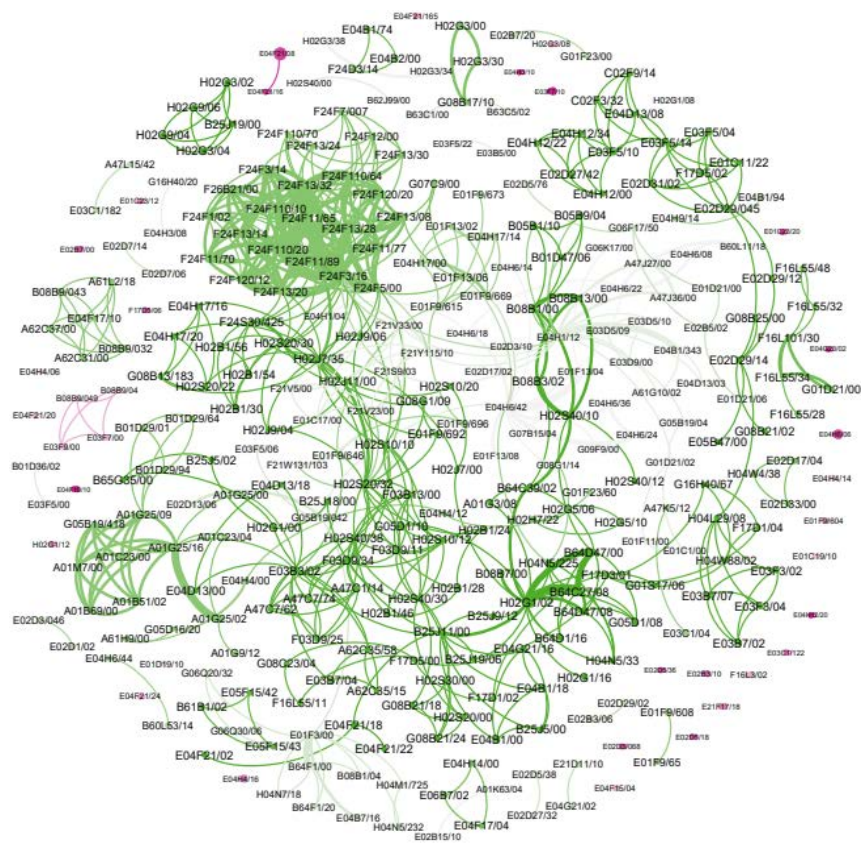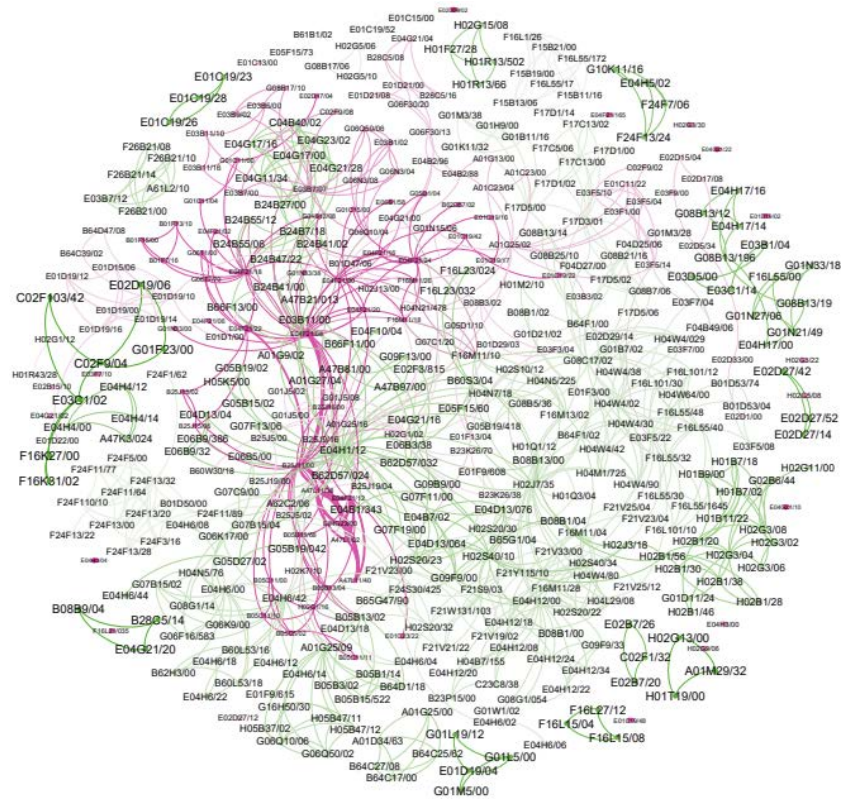**Figure 6.** Digital construction innovation network (2016).

Figure 7. Digital construction innovation network (2017).

Figure 8. Digital construction innovation network (2018).

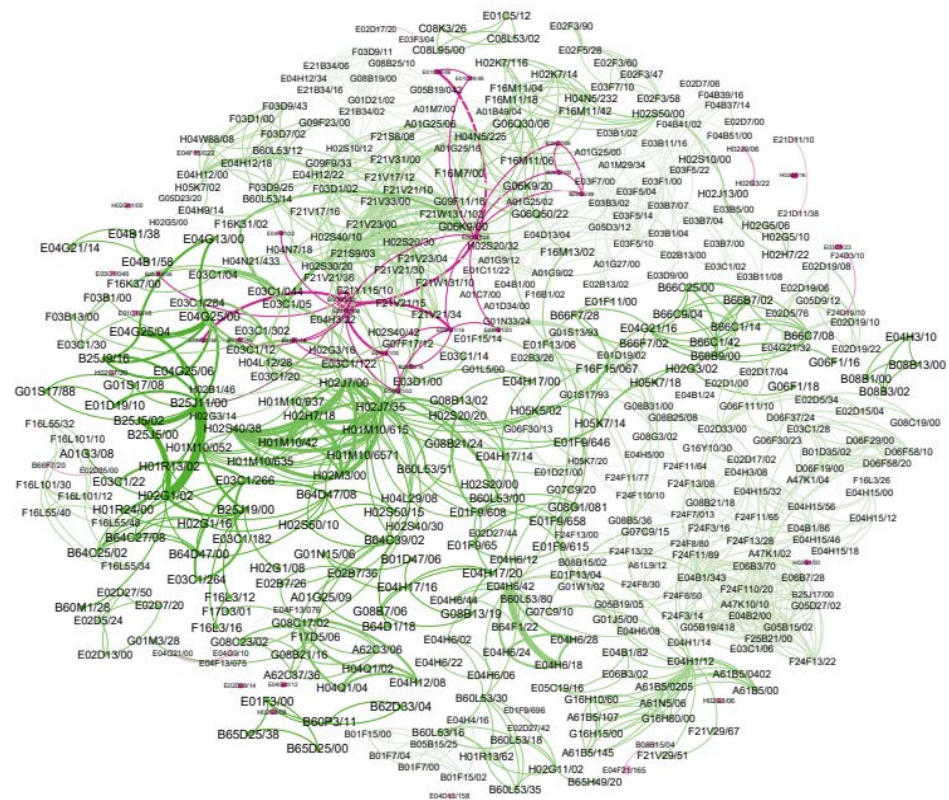**Figure 9.** Digital construction innovation network (2019).

Figure 10. Digital construction innovation network (2020).

In 2020, the number of small-scale clusters continued to decrease, but the numbers of large- and medium-scale clusters remained stable and no large-scale clusters emerged, indicating that the connectivity of both small- and medium-scale clusters did not diminish as their size continued to grow.

4.3. Evolution of the Innovation Network in the Digital Construction Industry

The annual research themes were determined through the identified cluster cores, and the evolutionary path of the innovation themes in the digital construction industry was then depicted. The key technologies of each year were determined by identifying the key connections of the clusters, and the evolutionary path of the key technologies of innovation in the digital construction industry was then described. The evolutions of the innovation theme and key technologies in the digital construction industry are shown in Figures 11 and 12.

(1)   Evolution of innovation themes in the digital construction industry

From 2016 to 2020, the scope of digital objects continued to expand from buildings to road and bridge engineering and water supply and drainage engineering, but buildings were always digital objects.

In terms of digital carriers, the types of digital carriers increased, and lighting devices were always an important digital carrier. In addition, power generation, power substations, power distribution devices, air conditioning devices, manipulator devices, and water-related devices were important carriers of digitization. After 2019, electrical communication technology, wireless communication technology, computing and calculation algorithm equipment, and basic electrical components became new digital carriers, indicating that the construction industry had begun to intelligently transform.

Digital objects	Digital carriers	Digital results
Buildings for parking cars, rail vehicles, aircraft, boats or similar vehicles	Functional features or components of lighting device or their systems	Fixed buildings combined with lighting installations and electrical
Water supply and drainage engineering, special purpose buildings or similar structures, ancillary works.	Lighting devices, air conditioning devices, and manipulator devices.	Fixed buildings combined with mechanical engineering, lighting engineering, transport, and electricity
Water supply and drainage engineering, ancillary works, buildings for parking cars, rail vehicles, aircraft, boats or similar vehicles	Lighting devices, power generation devices, air conditioning devices, manipulator devices, and watering devices.	Fixed buildings combined with human necessity, transportation, mechanical engineering, lighting engineering, and electricity
Water supply and drainage engineering, appliances for building renovation works, application of pumping station equipment for upgrading sewage, small buildings or other structures built inside or outside buildings for special business purposes.	Lighting devices, power generation devices, computing and calculation algorithm equipment, air conditioning devices, electrical communication technology, and wireless communication.	Fixed buildings combined with human necessity, transportation, mechanical engineering, lighting engineering, electricity, and physics
Water supply and drainage engineering, special purpose buildings or similar structure, swimming or jetting tub or pool, building renovation works, general building structure, excavate, fill, mast, and fence.	Lighting devices, air conditioning devices, manipulator devices, watering devices, electrical communication technology, computing and calculation algorithm equipment, basic electrical components, medicine or veterinary, medicine, and hygiene.	Fixed buildings combined with human necessity, transportation, mechanical engineering, lighting engineering, electricity, physics, textile, and papermaking

Figure 11. Evolution of innovation themes in the digital construction industry.

In terms of digital results, this research found that fixed buildings were first integrated with lighting engineering, electrical engineering, and then mechanical engineering. With the addition of digital carriers, the digital construction industry began to integrate with human necessity and transportation equipment fields. With the addition of new carriers, such as electrical communication technology, wireless communication technology, computing and calculation algorithm equipment, and basic electrical components, the digital construction industry began to integrate with the physics, textile and papermaking fields. To date, the digital construction industry has not integrated with the chemical and metallurgical fields.

(2)   Evolution of key technologies for innovation in the digital construction industry

In 2016–2017, lighting devices played a key role in the innovation of the digital construction industry. Buildings first combined the two fields of lighting engineering and electricity through combinations of lighting devices and other items and exposure recharging devices, and the key connection position of the exposure recharging devices was

then replaced by light emitting diodes. In 2017, light emitting diodes played a fundamental connectivity role in digital construction industry innovation.
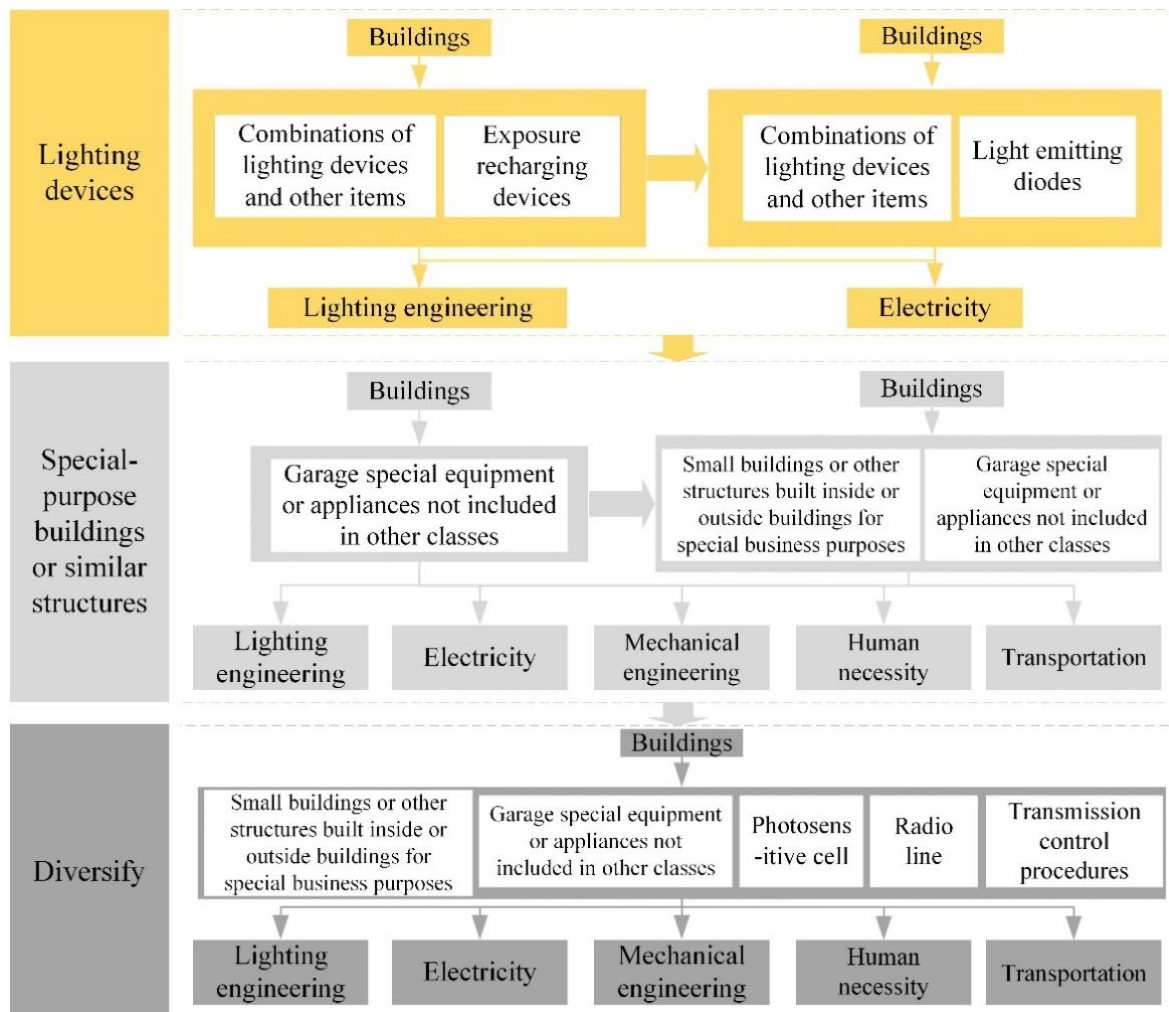

Figure 12. Evolution of key technologies for innovation in the digital construction industry (2016–2020).

In 2018–2019, special-purpose buildings or similar structures played a key role in digital construction industry innovation. Digital construction industry innovations began to combine mechanical engineering, human necessity, and transportation fields through special-purpose buildings or similar structures, which had a wider connection range than that of lighting devices.

In 2020, the key connections of the innovation network began to diversify. Photosensitive cells, radio lines, and transmission control procedures became new key connections, which led to new development directions and new technologies for digital construction industry innovation.

4.4. Qualitative Research on the Digital Construction Industry

This research used qualitative analysis software for open coding, axial coding and selective coding of data.

(1) Open coding

Open coding is the process of decomposing, abstracting, conceptualizing and categorizing data. Examples of open coding for this study are shown in Table 2.

Table 2. Examples of open coding.

Patent Description	Initial Category
Integrated construction robot for high-rise buildings	Intelligent building robot
Intelligent monitoring system for scenery complementation	Intelligent monitoring system
New energy haze removal and environmental protection lighting device based on the Internet of Things	Intelligent lighting device
......	......
Lead rubber bearing, intelligent bearing and bearing monitoring system	Intelligent monitoring system
Height detection system for the concrete pouring surface of superdeep pile holes	Intelligent detection system
Antistatic ventilation floor	Intelligent building materials
......	......
Intelligent firefighting integrated cover plate and integrated monitoring and fire-extinguishing system	Intelligent fire system
Intelligent integrated irrigation system	Intelligent irrigation equipment
Parking space lock, positioning base station and intelligent parking space lock system	Intelligent transportation equipment
......	......
Intelligent robot for building urban municipal green belts	Intelligent building robot
Box structure of an internet intelligent mini recording room	Intelligent building device
Cleaning robot for attached submarine tunnels	Robot cleaning

(2) Axial coding

Axial coding is a process that discovers and determines the logical relationship between categories. This research reorganized the original category into 40 subcategories and groups and then into 10 principal categories. The axial encoding results are shown in Table 3.

Table 3. Axial coding results.

Subcategory	Principal Category
Buildings, transportation	Construction industry
Intelligent building materials and intelligent materials for decoration	Construction materials
Computer control, temperature control equipment, and intelligent control equipment	Digital control equipment
Intelligent induction device, intelligent indicating device, and intelligent sensing equipment	Digital sensing equipment
Intelligent monitoring system, intelligent identification system, intelligent detection system, temperature monitoring equipment, temperature detection device, and intelligent flaw detection equipment	Digital monitoring equipment
Intelligent building robot, construction robot, working robot, inspection robot, detection robot, and robot cleaning	Digital construction robots
Unmanned aerial vehicle cleaning, unmanned aerial vehicle installation, and unmanned aerial vehicle detection	Digital construction UAV
Intelligent lighting device, intelligent fire system, intelligent irrigation equipment, intelligent connection equipment, intelligent air purification device, communication facilities, intelligent support equipment, and intelligent charging system	Digital building accessories
Intelligent buildings, intelligent transportation, and construction of intelligent buildings	Digital construction industry
Intelligent building equipment, intelligent building device, intelligent building machine, intelligent parking equipment, and intelligent transportation equipment	Digital construction equipment

(3)   Selective coding

Selective coding is a process that selects the core category, links it systematically with other categories and conceptualizes and theorizes it. In this step, this research first analyzed the connotations and properties of the 10 principal categories obtained by axial coding and then compared them with the original data records. The final results are shown in Figure 13.
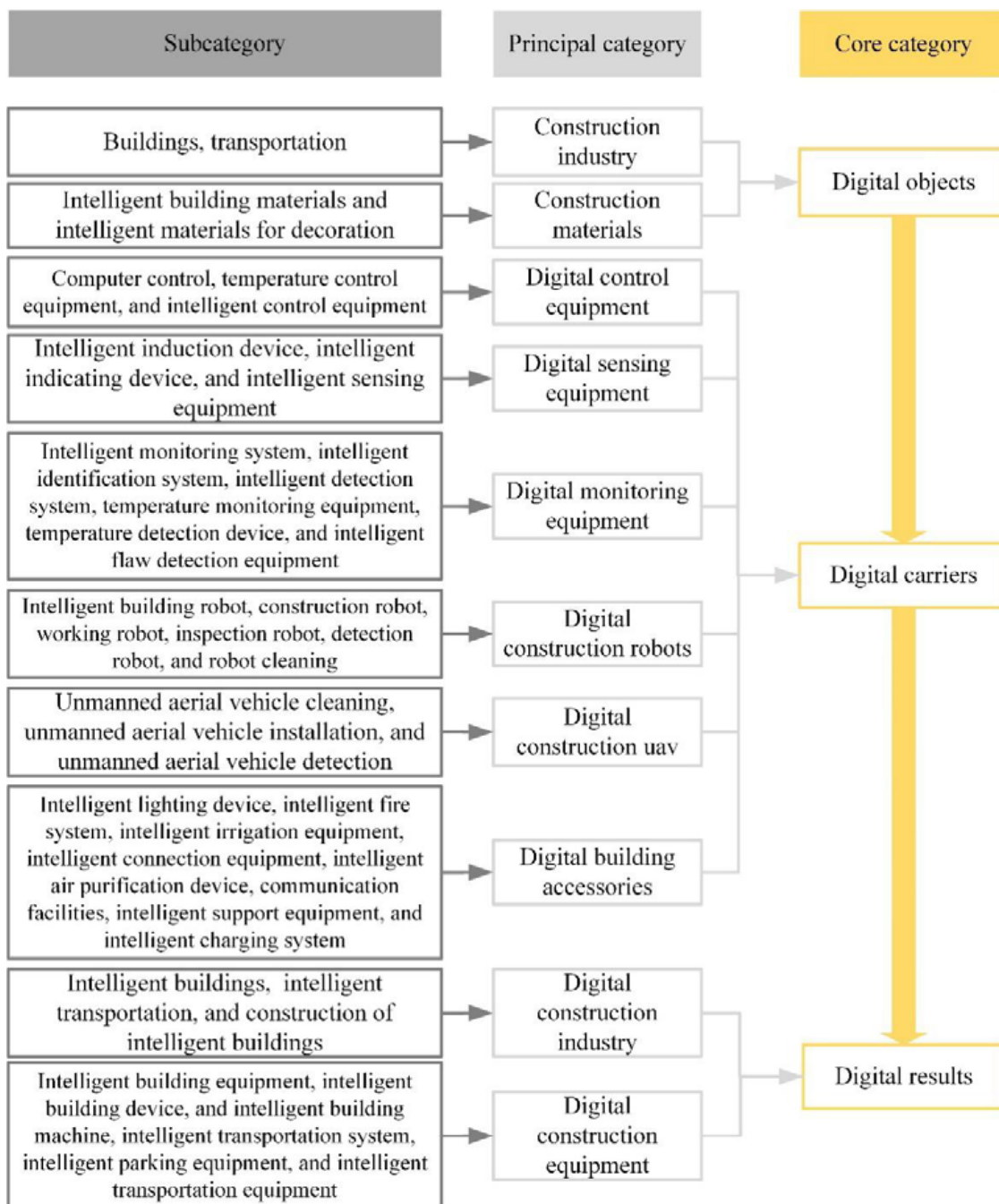

Figure 13. Coding procedure and results for patents in the digital construction industry.

5. Conclusions

This paper presents an explanatory sequence research on the innovation pathway for the digital construction industry using social network analysis and grounded theory based on patent data for Guangdong Province. Several important conclusions can be drawn from the results.

First, the findings indicate that the use of mixed methods improves the robustness of the results and that the quantitative research results are explained by the qualitative research results.

Second, the scale of the innovation network in the digital construction industry has expanded in recent years, the number of large-scale clusters has increased, and network connectivity has also gradually increased. The range of digital objects has broadened, and digital carriers have become diverse and transformed by intellectualization.

Third, the research themes of the digital construction industry are influenced by digital carriers, which started with the field of lighting engineering and then expanded to mechanical engineering and operational transport facilities and finally to the field of human necessity. With the addition of electric communication technology, wireless communication technology, basic electric components and other carriers, the research themes of the digital construction industry began to move in the direction of intelligence.

Finally, the grounded theory results further explain the digital construction industry innovation path, which is based on a digital carrier, then a clear digital object, and finally the digital transformation of the construction industry.

The main contribution of this paper is a methodology based on social network analysis techniques to model how different innovation pathways and clusters interact in a dynamic innovation network that evolves depending on how interconnected and diversified it is. This paper can help practitioners understand the development of digital technology innovation in the construction industry. Furthermore, it can provide academics with a theoretical basis and practical experience for deepening digital reform in the construction industry.

Author Contributions: Conceptualization, X.X., X.T, Q.H. and H.Z.; resources, X.X. and Q.H.; data curation, X.X. and H.Z.; formal analysis, X.T. and Q.H.; methodology, X.T.; software, X.T. and H.Z.; visualization, X.T. and J.C.; supervision, X.X. and Q.H.; funding acquisition, X.X., Q.H. and H.Z.; writing—original draft, X.T. and X.X.; writing—review and editing, X.T., X.X., Q.H., H.Z. and J.C. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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