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Exploring the Spatiotemporal Dynamics and Simulating Heritage Corridors for Sustainable Development of Industrial Heritage in Foshan City, China

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Abstract: Industrial heritage serves as a testament to the historical and cultural legacy of industrialization, and its preservation and adaptive reuse are crucial for promoting sustainable urban development. This study explores the spatiotemporal dynamics of industrial heritage in Foshan City, China, and simulates potential heritage corridors to inform effective conservation and revitalization strategies. By employing Kernel Density Estimation (KDE) and Standard Deviational Ellipse (SDE) methods, the research investigates the spatial and temporal distribution patterns of industrial heritage across different historical periods and industrial types. An Analytic Hierarchical Process (AHP) is used to construct a hierarchical model of resistance factors, which serves as the basis for simulating potential heritage corridors using the Minimum Cumulative Resistance (MCR) model. The results unveil distinct spatiotemporal distribution patterns, with concentrations of industrial heritage in the central Chancheng District and southeastern Shunde District. Two primary potential heritage corridors are identified, and prioritized strategies for their adaptive reuse are proposed. The findings contribute to a comprehensive understanding of industrial heritage distribution in Foshan City and provide valuable insights for the conservation, planning, and sustainable development of these significant sites. The study highlights the importance of integrating spatiotemporal analysis and heritage corridor modeling in the decision-making process for industrial heritage revitalization, ensuring the preservation of invaluable industrial history and culture while fostering sustainable urban growth.

Keywords: industrial heritage distribution; heritage corridors modeling; revitalization strategies; Foshan City; Standard Deviational Ellipse; Minimum Cumulative Resistance

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1. Introduction

Industrial heritage, as a vital component of cultural heritage, embodies significant historical, cultural, social, and scientific values [1–3]. It not only records the historical process of industrial development but also reflects profound industrial cultural heritage, showcases changes in social structure, demonstrates unique architectural artistic styles, and illustrates technological progress. Foshan City, a national-level historical and cultural city and the fourth largest industrial city in China, boasts a rich industrial heritage that serves as a testament to its industrial evolution. Protecting and inheriting these valuable industrial heritages is crucial for preserving the city's historical context, promoting cultural dissemination, and ensuring the continuity of its heritage.

Furthermore, the protection and adaptive reuse of cultural heritage have become increasingly prominent in achieving sustainable urban development [4]. As China's urban industrial structure undergoes adjustment and optimization, numerous high-polluting and energy-intensive industrial enterprises have gradually closed down or relocated, leaving behind a substantial number of industrial heritage sites awaiting redevelopment [5]. The rational protection and utilization of these industrial heritages contribute to the optimization and reorganization of urban spatial functions, the revitalization of urban land resources, and the injection of cultural connotations and vitality into the city. Consequently, industrial heritage has become an essential pathway for promoting urban renewal and high-quality development.

Western European countries began to recognize the importance of industrial heritage protection in the 1950s, as they faced the predicament of traditional industrial decline and transformation [5,6]. They subsequently introduced relevant laws and regulations and gradually established and improved industrial heritage management systems [7]. In contrast, China's research on industrial heritage started relatively late, with the concept of industrial heritage being introduced into the country only in the late 1990s. Since then, Chinese scholars have focused on international practices of industrial heritage protection and development, exploring industrial heritage development models suitable for China's national conditions [5,8]. The adoption of the "Wuxi Proposal" in 2006, the first consensus document on industrial heritage protection in China, provided essential guidance for the country's industrial heritage protection research [9]. Subsequently, research in this field has become increasingly diverse, encompassing multidisciplinary intersections that cover architecture [10–12], urban planning [13], geography [14], tourism [15,16], culture [17], economics [18], acoustics [19], aesthetics [20], sociology [21], policy [22], and many other fields. Research methods have also evolved from initial literature retrieval [23] and field surveys [23] to questionnaire surveys [24], GIS technology applications [25], analytic hierarchical process [26], value assessment [27], and so on.

Spatiotemporal analysis plays a pivotal role in heritage protection research. By analyzing the spatiotemporal distribution characteristics of heritage, researchers can gain an in-depth understanding of the historical evolution, spatial layout, and development trends of heritage sites [28]. This comprehensive grasp of the overall protection pattern of heritage enables the proposal of systematic spatial integration protection strategies [29] and provides data support and decision-making references for the scientific protection and utilization of heritage [30]. The concept of heritage corridor, proposed in the 1980s, refers to a linear space with special value or a passage connecting individual heritage sites [31,32]. In the context of scattered distribution, large value differences, and difficulties in protection and utilization of industrial heritage, the construction of heritage corridors offers new ideas for efficiently organizing heritage clusters, clarifying protection units, optimizing spatial structures, and refining cultural themes.

In light of this, the present study takes Foshan City as the research area and industrial heritage as the research object. It comprehensively applies methods such as Minimum Cumulative Resistance (MCR), Analytic Hierarchical Process (AHP), Kernel Density Estimation (KDE), and Standard Deviational Ellipse (SDE) to analyze the spatiotemporal distribution characteristics of industrial heritage and predict heritage corridors. The aim is to provide decision-making references for the protection and renewal of industrial heritage in Foshan City. This research not only enriches the research perspectives and methods of industrial heritage but also expands the application of heritage corridor prediction in the field of industrial heritage. Moreover, the research results can provide an important basis for relevant government departments to formulate industrial heritage protection plans in Foshan City, thus having strong practical guiding significance.

The structure of the paper is as follows: Section 2 introduces the research object, area, and methods; Section 3 systematically analyzes the research results; Section 4 summarizes the research conclusions; and Section 5 presents prospects for future research.

2. Materials and Methods

2.1. Research Object

Industrial heritage, the research object of this study, encompasses a wide range of industrial cultural remains that possess historical, technological, social, architectural, or scientific value. These include buildings, machines, workshops, factories, mining areas and their ancillary structures, storage facilities, energy production sites, transportation and utilization sites, transportation infrastructure, and social activity sites associated with industry [2,33,34]. As a crucial carrier of urban characteristics and culture, industrial heritage encapsulates the industrial development trajectory of a city. Conducting in-depth research on industrial heritage is of paramount significance for preserving urban industrial civilization, accentuating urban distinctiveness, and catalyzing urban industrial transformation, upgrading, and sustainable development.

2.2. Study Area

Foshan City, located in the central part of Guangdong Province, China (110°00′–115°00′ E, 22°00′–25°00′ N), serves as the study area for this research, as shown in Figure 1. Situated in the hinterland of the Pearl River Delta, Foshan maintains close ties with Guangzhou, Shenzhen, Hong Kong, Macao, and other cities in the core region of the Pearl River Delta urban agglomeration. With a total area of 3798 square kilometers, Foshan City comprises five districts: Chancheng, Nanhai, Shunde, Gaoming, and Sanshui. As of the end of 2022, the city's permanent resident population stood at 9.4034 million.

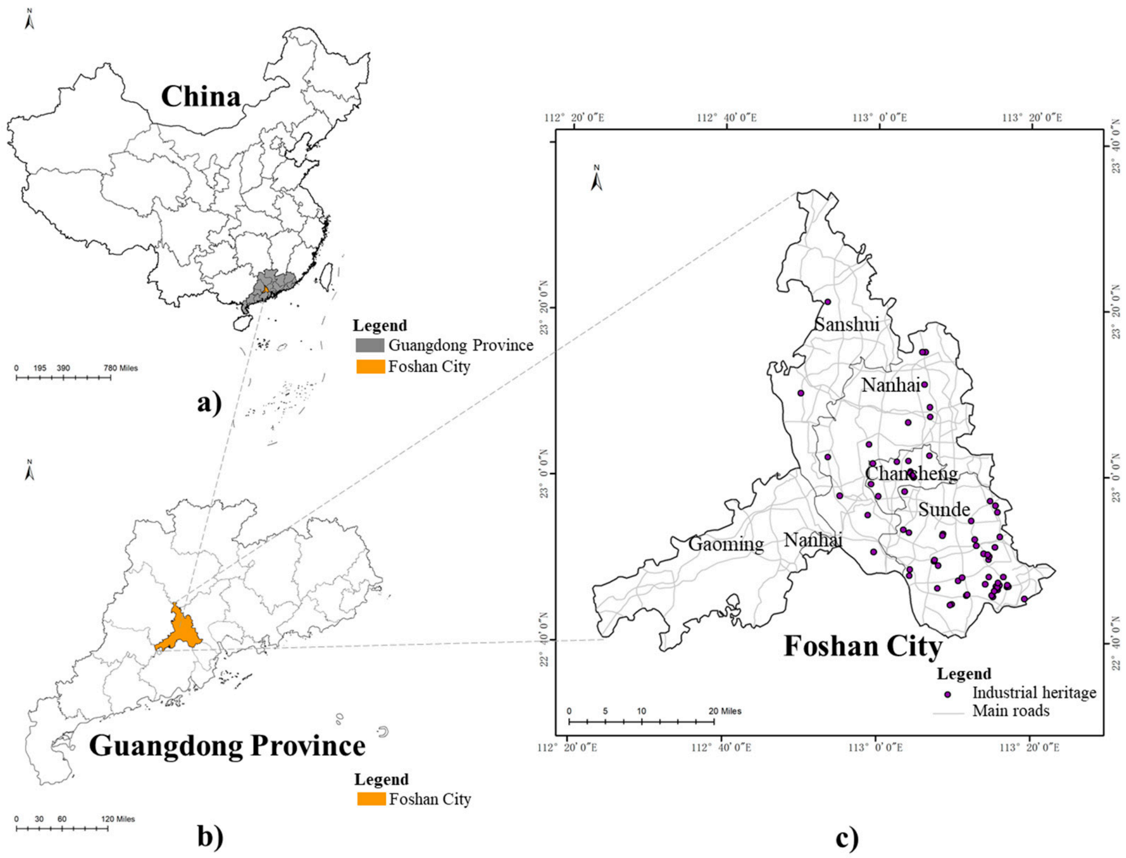

Figure 1. Study area. (**a**) Location of Guangdong Province in China. (**b**) Location of Foshan City in Guangdong Province. (**c**) Distribution of industrial heritage in Foshan.

Renowned as a historical and cultural city in China, Foshan was designated as a national-level historical and cultural city in 1994. The city's urban development history is intimately intertwined with its industrial evolution, establishing it as one of the birthplaces of Chinese industry. The ceramics, casting, and textile industries in Foshan took shape during the Tang and Song dynasties [35]. In the Ming and Qing dynasties, Foshan emerged as one of the "Four Famous Towns in China", boasting thriving industry and commerce, particularly in ceramics, casting, textiles, pharmaceuticals, folk handicrafts, dyed paper, and hardware [36]. The late Qing Dynasty and early Republic of China witnessed Foshan's rise as a pivotal birthplace of modern Chinese national industry, marked by the establishment of China's first match factory and the pioneering modern silk reeling factory. Following the founding of the People's Republic of China, Foshan's industrial economy continued to flourish, forming a comprehensive and distinctive industrial system. Since the reform and opening up, Foshan has capitalized on opportunities and vigorously developed its manufacturing industry, gradually evolving into a prominent national advanced manufacturing base. In 2023, Foshan's total industrial output value surpassed 3 trillion yuan, ranking fourth in the country, trailing only Shenzhen, Suzhou, and Shanghai.

Given Foshan City's rich industrial heritage and its status as an ideal area for industrial heritage research, systematically investigating and analyzing the spatiotemporal distribution characteristics of its industrial heritage holds immense theoretical and practical significance. Such an endeavor contributes to unearthing the historical and cultural value of Foshan's industrial heritage, tracing its industrial development context, facilitating the protection and rational utilization of industrial heritage, and propelling urban renewal and sustainable development.

2.3. Data Sources and Processing

To ensure a comprehensive dataset, this study extensively collected and collated materials pertaining to industrial heritage in Foshan City from various sources. These include: (1) One officially recognized industrial heritage site and fifty-six recommended industrial heritage clues outlined in the "Foshan Historical and Cultural City Protection Plan (2020–2035)" [37]; (2) Three national key cultural relics protection units, seven municipal cultural relics protection units, and nine registered immovable cultural relics; (3) Nine historical buildings and five recommended historical building clues; (4) Additional industrial remains information gleaned from field investigations. Based on the above information, a dataset of industrial heritage in Foshan City is organized, including information such as heritage name, type, administrative district, address, construction date and protection level. Based on the field research, omap V22.11.9.1 software was used to mark the points and export vector data in shp format to generate the heritage distribution map.

Rigorous data screening, de-duplication, and supplementation processes were employed, yielding a total of 72 industrial heritage sites in Foshan City. Table 1 showcases an overview of representative industrial heritage sites in the city.

Table 1. Overview of typical industrial heritage in Foshan City.

Name	Administrative District	Age of Construction	Stages of Industrial Development	Large Categories	Subcategories	Protection Level
Nanfeng Guzao	Chancheng	1644–1839	Traditional handicrafts stage	Manufacturing	Ceramics	National Key Cultural Relics Protection Unit
Tongqing stove	Chancheng	1644–1839	Traditional handicrafts stage	Manufacturing	Ceramics	Registration of immovable cultural property
Former site of Ryujin Liangbao Silk Foil	Chancheng	1949–1978	Traditional handicrafts stage	Textile	Reeling process	Registration of immovable cultural property
Former site of Yick Hing Flower Yarn Company	Chancheng	1913–1948	Pre-modern industrial stage	Textile	Fancy yarn	Historical building

Table 1. *Cont.*

Name	Administrative District	Age of Construction	Stages of Industrial Development	Large Categories	Subcategories	Protection Level
Shiwan Ceramics Factory	Chancheng	1949–1978	Pre-modern industrial stage	Manufacturing	Ceramics	Historical building
Odd Stone Kiln Site	Nanhai	618–1644	Traditional handicrafts stage	Manufacturing	Ceramics	Foshan Municipal Cultural Relics Protection Unit

Drawing upon domestic and international industrial heritage classification systems [30,38,39], Foshan's industrial heritage was systematically categorized based on industrial sectors, as presented in Table 2. The classification scheme encompasses 8 major categories and 26 subcategories. The results reveal that the existing industrial heritage in Foshan City is primarily dominated by manufacturing (40.3%) and textile (25.0%) industries. Within the manufacturing sector, ceramics (12.5%) and food manufacturing (9.7%) emerge as the main subsectors, while the textile industry is chiefly represented by the reeling process (20.8%). The public service category, accounting for 11.1%, reflects the distinct industrial characteristics of Foshan's industrial development.

Table 2. Classification of industrial heritage in Foshan city based on industrial sectors.

Large Categories	Number of Large Categories	Ranking of Large Categories	Percentage	Subcategories	Number of Subcategories	Ranking of Subcategories	Percentage
Mining	2	(6)	2.8%	Non-metallic mining	2	(7)	2.8%
Electricity, heat, gas & Water production & supply	4	(5)	5.6%	Hydroelectricity	2	(7)	2.8%
Textile	18	(2)	25.0%	Liquefied petroleum gas production & supply	1	(13)	1.4%
				Tap water production & supply	1	(13)	1.4%
				Reeling process	15	(1)	20.8%
				Fancy yarn	1	(13)	1.4%
				Plastic weaving	1	(13)	1.4%
				Embroidery	1	(13)	1.4%
Public administration, social security & social organizations	8	(3)	11.1%	Public service	8	(3)	11.1%
Transportation, storage & postal services	7	(4)	9.7%	Waterborne transport	3	(6)	4.2%
				Repository	2	(7)	2.8%
				Railway transport	1	(13)	1.4%
				Road transportation	1	(13)	1.4%

Table 2. *Cont.*

Large Categories	Number of Large Categories	Ranking of Large Categories	Percentage	Subcategories	Number of Subcategories	Ranking of Subcategories	Percentage
Water conservancy, environment & public facilities management	2	(6)	2.8%	Hydraulic engineering	2	(7)	2.8%
Culture, sports & recreation	2	(6)	2.8%	Art & culture	2	(7)	2.8%
Manufacturing	29	(1)	40.3%	Ceramics	9	(2)	12.5%
				Food manufacturing	7	(4)	9.7%
				Electrical manufacturing	4	(5)	5.6%
				Fans, fan manufacturing	2	(7)	2.8%
				Manufacture of basic precious & non-ferrous metals	1	(13)	1.4%
				Manufacture of specialized equipment electrical machinery	1	(13)	1.4%
				Manufacture of internal combustion engines & accessories	1	(13)	1.4%
				Beer manufacturing	1	(13)	1.4%
				Medicine manufacturing	1	(13)	1.4%
				Paper & paper products	1	(13)	1.4%
				Manufacture of bicycle parts & accessories	1	(13)	1.4%

2.4. Research Methods

This study employs a synergistic approach, integrating quantitative and qualitative methods to systematically investigate the spatiotemporal distribution characteristics, influencing factors, and corridor simulation of industrial heritage in Foshan City, as shown in Figure 2. The primary methods employed in this research encompass:

Spatiotemporal analysis methods. Spatial statistical techniques, namely Kernel Density Estimation (KDE) and Standard Deviational Ellipse (SDE), are harnessed to quantitatively characterize the spatiotemporal distribution patterns of industrial heritage in Foshan City across two dimensions: period and type. KDE quantifies the spatial agglomeration degree of industrial heritage by computing the kernel density value for each grid cell. Complementarily, SDE captures the overall shape and directional characteristics of the spatial distribution of industrial heritage by fitting parameters such as the center, direction, and long and short axes of the ellipse. The synergistic application of these methods enables a comprehensive revelation of the spatiotemporal distribution patterns and evolution of industrial heritage across different historical periods and industrial sectors.

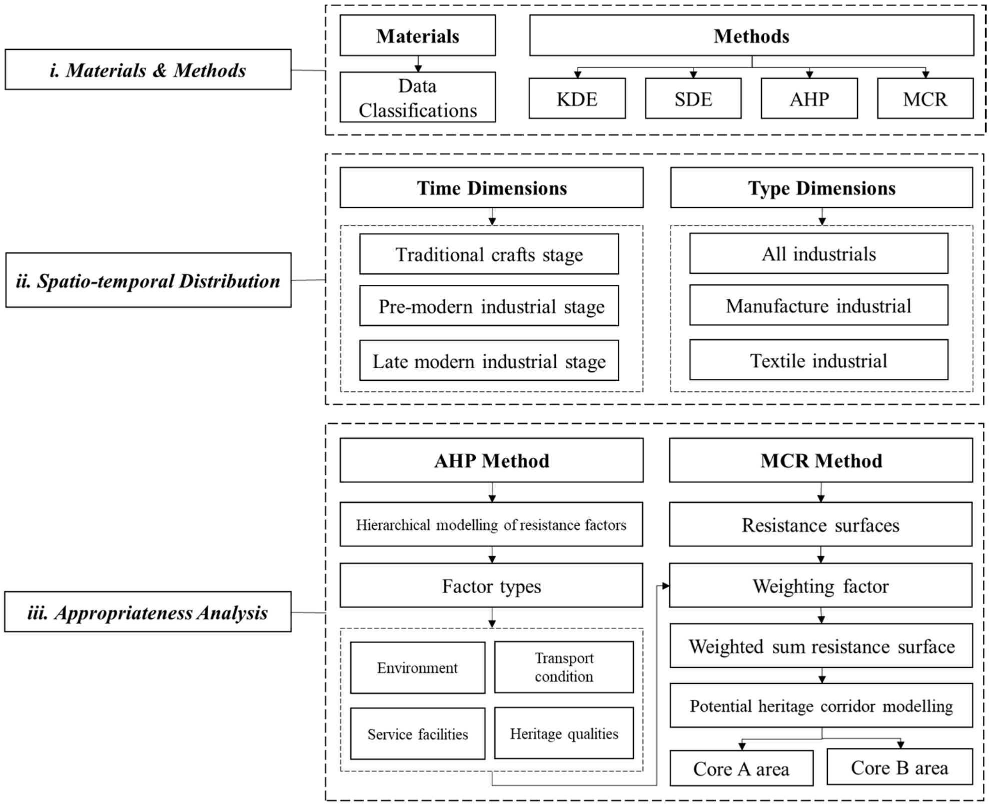

Figure 2. Research framework.

Hierarchical analysis method. The Analytic Hierarchy Process (AHP) is employed to construct a multi-perspective evaluation index system of resistance factors for industrial heritage corridors, encompassing natural, social, economic, and transportation dimensions. Expert scoring and matrix calculation techniques are utilized to determine the weights of each factor and quantitatively assess the suitability of different regions for industrial heritage corridor construction. AHP facilitates the hierarchization and quantification of the complex factors influencing industrial heritage corridor construction, providing a scientific foundation for subsequent MCR simulation.

Corridor simulation method. Leveraging the weights of resistance factors derived from AHP, the Minimum Cumulative Resistance (MCR) model is employed to simulate the spatial distribution of potential industrial heritage corridors in Foshan City. MCR computes the cumulative resistance value from each industrial heritage site to other regions and performs cost distance analysis to identify the corridor path with the minimum cumulative resistance, representing the optimal route connecting industrial heritage nodes. The simulation results offer valuable insights for the planning, layout, and construction of industrial heritage corridors in the city.

Qualitative analysis methods. Complementing the quantitative analysis, this study integrates qualitative data, including the industrial history of Foshan City, field investigations, and relevant literature, to provide a holistic analysis and interpretation of the value connotation, protection status, and utilization methods of industrial heritage. Based on the findings, targeted optimization strategies and protection and utilization recommendations for industrial heritage corridors are proposed, enhancing the practical applicability of the research.

The research framework constructed in this study exhibits innovation and practicality, building upon previous studies on spatiotemporal analysis and corridor simulation. The study distinguishes itself through the following optimizations and extensions: (1) Systematically analyzing the spatiotemporal distribution of industrial heritage from the dual dimensions of time and type, addressing the limitations of existing studies that predominantly focus on a single time point or a specific type of industrial heritage; (2) Integrating AHP into industrial heritage corridor simulation, constructing a comprehensive resistance surface that encompasses multiple factors, including natural, social, economic, and transportation aspects, thereby enhancing the scientific rigor of the simulation results; (3) Seamlessly combining quantitative and qualitative analysis, enriching the research content through field investigations and literature review, bolstering the explanatory power and reliability of the research conclusions. Although we have tried our best to optimize the research framework, it still has limitations, including: sensitivity to bandwidth parameter selection, sensitivity to outliers, and high subjectivity.

This research framework serves as a valuable reference for other regions seeking to conduct research on the spatiotemporal analysis and corridor simulation of industrial heritage. In summary, the methods employed in this study, encompassing kernel density analysis, standard deviational ellipse, hierarchical analysis, and minimum cumulative resistance, form a systematic research framework of "spatiotemporal characteristics analysis-influencing factor identification-corridor simulation construction-optimization strategy proposal", as shown in Figure 2. The spatiotemporal distribution patterns and corridor construction strategies of industrial heritage in Foshan City are analyzed from macro to micro scales and from quantitative to qualitative perspectives. The overarching aim is to provide a scientific basis and decision-making reference for the protection, utilization, and coordinated development of industrial heritage in Foshan City.

2.4.1. Kernel Density Estimation

Kernel Density Estimation (KDE), a non-parametric estimation method, is commonly employed to visualize and analyze the spatial distribution characteristics of point features [31]. The fundamental principle of KDE involves establishing a kernel function centered at each sample point and estimating the probability density of points by calculating the number of points falling within the range of the kernel function. Higher density values indicate a greater degree of spatial agglomeration. The selection of the kernel function is a critical aspect of KDE, with common options including uniform, triangular, quadratic, and Gaussian kernels. This study adopts the Gaussian kernel function, expressed as [40]:

$$f(x) = \frac{1}{nh}\sum_{i}^{n} k\left(\frac{x - x_i}{h}\right) \quad (1)$$

where $f(x)$ represents the kernel density estimation value at point; h denotes the bandwidth that controls the width of the kernel function; n signifies the number of points falling within the bandwidth range; $(x - x_i)$ represents the distance from point x to point x_i; and $k(\cdot)$ is the Gaussian kernel function. By computing the kernel density value for each grid cell using Equation (1), a kernel density map illustrating the hotspot areas of industrial heritage spatial distribution can be generated.

2.4.2. Standard Deviational Ellipse

Standard Deviational Ellipse (SDE), introduced by Lefever, is a widely-used method for characterizing the overall morphological attributes of spatial point distributions. The core principle of SDE involves establishing the center of gravity of the point distribution as the ellipse's center. By calculating the standard deviation of points relative to the ellipse's center in the x and y directions, a minimum ellipse encompassing all points is fitted. The points within the ellipse are adjusted to the center, minimizing the average distance. The major and minor axes of the ellipse depict the extent of point distribution dispersion and the primary trend direction [41].

2.4.3. Analytic Hierarchical Process

The Analytic Hierarchy Process (AHP) is a prevalent decision analysis method employed for the quantitative analysis of qualitative problems. In hierarchical analysis, a complex problem is conceptualized as a system, with its objectives decomposed into multiple levels [41]. By quantifying qualitative indicators, the weights of these indicators at each level are calculated to serve as the decision-making basis for solving multi-objective optimization problems [42]. The essence of AHP lies in the integration of quantitative and qualitative methods, rendering it widely applied, logical, and systematic.

2.4.4. Minimum Cumulative Resistance

The Minimum Cumulative Resistance (MCR) model utilized is a modified and adapted version developed by Yu [43] and Chen [44], building upon the research of Knaapen [45] and other scholars. The MCR model primarily assesses regional suitability by examining the efforts required to overcome various types of resistance, resulting in incurred costs. The mathematical formulation of MCR is as follows [46]:

$$MCR = f_{min} \sum_{j=n}^{i=m} \left(\mathrm{D}_{ij} * R_i\right) \tag{2}$$

where, MCR represents the minimum cumulative resistance value; f denotes a monotonically increasing function indicating a positive correlation between cumulative resistance and the motion process; min signifies the minimum value of cumulative resistance; D_{ij} represents the distance from the target spatial unit source j to other spatial unit i; R_i stands for the coefficient of diffusion resistance of spatial unit i to a certain motion; and $\sum$ indicates the cumulative resistance from the target spatial unit source j to spatial unit i.

3. Results

3.1. Spatiotemporal Distribution Characteristics of Industrial Heritage

3.1.1. Period Dimension Analysis

Drawing upon existing research on the stages of industrial development [29] and considering the unique characteristics of Foshan's industrial evolution, as well as the historical, cultural, and economic factors of the region, this study categorizes Foshan's industrial development into three distinct stages: traditional handicrafts stage (ancient times–1839), pre-modern industrial stage (1840–1948), and late modern industrial stage (1949–present). The industrial categories, number of heritage sites, and developmental trends exhibit significant variations across these different stages of industrial heritage development in Foshan City, as shown in Figures 3 and 4, and Table 3.

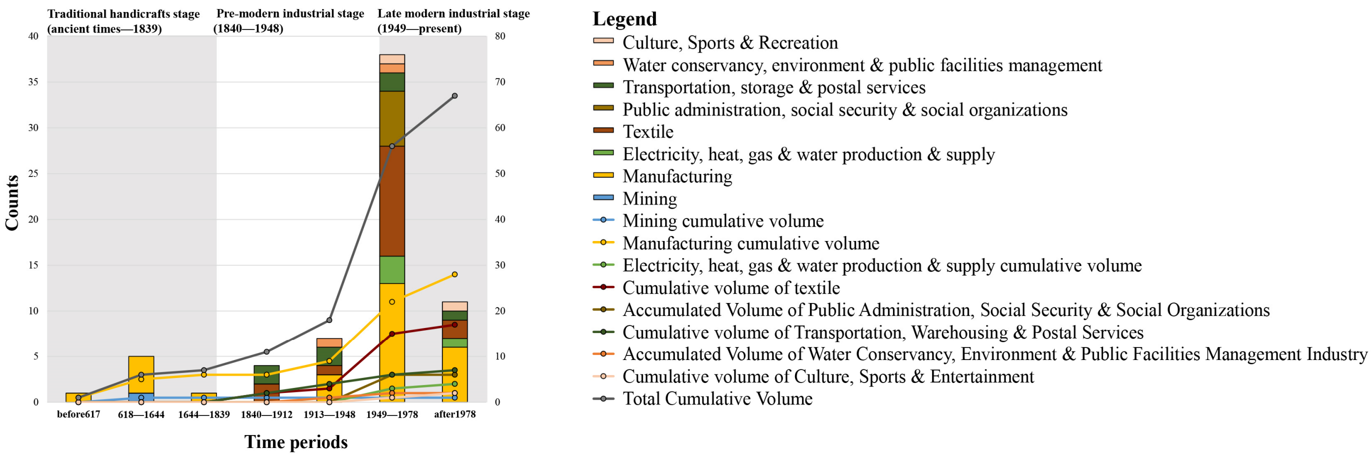

Figure 3. Number and types of industrial heritage across different stages of development.

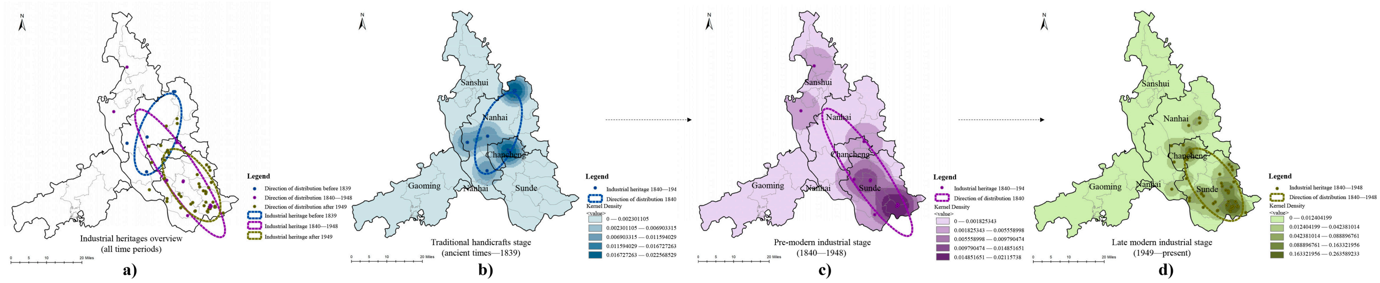

Figure 4. Spatial distribution of industrial heritage across different stages of development. (**a**) Distribution of industrial heritages of all time periods. (**b**) Distribution of industrial heritages of traditional handicrafts stage. (**c**) Distribution of industrial heritages of pre-modern industrial stage. (**d**) Distribution of industrial heritages of late modern industrial stage.

Table 3. Standard deviational ellipse of industrial heritage across different stages of development.

Name	Shape Length	Shape Area	Center of Gravity	Semi-Axis	Long Semi-Axis	Rotation
Traditional handicrafts stage (ancient times–1839)	146,566.11 m	834,717,070.08 m^2	113.13° E, 22.92° N	7687.09 m	34,578.06 m	145.81°
Pre-modern industrial stage (1840–1948)	91,075.25 m	547,246,969.49 m^2	113.18° E, 22.87° N	9195.84 m	18,944.56 m	145.03°
Pre-modern industrial stage (1949–present)	91,605.96 m	527,367,733.40 m^2	113.03° E, 23.08° N	8617.14 m	19,482.74 m	21.23°

The traditional handicrafts stage encompasses seven industrial heritage sites, primarily dominated by ceramic manufacturing (85.7%) and non-metallic mining (14.3%). Despite the limited sample size, the findings align with Zhang's [29] observations regarding the industrial heritage of China as a whole, indicating that the industrial heritage from this stage predominantly comprises traditional manufacturing and mining. Foshan City exhibits a similar pattern, with ceramic manufacturing, a traditional industry, taking precedence. The industrial heritage of ceramic manufacturing in Foshan traces back to the Zhuangbian kiln site in the Shang Dynasty. Historically, Foshan's ceramic manufacturing industry flourished, boasting over a hundred kilns during the heyday of Shiwan Town, establishing it as one of the largest ceramic manufacturing centers in China at that time.

The pre-modern industrial stage comprises 11 industrial heritage sites, encompassing transportation, storage & postal services (36.4%), manufacturing (27.3%), textile (27.3%), and water conservancy, environment & public facilities management (9.1%). These sites exhibit a higher concentration in Leliu, Daliang, and Ronggui streets within Shunde District. During this period, at the end of the Qing Dynasty, Foshan emerged as a pioneer of modern national industry in China, housing surviving early structures such as the Early Building of Shunde Sugar Factory, Longjiang Daguangming Rice Mill Office Building, and other significant industrial heritage sites.

The late modern industrial stage boasts a diverse array of 49 industrial heritage sites, spanning manufacturing (38.78%), textiles (28.57%), public administration, social security & social organizations (12.24%), electricity, heat, gas & water production & supply (8.16%), transportation, storage & postal services (6.12%), culture, sports & recreation (4.08%), and water conservancy, environment & public facilities management (2.04%). This phase exhibits the highest concentration of sites in Daliang and Ronggui streets within Shunde District. Following the establishment of the People's Republic of China, Foshan's industry and commerce experienced continuous development, gradually evolving into a renowned manufacturing hub both domestically and internationally.

3.1.2. Type Dimension Analysis

The industrial heritage of Foshan City exhibits a spatial concentration in the central part of Chancheng District and the southeastern part of Shunde District, with the distribution characteristics of manufacturing and textile industry heritage being most prominent, as shown in Figure 5. The manufacturing industry heritage displays a bimodal spatial distribution, clustered around Shiwan Town in Chancheng District and Ronggui Street in Shunde District. However, these dual cores exhibit distinct cultural heritage characteristics. The streets surrounding Shiwan Town primarily focus on ceramic manufacturing, perpetuating the ceramic culture that has thrived in the area for millennia. In contrast, the industrial heritage around Ronggui Street in Shunde is more diverse, encompassing various industries such as food, electrical appliances, and hardware. Shunde has played a pivotal role in China's manufacturing sector, with five of the nation's top ten township enterprises located in Shunde in 1991, and the production and sales of electrical appliances, including refrigerators, washing machines, rice cookers, and microwave ovens, leading the country.

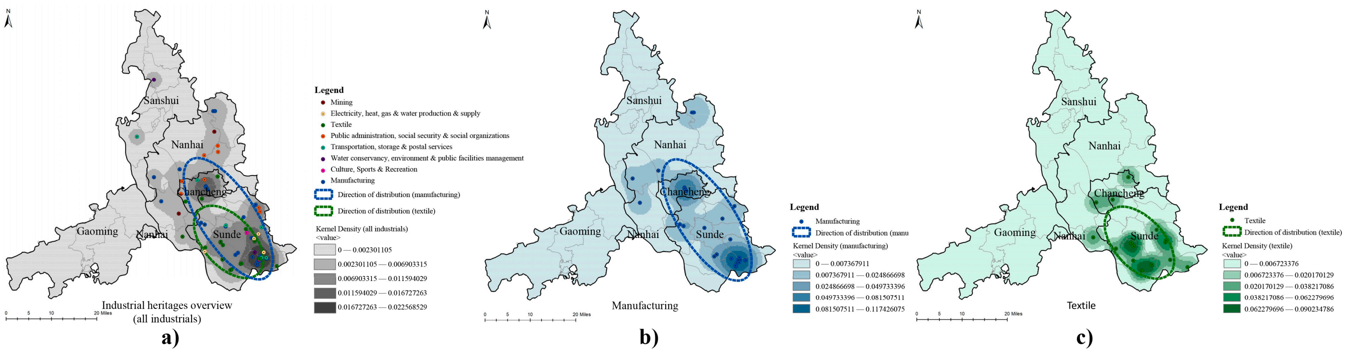

Figure 5. Spatial distribution of industrial heritage based on industrial categories. (**a**) Distribution of industrial heritages of all industrials. (**b**) Distribution of industrial heritages of manufacturing. (**c**) Distribution of industrial heritages of textile.

The textile industrial heritage is principally distributed in the central and southern parts of Shunde District, with the textile industry dominated by mulberry processing and silk reeling. Shunde boasts a long history of silkworm cultivation dating back to the Ming Dynasty. In the 1820s, Shunde emerged as the center of Guangdong's silk industry, with cocoon markets, cocoon houses, and cocoon stacks accounting for approximately 80% of the province's total [47,48]. The modern development of China's silk industry commenced in the 1870s, and by 1887, Shunde housed 42 machine-reeling factories, constituting over 90% of the province's total. However, the economic crisis and the rise of rayon in the 1930s led to a decline in Shunde's modern silk reeling industry. Following the establishment of the People's Republic of China, the silk industry gradually recovered under the promotion of the party and government. In 1952, Shunde County's silk production surpassed 400 tons. By 1979, Shunde County's cocoon production exceeded 235,000 quintals, ranking first in the country at that time, highlighting the development of the mulberry and silkworm industry [49]. However, after the reform and opening, due to factors such as economic efficiency and production environment, Shunde's silk industry experienced a gradual decline, with cocoon production in 1983 falling by 52.2% compared to 1979. This may partially explain why the textile industrial heritage, primarily associated with mulberry and sericulture, was mainly constructed before the reform, and opening period. The concentration of textile industrial heritage in Shunde District reflects the former prosperity of the silk industry in the area.

3.2. Suitability Analysis for Industrial Heritage Corridor Construction

3.2.1. Weight Assignment Using AHP Method

The Analytical Hierarchy Process (AHP) was employed to hierarchize and structure the problem of industrial heritage corridor construction, enabling a more scientific and effective decision-making analysis in the face of multiple factors, criteria, and the complexity of influencing factors [50]. Drawing upon the research of Zhang [51] and He [50], a hierarchical model of resistance factors was constructed, as shown in Figure 6. The model comprises four middle layers: environment, traffic conditions, service facilities, and heritage qualities, encompassing 13 resistance factors: altitude, elevation, distance to major water systems, distance to bus & subway stops, distance from major roads, distance to scenic spots, distance to food service, distance to accommodation services, distance to financial & insurance services, distance to health care services, distance to leisure & entertainment services, industrial heritage kernel density estimation, and ontological value of industrial heritage.

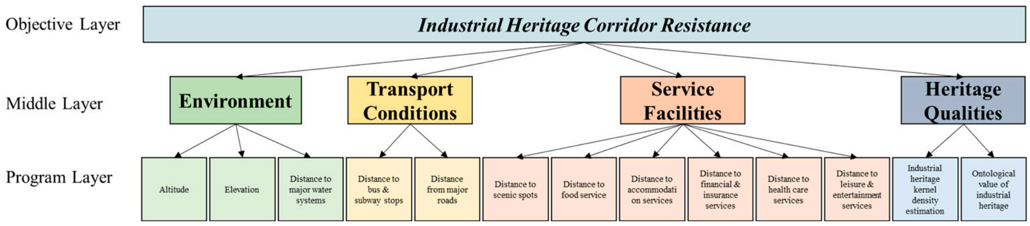

Figure 6. Hierarchy model of resistance factors for industrial heritage corridor construction.

The relative importance of each resistance factor was determined through pairwise comparison, and a judgement matrix was established to calculate the relative weight value K, as shown in Table 4. The consistency test was conducted using yaahp V11.0 software, and the stochastic consistency ratios were all found to be less than 0.1, indicating the validity of the weights.

Table 4. Weights and resistance values of resistance factors for heritage corridor construction.

Program Layer	Weights	Resistance Value				
		1	2	3	4	5
Altitude (m)	0.0122	<37	37–104	104–201	201–349	>349
Elevation (°)	0.0462	<3.9	3.9–8.7	8.7–15.5	15.5–24.7	>24.7
Distance to major water systems (m)	0.0194	<1343.1	1343.1–3089.0	3089.0–5775.2	5775.2–10,274.4	>10,274.4
Distance to bus & subway stops (m)	0.0706	<579.1	579.1–1336.5	1336.5–2160.6	2160.6–3229.8	>3229.8
Distance to major roads (m)	0.2563	<574.1	574.1–1530.8	1530.8–2838.4	2838.4–4815.8	>4815.8
Distance to scenic spots (m)	0.0395	<934.1	934.1–2439.0	2439.0–4566.7	4566.7–8043.7	>8043.7
Distance to food service (m)	0.0284	<2120.2	2120.2–5104.1	5104.1–8951.8	8951.8–13,270.7	>13,270.7
Distance to accommodation services (m)	0.0235	<1328.2	1328.2–3254.1	3254.1–6109.7	6109.7–9961.5	>9961.5

Table 4. *Cont.*

Program Layer	Weights	Resistance Value				
		1	2	3	4	5
Distance to financial & insurance services (m)	0.0112	<1336.5	1336.5–3079.8	3079.8–5520.3	5520.3–9123.1	>9123.1
Distance to health care services (m)	0.0150	<1503.4	1503.4–3064.7	3064.7–5204.1	5204.1–8211.0	>8211.0
Distance to leisure & entertainment services (m)	0.0197	<581.9	581.9–1779.8	1779.8–3080.4	3080.4–4928.7	>4928.7
Industrial heritage kernel density estimation (per square kilometer)	0.3279	>0.163552	0.08597–0.163552	0.040888–0.08597	0.012581–0.040888	<0.012581
Ontological value of industrial heritage	0.1302	National key cultural relics protection units	Foshan municipal cultural relics protection units	Registered immovable cultural heritages	Historic buildings	Other industrial heritages

3.2.2. Resistance Surface Construction

Resistance surfaces were constructed for each of the 13 resistance factors. Elevation and slope were reclassified into five categories based on their actual values using the Natural Breaks method, which classifies objects based on statistically significant natural turning points and breakpoints. The five categories were assigned resistance values to construct the resistance surfaces. Higher elevation and slope values correspond to lower suitability for corridor construction and higher resistance values. Euclidean distances from each spatial unit to the main water system, bus and metro stations, main roads, scenic spots, catering services, accommodation services, financial and insurance services, healthcare services, and leisure and entertainment services were calculated. These distances were reclassified into five categories and assigned values to construct the resistance surfaces. The industrial heritage kernel density and ontological value reflect the heritage characteristics of the spatial unit. A circular buffer zone with a radius of 2 km was generated around each industrial heritage point, and resistance values were assigned to national key cultural relics protection units, Foshan municipal cultural relics protection units, registered immovable cultural relics, historical buildings, and other industrial heritages, respectively. Finally, based on AHP method, 13 resistance factors were assigned weights, and a weighted sum resistance surface was obtained, as shown in Figure 7.

3.2.3. Potential Heritage Corridor Simulation

The Minimum Cumulative Resistance (MCR) model was employed to generate a minimum cost path for constructing an industrial heritage corridor in Foshan City. Factors such as natural environment, traffic environment, service facilities, and heritage qualities introduce resistance to the construction of industrial heritage corridors, with lower resistance indicating higher suitability for corridor construction. Cost connectivity analysis was applied to obtain the lowest resistance path optimization network between each industrial heritage site, simulating potential heritage corridors, as shown in Figure 8.

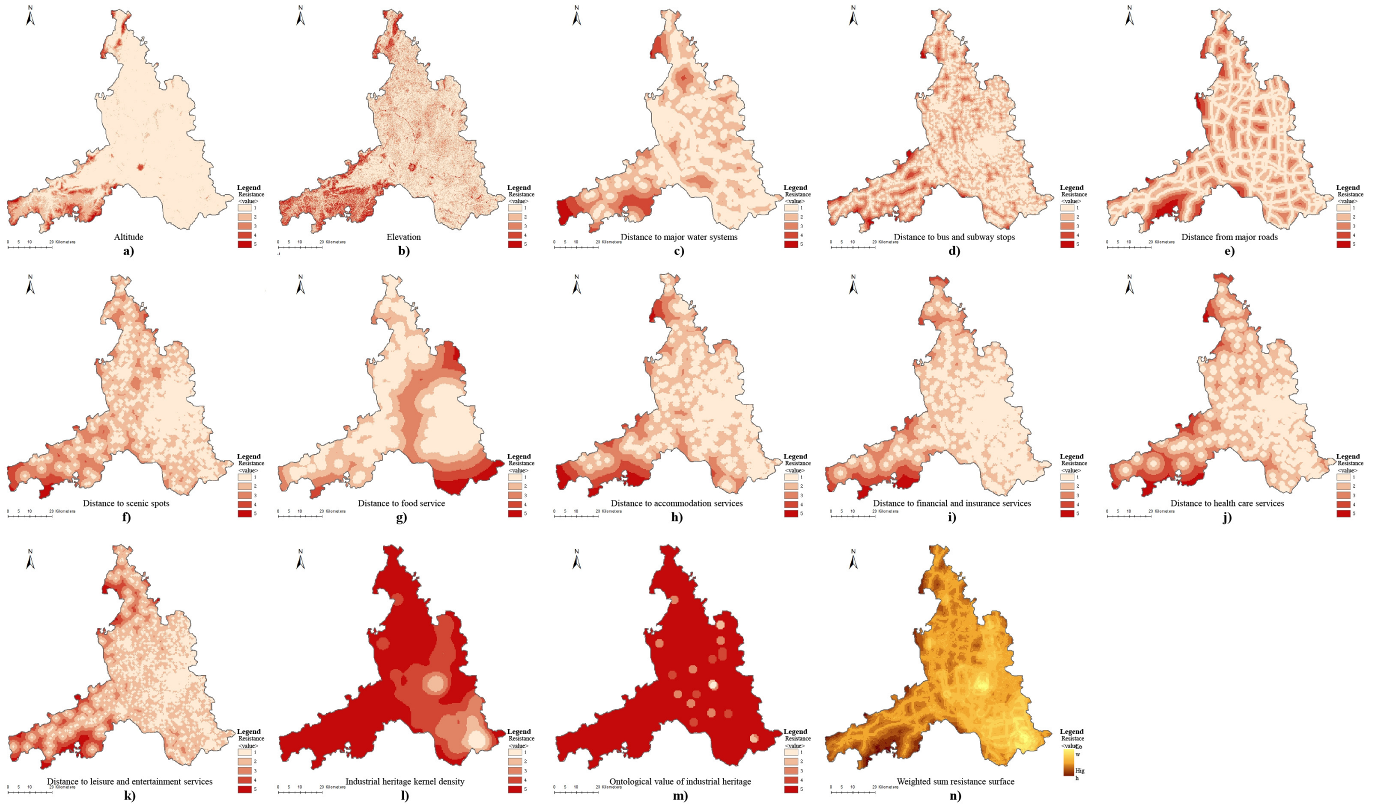

Figure 7. Weighted sum resistance surface for industrial heritage corridor construction. (**a**) Resistance surface of altitude. (**b**) Resistance surface of elevation. (**c**) Resistance surface of distance to major water systems. (**d**) Resistance surface of distance to bus & subway stops. (**e**) Resistance surface of distance to major roads. (**f**) Resistance surface of distance to scenic spots. (**g**) Resistance surface of distance to food service. (**h**) Resistance surface of distance to accommodation services. (**i**) Resistance surface of distance to financial & insurance services. (**j**) Resistance surface of distance to health care services. (**k**) Resistance surface of distance to leisure & entertainment services. (**l**) Resistance surface of industrial heritage kernel density estimation. (**m**) Resistance surface of ontological value of industrial heritage. (**n**) Weighted sum resistance surface.

The heritage corridor simulation results reveal two major cores, characterized by less integrated resistance and higher suitability for generating industrial heritage corridors. The two main cores are: A. the junction of Zhangchu Street, Shiwan Town, Nanzhuang Town, and Lechong Town; B. the area encompassing Lunjiao Street, Daliang Street, Ronggui Street, Xingtan Town, and Leliu Street. Core Heritage Corridor A, with Nanfeng Guzao as the major node and the Garden of Shiwan Fine Arts Ceramics Factory as the secondary node, links nine industrial heritage sites, including the Former site of Mao Zedong Thought Silkworm Breeding Room in Liangsha Village, Lodi People's Canteen, Dajiang Village Warehouse of the Cheonghwari Production Unit, Muradou Village Warehouse at 1506 International Ceramic City, Wah Kong San Tsuen, Shiwan Distillery Marketing Office, Shiwan Ceramics Factory, and Tongqing Stove. Core Heritage Corridor B, with the Early Building of Shunde Sugar Factory as the major node and Ma Gang Drainage and Irrigation Station and Xinchong Cocoon Inn as the secondary nodes, connects 25 industrial heritage sites, including the former site of Lunjiao Silkworm Breeding Farm in Guangdong Province, Continental Granary, Xiangyunsa Cultural Heritage Protection Base, Jichu Power Station, Shunde Wanshifa Bakery Company, and Dalyan Water Treatment Plant. Integrating the above analysis of spatial and temporal distribution characteristics, it can be observed that Core Heritage Corridor A is predominantly characterized by the ceramic manufacturing culture inherited from the traditional handicrafts stage to the present day, while Core

Heritage Corridor B is dominated by the diversified manufacturing culture developed from the modern industrial stage to the present day.

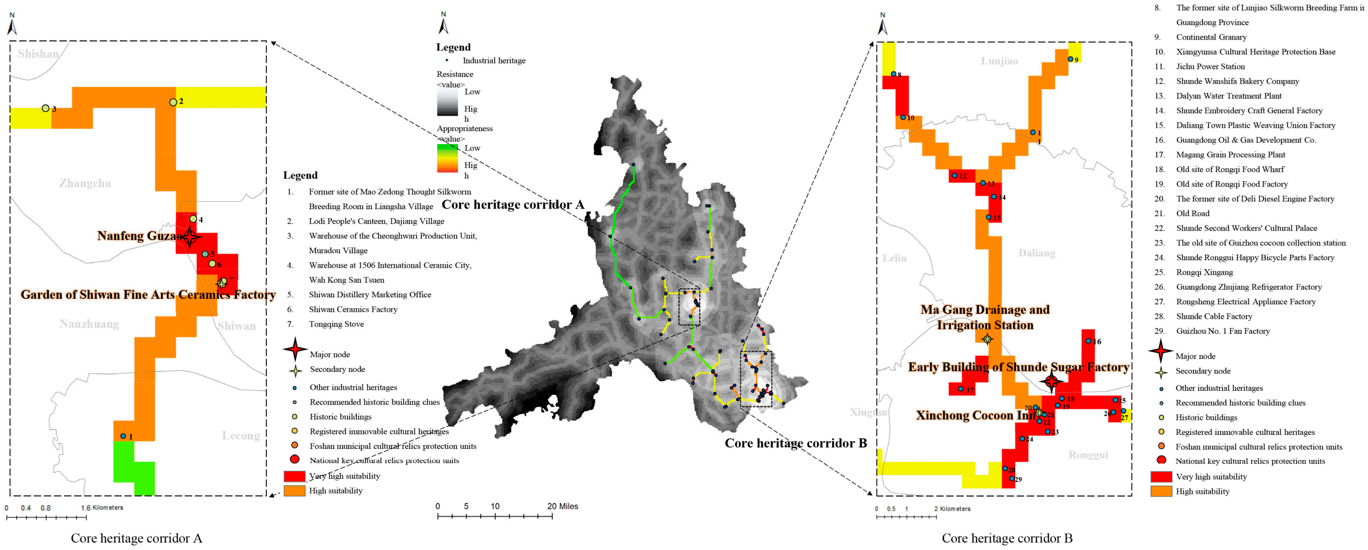

Figure 8. Simulated potential industrial heritage corridors.

4. Discussion

This study investigates the spatial and temporal distribution characteristics of industrial heritage in Foshan City from two dimensions: period and type. By considering factors such as natural environment, traffic conditions, service facilities, and heritage qualities, a hierarchical model of resistance factors is constructed. The Analytic Hierarchical Process (AHP) is employed to assign weights to each resistance surface, generating a weighted sum of resistance surfaces. Based on the Minimum Cumulative Resistance (MCR) model, the minimum cost path is derived, enabling the prediction of industrial heritage corridors.

The findings of this study hold significant implications for the protection and reuse of industrial heritage. By identifying areas with dense industrial heritage, determining the dominant types of industrial heritage in the region, and uncovering the core industrial culture, more targeted and appropriate protection measures can be formulated. This approach facilitates the prioritization of renovation efforts and the selection of more efficient reuse strategies, ultimately contributing to the resolution of social issues arising from urban industrial transformation and factory relocation, thereby promoting sustainable urban development.

Drawing upon the research outcomes, it is recommended to adopt an industry cluster approach for the protection of textile and manufacturing industries, aiming to preserve regional industrial memory and unveil the distinctive characteristics of industrial culture. Priority should be given to the industrial heritage sites located within the two main cores of the simulated heritage corridors, implementing adaptive use in a graded, classified, and batch manner. This strategy promotes the protection of industrial heritage, the renewal and revitalization of buildings, the development of industrial culture, and the advancement of cultural tourism, collectively fostering the sustainable development of Foshan City. It is suggested to utilize the predicted heritage corridors as a reference, considering factors such as construction cost, crowd vitality, development potential, and sustainability when connecting various industrial heritage sites to create joint routes.

Although the prediction results of industrial heritage corridor construction obtained through the combined application of Minimum Cumulative Resistance (MCR), Analytic Hierarchical Process (AHP), Kernel Density Estimation (KDE), and Standard Deviational Ellipse (SDE) are reliable, certain limitations inherent to this study should be acknowledged. Firstly, the continuous updating of the heritage conservation list may lead to changes in the information regarding the number, grade, and age of heritage sites. Consequently, this study cannot guarantee the inclusion of all industrial heritage sites and potential industrial heritage resources. Secondly, the influencing factors affecting the construction of industrial heritage corridors are complex, diverse, and challenging to quantify precisely. Furthermore, while the spatial distribution analysis of industrial heritage conducted using software such as ArcGIS 10.7 yielded conclusions consistent with the historical and cultural background of Foshan, an in-depth investigation of the influence mechanism underlying the spatial distribution characteristics was not performed.

To further advance the research on industrial heritage corridors, future studies can focus on the following aspects: (1) Expanding the scope of data collection to incorporate a broader range of potential industrial heritage resources, enhancing the comprehensiveness and accuracy of the research. (2) Conducting more in-depth investigations and analyses of the influencing factors affecting the construction of industrial heritage corridors, exploring methods to quantify these factors with greater precision. (3) Investigating the influence mechanism of the spatial distribution characteristics of industrial heritage, integrating quantitative analysis with qualitative research to gain a deeper understanding of the factors shaping the distribution patterns. (4) Exploring the practical applications of industrial heritage corridors, including the development of cultural tourism routes, the integration of industrial heritage with urban renewal projects, and the promotion of public participation in heritage conservation.

By addressing these aspects, future research can contribute to a more comprehensive and practical understanding of industrial heritage corridors, ultimately promoting the protection, utilization, and sustainable development of industrial heritage in Foshan City and beyond. The insights gained from this study serve as a foundation for further exploration and implementation of strategies aimed at preserving the valuable industrial heritage while fostering sustainable urban growth.

5. Conclusions

This study employs Kernel Density Estimation (KDE) and Standard Deviational Ellipse (SDE) techniques to analyze the spatiotemporal distribution characteristics of industrial heritage in Foshan City, focusing on two dimensions: period and type. The period dimension analysis reveals distinct patterns across the traditional handicraft stage, pre-modern industrial stage, and late modern industrial stage. The traditional handicraft stage is dominated by ceramic manufacturing and mining heritage, while the pre-modern industrial stage exhibits a dense distribution of heritage in Leliu, Daliang, and Ronggui streets of Shunde District. The late modern industrial stage boasts a rich variety of industrial heritage, with the highest density concentrated in Daliang and Ronggui streets of Shunde District. Regarding the category dimension, the study finds that the industrial heritage of Foshan City is densely distributed in the central part of Chancheng District and the southeastern part of Shunde District. The manufacturing industrial heritage exhibits a bimodal spatial distribution, clustering in the central part of Chancheng District and the southeastern part of Shunde District. Furthermore, the textile industrial heritage is primarily located in the central and southern Shunde District, with the textile industry dominated by mulberry and silk reeling processing.

To assess the suitability of industrial heritage corridors, the study employs the Minimum Cumulative Resistance (MCR) method and the Analytic Hierarchical Process (AHP). The AHP is utilized to hierarchize and structure the industrial heritage corridor construction problem, constructing a hierarchical model of resistance factors and assigning weights to 13 resistance factors. Using ArcMap 10.7 software, 13 resistance surfaces are constructed, and a weighted sum resistance surface is calculated. Based on the MCR model, the minimum cost path is generated to construct the industrial heritage corridor in Foshan City. The simulation results of the heritage corridor reveal two main cores: the junction of Zhangcher Street, Shiwan Town, Nanzhuang Town, and Lechong Town, and the area encompassing Lunjiao Street, Daliang Street, Ronggui Street, Xingtan Town, and Leliu Street.

The findings of this study contribute to a deeper understanding of the spatiotemporal distribution characteristics of industrial heritage in Foshan City and provide a research basis for the protection and reuse of industrial heritage. By predicting the industrial heritage corridors in Foshan City, the study offers valuable insights for future planning and construction. Moreover, this thesis introduces a novel research approach for industrial heritage-related studies, paving the way for further exploration in this field.

To enhance the robustness and applicability of the study, future research should focus on several key aspects. Firstly, supplementing the dataset with comprehensive industrial heritage data will ensure a more complete representation of the industrial heritage landscape. The current dataset for this study is derived from the publicly available conservation lists in the city of Foshan; however, heritage conservation in Foshan is still a work in progress, and there are still industrial heritages that have not yet been included in the conservation system. The dataset of this study still has the potential and need to be expanded in the future. Secondly, conducting an in-depth investigation into the mechanisms underlying the formation of spatiotemporal distribution characteristics will provide a deeper understanding of the factors shaping the distribution patterns. Additionally, optimizing the resistance factor hierarchy model and improving the grading and classification of heritage corridors will lead to the establishment of more efficient industrial heritage corridors. Furthermore, exploring more systematic methods for constructing industrial heritage corridors will contribute to the development of comprehensive strategies for the protection, utilization, and sustainable development of industrial heritage.

By addressing these aspects, future research can build upon the findings of this study and contribute to the advancement of industrial heritage conservation and management practices in Foshan City and beyond. The insights gained from this study serve as a foundation for further exploration and implementation of strategies aimed at preserving the valuable industrial heritage while fostering sustainable urban growth. Through the integration of spatiotemporal analysis, corridor simulation, and qualitative research, this study provides a holistic approach to understanding and safeguarding the industrial heritage of Foshan City, ultimately promoting the protection, utilization, and sustainable development of these significant cultural assets. In addition, this study is generalizable, and by varying the resistance factors as well as their weights, it can be generalized and applied to heritage studies of different periods, types, and regions.

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