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Determination of the temporal-spatial pattern distribution and evolution of industrial heritage in Northeast China and its influencing factors

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Abstract:

This study investigates the spatiotemporal evolution and influencing factors of industrial heritage in Northeast China based on a dataset of 635 sites. Spatial analytical methods, including kernel density analysis, nearest neighbor index, standard deviation ellipse, trend surface analysis, and Voronoi polygon analysis, were applied using ArcGIS 10.8. The results indicate that: (1) The development of industrial heritage in Northeast China can be divided into 5 distinctive historical stages (2) Spatially imbalanced distribution showing increasing clustering over time, with east-west concentration along resource-rich eastern zones and north-south shifts from peripheral to central dominance. Spatial transitions occurred from railway corridors to resource zones and back. (3) Regional specialization: Liaoning dominates metal mining/metallurgy, Heilongjiang in coal/petroleum/transportation, Jilin in food/light industries, and eastern Inner Mongolia in transportation/energy. Multifactorial analysis identifies combined influences of resource availability, railway networks, hydrography, topography, climate, and policy shifts. The research proposes targeted conservation strategies informed by these spatiotemporal patterns and regional industrial characteristics, offering methodological frameworks for heritage revitalization in post-industrial regions. This systematic approach enhances understanding of industrial civilization trajectories while supporting sustainable heritage management in Northeast China.

Keyword: Northeast China, Industrial heritage, Geographic information systems (GIS), Temporal-spatial distribution, Influencing factors

1. Introduction

Industrial heritage is a relatively recent form of heritage, made up of remnants of industrial culture that often possess historical, technical, social, architectural, or scientific significance. Specifically, these remnants consist of buildings and machinery, workshops, manufacturing plants, factories, mines, processing/refining sites, warehouses and storage rooms, energy production, transmission, usage, and transportation facilities, as well as all underground structures, and include places associated with social activities tied to industry, such as residences, religious sites, or educational institutions. (Charter – TICCIH, n.d.) In the context of post-industrial society, (Bell, 1972, 2001) the preservation and transmission of industrial heritage has become a global challenge. (Szromek et al., 2021) Especially in the field of urban renewal, the protection and reuse of industrial heritage has increasingly become a vital force in promoting urban revitalization (Guo et al., 2021) and accelerating economic growth. (Chung & Lee, 2023)

Research on industrial heritage can be traced back to the 20th century. In the 1960s and 1970s, resource depletion and economic changes led to the collapse of traditional industries. Industrial sites, buildings, and equipment were abandoned and neglected, resulting in massive unemployment among industrial workers and worsening environmental and social issues. People began to reflect on the negative impacts of industrialization, leaving a significant number of abandoned industrial buildings and facilities in cities. With the emergence and development of industrial archaeology, it was found that old industrial areas from hundreds of years ago were not in conflict with the requirements of modern urban life. The factories, equipment, and infrastructure in industrial heritage were also important economic factors in society and have witnessed the development of human civilization. This sparked a global wave of research into the protection and regeneration of industrial heritage.

In China, research on industrial heritage began with the publication of the Wuxi Industrial Heritage Protection Recommendations in 2006, which drew domestic attention to the protection and reuse of industrial heritage, leading to extensive research and notable results. (Mo et al., 2022a; Zhang et al., 2020a) Early research focused on qualitative studies, emphasizing the development of strategies and frameworks for the protection and reuse of industrial heritage. It explored methods for the protection and reuse of industrial heritage (Hou, 2012; C. Huang & Zhou, 2015; Li et al., 2011a; Mao & Yu, 2015; X. Wang et al., 2013; Wei & Meng, 2012; Ye & Zhou, 2014; Zhu, 2015) while also examining the potential of industrial heritage in tourism and starting to build a value assessment system for industrial heritage. (Cai & Yao, 2012; Li et al., 2011b; Xiao et al., 2014; Xu et al., 2013) In the past decade, the study of industrial heritage has shifted from qualitative to quantitative research. Advanced technological capabilities, abundant industrial heritage reserves, and the widespread adoption of advanced research methodologies drive this shift. First, technologies like remote sensing and Geographic Information Systems (GIS) have been widely applied. Specifically, the widespread use of GIS technology in heritage research, (Y. Huang, 2024; B. Liu et al., 2024) with its strong spatial analysis capabilities, allows for a deeper analysis of site concentration, distribution patterns, and potential influencing factors, addressing the gaps in the study of industrial heritage spatial distribution in specific regions. (Lv et al., 2024; Mo et al., 2022b; Wu et al., 2022a; Yan et al., 2024; Zhang et al., 2024a; Zhang, Sun, et al., 2022)

Currently, research on the temporal and spatial patterns of industrial heritage in China is concentrated in economically developed regions such as Beijing, Wuhan, and Nanjing (H. Wang et al., 2024; Wu et al., 2022b), with limited focus on Northeast China. Nonetheless, it was once China's largest industrial base (Mei et al., 2006a), developing after the establishment of the People's Republic of China due to its rich natural resources, unique development history, and geopolitical relations with the Soviet Union. It was the nation's heavy industry center and a crucial engine for national development in the 1950s. (S. Liu et al., 2016) The provinces and cities in this region have similar social backgrounds and economic structures, situated in a comparable cultural context. They are interrelated and inseparable, and should be studied as an integrated whole. While GIS-based spatial analyses have been widely applied in industrial heritage studies, this research distinguishes itself by focusing on Northeast China as an integrated historical-industrial region, rather than isolated cities or individual heritage types. The primary contribution of this study is regional and analytical, providing a long-term,

stage-based interpretation of spatiotemporal industrial heritage evolution within a unified geopolitical and industrial context. Additionally, various factors influencing the temporal and spatial distribution of industrial heritage are explored from different perspectives. This analysis aims to provide a clearer understanding of the factors influencing the historical distribution of industrial heritage in Northeast China. Finally, based on the findings and research progress, targeted recommendations are provided to contribute to the regional conservation, renewal, and transmission of industrial heritage in Northeast Chinese cities.

2. Data Sources and Research Methods

2.1. Study Area

The study area of this research is defined based on the *Revitalization Plan for Northeast China* issued by the National Development and Reform Commission and the Office of the Leading Group for the Revitalization of Old Industrial Bases in 2011, which includes Liaoning Province, Jilin Province, Heilongjiang Province, and Inner Mongolia's Hulunbuir, Xing'an League, Tongliao, Chifeng, and Xilin Gol League (Eastern Inner Mongolia). (<https://www.ndrc.gov.cn/>) The total area is 1.45 million square kilometers (D. Liu et al., 2020), with 39 cities. The region exhibits certain similarities in climate, topography, economic conditions, and evolutionary development patterns (Mei et al., 2006b), which is why it is commonly studied as a unified entity (Zhang et al., 2021). Northeast China's northern and western borders are with Russia and Mongolia, and the southeastern border is with North Korea.

2.2. Data Sources

The dataset of 635 industrial heritage sites was compiled from two complementary sources. Officially recognized sites were obtained from national and provincial industrial heritage lists: *National Industrial Heritage List (1st-5th batches)* (<https://www.gov.cn/>), the *Heilongjiang Industrial Heritage List* (<https://gxt.hlj.gov.cn/>), the *Jilin Industrial Heritage List* (<http://gxt.jl.gov.cn/>), and the *Liaoning Industrial Heritage List* (<http://gxt.ln.gov.cn/>), ensuring institutional validity. Additional sites were identified through authoritative historical monographs on modern Chinese industrial development. The literature sources for information conversion include *A History of Modern Chinese Industry* by Zhu Cishou, *A History of Modern Chinese Industrial Development (1840–1927)* co-authored by Fan Xicheng and Lu Baozhen, *Materials on Modern Chinese Industrial History Volumes 1–4* edited by Chen Zhen and Yao Luo, and *A History of Modern Chinese Railways* edited by Yang Yonggang, among others. These sources were cross-referenced to avoid duplication and to improve temporal and spatial completeness. For sites derived from historical literature, establishment dates and functional attributes were verified through multiple textual sources where possible, and only sites with clearly identifiable locations and approximate founding periods were retained. The temperature, elevation, resource, railway, and river data for Northeast China are sourced from the Geospatial Data Cloud (<http://www.gscloud.cn/sources/>) and the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>).

2.3. Research Methods

2.3.1 Kernel Density Analysis

Kernel density estimation can effectively reflect the distribution density and clustering state of industrial heritage in Northeast China, and can explore its evolutionary patterns through temporal slicing. The corresponding formula is as follows:

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

Where k is the kernel function; X is the location of the industrial heritage target point; X_i is the location of the i -th important industrial heritage within a spatial range centered at x with a radius of h ; m is the number of significant industrial heritage sites. The choice of h in the formula affects the smoothness of the kernel density estimation (Ge et al., 2024).

2.3.2 Trend Surface Analysis

Trend surface analysis is a method that uses global polynomial functions to fit a mathematical model to spatial sample point values. Notably, converting two-dimensional spatial sample point data into three-dimensional visual smooth curves reflects the spatial variation of geographic features. This study uses trend surface analysis to express the trends in the distribution of industrial heritage in Northeast China across different time periods. $Z_i(x_i, y_i)$ represents the true observed value of the i -th geographic feature, while $T_i(x_i, y_i)$ represents the fitted value of the trend surface. The corresponding formula is as follows:

$$z_i(x_i, y_i) = T_i(x_i, Y_i) + \varepsilon_i$$

In the equation, (x_i, y_i) are the geographical coordinates, and ε_i represents the deviation between the true value and the fitted value.

2.3.3 The Nearest Neighbor Index

The nearest neighbor index is used to determine the distance between the centroid of each object point in a spatial unit and the centroid position of its nearest neighboring object point. This index is crucial for studying the spatial distribution types of point features in geography (uniform, random, or clustered). The calculation formula for this index is as follows:

$$E = \frac{\bar{r}_1}{r_E} = \sqrt[2]{D}$$

In the equation, E is the nearest neighbor index, r_1 is the average nearest neighbor distance between features, r_E is the theoretical average nearest neighbor distance between features, and D is the point density. When $E = 1$, it indicates a random spatial distribution of point features. When $E > 1$, the point features tend to be uniformly distributed. In contrast, when $E < 1$, the point features exhibit a clustered distribution pattern.

2.3.4 Standard Deviation Ellipse

The Directional Distribution (Standard Deviation Ellipse) tool in ArcGIS calculates the standard deviation of the x and y coordinates from the mean center to define the long and short axes of the ellipse. It can create a standard deviation ellipse based on sample points to determine whether the feature distribution is elongated and summarize spatial characteristics such as central trend, dispersion, and directional trends of geographic features based on its specific direction.

2.3.5 Voronoi Polygon Analysis and Coefficient of Variation

Voronoi polygon analysis is a statistical analysis of the distribution of spatial centroids, classifying the distribution of centroids into three categories: random, dispersed, and clustered, based on the results of the statistical analysis (Zhang, Cenci, et al., 2022). The analysis parameter is the coefficient of variation (C_v), which can be used to measure the distribution of point features, and is calculated as follows:

$$C_v = \frac{\sigma}{A}$$

In the formula, σ and A represent the standard deviation and mean of the Voronoi polygon area, respectively. When $C_v < 33\%$, point features are evenly distributed; when $33\% \leq C_v \leq 64\%$, point features are dispersed; when $C_v > 64\%$, point features are clustered. (Duyckaerts & Godefroy, 2000)

3. Results

3.1. Evolution characteristics of industrial heritage distribution in the time dimension

Each industrial heritage site was assigned to a decadal time slice based on its initial construction or earliest documented operation date. When exact years were unavailable, approximate decades were determined according to historical records and secondary literature. These decadal slices were then used as the basic temporal units for kernel density and other spatial analyses (Figure 1). While the spatial analyses were conducted using decadal time slices, these slices were subsequently interpreted within five broader historical stages derived from major political, economic, and industrial transitions in Northeast China. Each historical stage therefore represents an interpretive synthesis of multiple adjacent decades, rather than a replacement of the decadal analytical framework.

The Period of Initial and Germination (1900-1945)

After the signing of the Chinese Eastern Railway Contract in 1898, Russia, under the pretext of constructing the Chinese Eastern Railway, established railway-affiliated factories, locomotive repair shops, and other industrial facilities in Harbin, Manzhouli, and other places. Post the 1905 Russo-Japanese War, Japan supplanted Russian influence in the Northeast, founding the South Manchuria Railway Company to operate industries including railways, mining, and steel production. The Northeast of China, abundant in coal and iron ore, laid the groundwork for heavy industry development, while its expansive territory and broad plains provided natural advantages for erecting large-scale industrial complexes and railway systems. Consequently, Japan and Russia utilized these favorable conditions to aggressively develop industries in Northeast China, exploiting resources and aiding their military and economic expansion.

The industrial heritage from this era largely consisted of colonial industrial remnants, predominantly controlled and managed by Japan and Russia, with industrial arrangements and orientations designed to fulfill the economic interests of the colonizers. Light industry development lagged behind. The late Qing government introduced new policies aiming to rejuvenate the Northeast economy through industrial initiatives, yet with limited effectiveness. In the Republic of China period, the Northeast local government, spurred by external economic influences, advanced local industrialization somewhat by fostering military, railway, and other industrial sectors.

The architectural style of this period's industrial heritage was markedly influenced by Japanese and Russian colonial cultures, displaying an eclectic style that merged Russian and Japanese architectural features, predominantly characterized by Russian brick-wood constructions and Japanese reinforced concrete frameworks, complemented by classical adornments like arched windows and Roman columns. Simultaneously, the technological transfer introduced modern structures such as large-span factory buildings and functional designs. The industrial heritage from this era bore pronounced militaristic traits, featuring sturdy structures integrated with defensive designs to cater to military requirements, and was replete with colonial symbols in its decorative elements, alongside some level of localization.

The Period of Vigorous Development (1946-1957)

During this period, the People's Government took over the industries in Northeast China, focusing on developing heavy industries such as machinery manufacturing and automobile manufacturing, and building new industrial bases for China. Following the establishment of the People's Republic of China in 1949, a three-year economic recovery period followed. In this context, the Northeast region's economic conditions, resource richness, industrial base, and geographic position offered distinct advantages, designating it as the prime location for heavy industrial development under the First Five-Year Plan, and marking the start of extensive industrial growth.

Throughout the First Five-Year Plan, China surmounted constraints in resources, funding, and technology, focusing on 156 major industrial projects supported by the Soviet Union, and concurrently initiating more than ten thousand construction projects for industrial and mining enterprises. Among these, in the Soviet-aided projects, 58 projects in the Northeast region were fully or partially completed and put into operation, becoming the focal point of China's industrial development during this period. Ultimately, Liaoning Province, with the three major projects in Anshan at its core, signaled the successful initiation of the First Five-Year Plan; Jilin Province, centered on Changchun's automobile industry, developed an industrial framework primarily consisting of heavy industry sectors like power and chemical industries; Heilongjiang Province, beginning with the three major power initiatives in Harbin, had energy raw materials, equipment manufacturing, and heavy and chemical industries as its defining characteristics.

In the early part of this period, buildings predominantly used reinforced concrete frame structures, with factory designs emphasizing pragmatism, simple facades, and locally retaining elements of Japanese industrial architecture such as sloped roofs and arched windows. Soviet-aided projects introduced a socialist style, with factories often adopting standardized designs, emphasizing symmetrical axial layouts, brick facades adorned with decorative moldings, and adding political symbolic elements like columns or reliefs at entrances. The design of industrial zones incorporated the unit compound model, with associated worker residences featuring Soviet-style pitched-roof red brick structures, forming an integrated production-living environment. Technologically, it exhibited mixed characteristics, reflecting the historical process of

Northeast China's transition from a colonial industrial system to socialist industrialization, embodying both technological historical value and ideological imprints.

The Period of Overheating and Adjustment (1958-1965)

From 1958 to 1965, China embarked on large-scale economic construction nationwide. The Northeast, as China's heavy industrial base, shouldered the responsibility of national industrialization, while also experiencing the economic overheating brought by the Great Leap Forward movement and subsequent adjustments. In this era, the Northeast region aggressively expanded into emerging sectors like petroleum and chemical industries, producing exemplary workers epitomized by Wang Jinxi, and generating a multitude of industrial legacies exemplified by Daqing Oil Field, Fushun Petroleum Refinery, and Jilin Chemical Industry Company, propelling the socialist industrialization forward.

Analysis of time slices from nuclear density reveals that the industrial distribution in the Northeast region during this era progressively extended from conventional transportation centers like Shenyang and Harbin to resource-abundant zones such as Daqing and Fushun, with industrial infrastructure development frequently executed through large-scale mass campaigns. In this era, as Soviet aid waned, Northeast industry started to pursue self-reliant technological advancements. Industrial structures and installations stressed functionality and efficiency, while also carrying a pronounced political propaganda tone, serving as a significant testament to China's socialist development. In this epoch, Northeast industry, centered on heavy industry, prioritized the growth of nascent sectors like petroleum and chemical industries, and, driven by the Great Leap Forward, embodied the period's hallmark of extensive construction. Despite the economic overheating and resource squandering induced by the Great Leap Forward, the introspection and enhancements during the readjustment phase established the groundwork for the sustainable progression of Northeast industry, marking a pivotal juncture in the region's industrialization journey (Ma et al., 2024).

The industrial heritage architecture and facility styles of this era displayed the persistence and streamlining of socialist realism, maintaining the integrated production-living community design of factory zones, where industrial elements like chimneys, water towers, and ventilation ducts evolved into minimalist iconic emblems, serving both practical and emblematic purposes. Meanwhile, local technological innovations gave rise to highly localized functional designs, with architectural techniques emphasizing adaptation to local conditions, and structural innovations began to emerge.

The Period of Twists and Transformation (1966-1985)

From 1966 to 1976, Northeast industry, as the nation's heavy industrial base, was impacted by political movements, disrupting production order, stagnating technological innovation, and causing some factories to halt or reduce production. Industrial development was once disrupted, but the Northeast's military and heavy industries maintained some growth due to national strategic needs, especially in the defense industry sector. On this foundation, Northeast China contemplated its developmental status quo and initiated industrial adjustments and technological upgrades, laying the groundwork for industrial growth in the initial phase of reform and opening. Post the 1978 reforms, Northeast industry embarked on a shift from a planned to a market economy, progressively incorporating foreign investment and technological improvements. The industrial legacy from this era embodies both the large-scale and centralized traits of the planned economy and the early reform period's technological imports and market-oriented experiments.

During this period, the light industry in Northeast China experienced rare development, giving birth to famous light industrial heritages such as Changchun Film Studio and Harbin Linen Factory. The industrial heritage from this era mirrors the convoluted path and transformative exploration of China's industrial advancement, with the spatial distribution framework of industrial heritage in Northeast China largely taking shape.

Influenced by the political environment of the time, industrial architecture further weakened decorative elements, turning to minimalism, only strengthening ideological expression through political symbols such as slogans. The architectural layout continued the row-style arrangement, but the planning of production and living areas became tighter, forming closed communities. Factory area planning added storage and logistics functional areas, and worker housing saw the emergence of the prototype of unit buildings. During this phase, industrial edifices commonly utilized a blend of brick-

concrete structures and prefabricated concrete elements, with some industrial constructions starting to incorporate lightweight steel frameworks and extensive glass facades. Notably, the architectural hallmarks of the pseudo-Manchukuo era, like sawtooth roofs and arched portals, largely vanished during this time, supplanted by new industrial motifs such as square skylights and revealed concrete frameworks.

The Period of Pattern Formation (1986-2003)

In 1986, the Chinese government introduced the Seventh Five-Year Plan, which focused on the technological transformation and industrial upgrading of old industrial bases. The government promoted the modernization of Northeast China's industries through policy support and financial investment. In the late 1980s, China's reform and opening-up entered a phase of deepening. Northeast China, as an old industrial base, was included in the national strategy for external opening. Against the backdrop of state-owned enterprise reform, some state-owned enterprises in Northeast China underwent shareholding reforms and market transformation. Meanwhile, the private economy gradually grew and strengthened. Traditional industries in Northeast China, such as steel, machinery manufacturing, and coal, underwent large-scale technological upgrades and equipment transformations during this period. As reform and opening-up progressed, Northeast China began developing high-tech and emerging industries such as electronics, biotechnology, and new materials. In the 1990s, with the acceleration of global economic integration, industries in Northeast China faced both competition and opportunities in the international market. This period saw new development opportunities brought by reform and opening-up, leading to structural adjustments in Northeast China's industries, with high-tech industries and modern services experiencing rapid growth. However, most of the industrial buildings and facilities created during this period are still in use and have not undergone the heritage process. Consequently, the number of industrial heritage sites from this period is relatively small, and by this time, the spatial distribution pattern of industrial heritage in Northeast China was essentially formed.

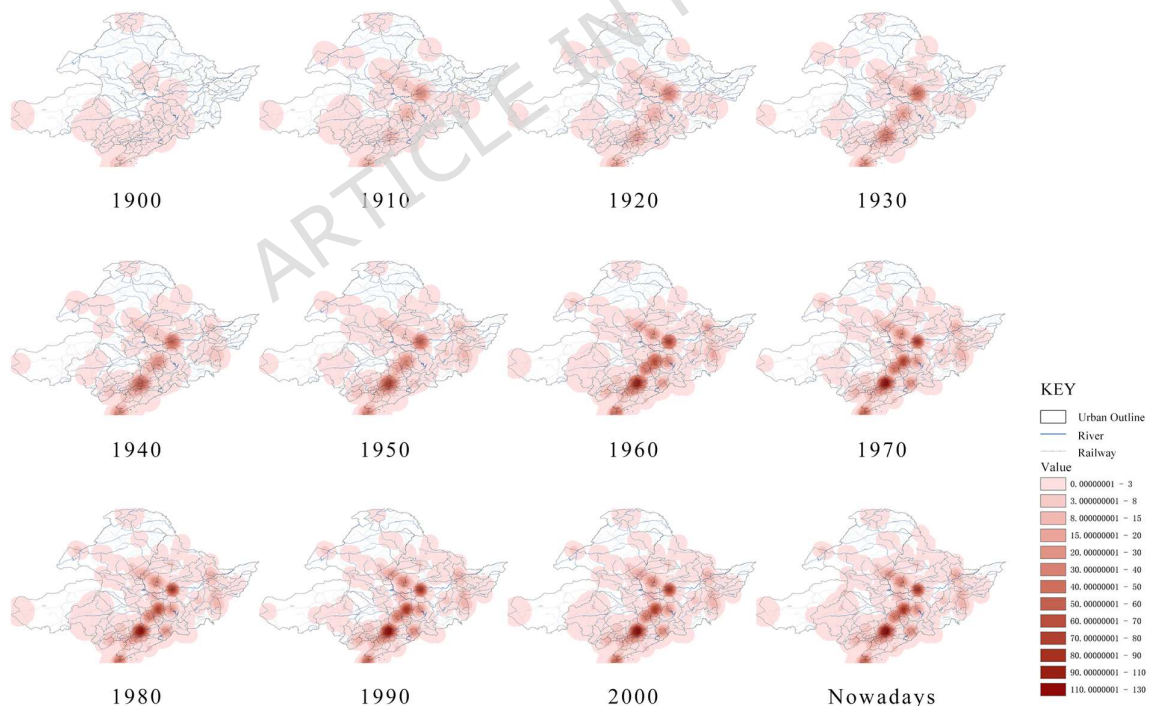


Figure 1. Kernel Density Analysis of Industrial Heritage in Northeast China

3.2. Evolution characteristics of industrial heritage distribution in spatial dimension

3.2.1 Spatial Agglomeration Characteristics

As shown in Table 1, with the passage of time, the number of industrial heritage sites has increased, and the average

observation distance typically shows a decreasing trend. The shortest distance appeared after 2000, while the longest average observation distance occurred before 1900. When the nearest neighbor ratio is less than 1 and the Z-score is below 0, it indicates that the spatial distribution of industrial heritage in this period is in a clustered state. However, over time, the degree of concentration in the spatial distribution of industrial heritage also changes, and data analysis indicates that this change is almost unidirectional. Before 1900, the spatial distribution of industrial heritage in Northeast China exhibited the lowest degree of concentration, suggesting that industrial heritage was most dispersed during this period. Afterwards, with the development of modern industry, industrial heritage began to cluster, and the trend became increasingly evident. From before 1900 to after 1930, the nearest neighbor ratio of industrial heritage in Northeast China decreased from 0.67 to 0.31. From before 1900 to after 1950, the Z-score of the spatial distribution of industrial heritage in Northeast China rapidly dropped from -4.18 to -30.21, then gradually continued to decrease. The continuous decline in the nearest neighbor ratio and the increasingly negative Z-scores indicate not only a growing spatial concentration of industrial heritage, but also a transformation in industrial location logic over time. In the early stage, industrial sites were relatively dispersed, reflecting exploratory development under limited transportation infrastructure and fragmented industrial organization. With the acceleration of industrialization after 1900, industrial facilities increasingly clustered around transport corridors, resource bases, and emerging industrial cities, leading to a rapid increase in spatial agglomeration. After the 1950s, although the overall clustering level remained high, the rate of concentration slowed, suggesting that the basic spatial framework of industrial development in Northeast China had largely stabilized. From 1900 to 1950, the rapid concentration of industrial heritage corresponds to the period of colonial industrial expansion followed by state-led socialist industrialization, during which industrial development was highly centralized and project-oriented. After this period, subsequent industrial construction largely reinforced existing industrial centers rather than generating new clusters, resulting in a slower pace of further spatial concentration. The Voronoi polygons of the industrial heritage point distribution were generated using the Thiessen polygons tool and then clipped using the administrative boundaries of Northeast China as the clipping feature. The area of each polygon was calculated, yielding an average area of 5129.51 km², with a standard deviation of 15162.47 and a coefficient of variation significantly greater than 64%. This further supports the conclusion that the industrial heritage distribution in Northeast China is clustered, consistent with the earlier findings (Figure 2).

Table 1. The Nearest Neighbor Index

Period	Average observation distance (km)	Expected average distance (km)	Nearest neighbour ratio (R)	Z score	P	Distribution pattern
Before 1900	58.649	87.442	0.67	-4.18	0	Cluster
1900s	27.560	52.726	0.52	-7.01	0	Cluster
1910s	17.670	47.239	0.37	-16.64	0	Cluster
1920s	13.787	40.613	0.34	-20.49	0	Cluster
1930s	11.315	36.380	0.31	-24.62	0	Cluster
1940s	10.576	34.248	0.31	-26.45	0	Cluster
1950s	9.459	30.241	0.31	-30.21	0	Cluster
1960s	9.333	29.323	0.32	-30.97	0	Cluster
1970s	9.249	28.916	0.32	-31.34	0	Cluster
1980s	9.095	28.909	0.31	-32.09	0	Cluster
1990s	8.938	28.648	0.31	-32.51	0	Cluster
After 2000	8.960	28.324	0.32	-32.67	0	Cluster

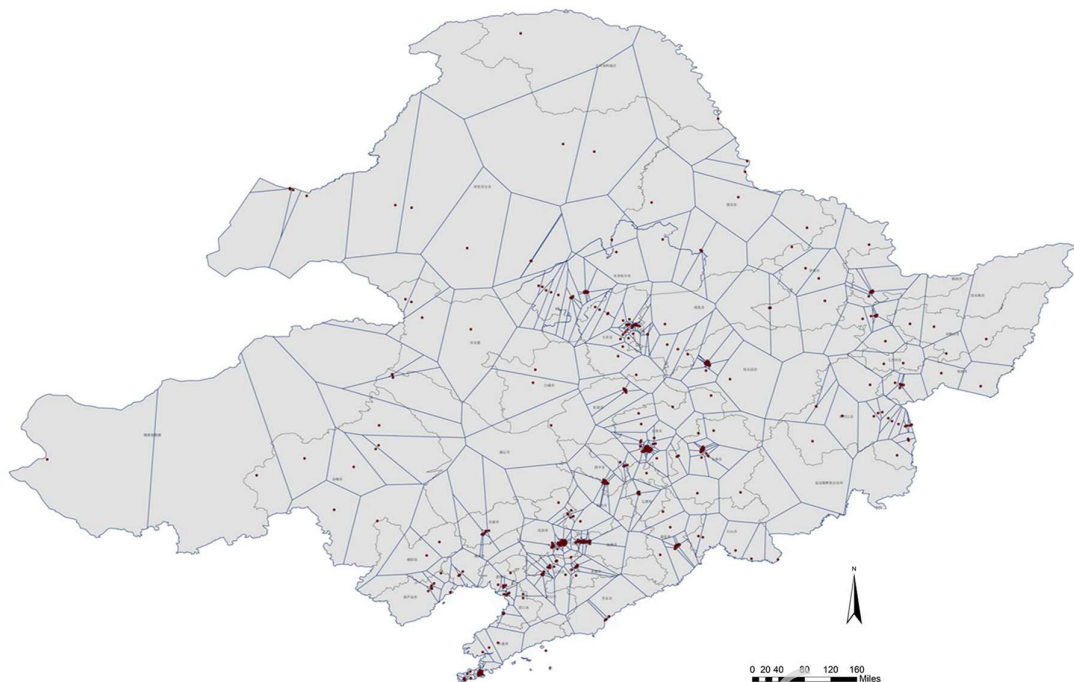


Figure 2. Voronoi Polygon Analysis of Industrial Heritage Point Distribution in Northeast China

3.2.2 Spatial Direction Characteristics

Since 1900, factors such as social structure, political policies, resource utilization, and cultural dissemination have led to significant changes in the quantity and spatial location of industrial heritage, resulting in differences in the centers of industrial heritage distribution across different historical periods. As shown in Figure 3, this study analyzes the shift in the center of industrial heritage over different time periods using the standard deviation ellipse analysis model. The results show that between 1900 and 2000, the spatial center of industrial heritage distribution experienced a directional shift from railway corridors to resource-rich areas and subsequently back toward major transportation axes. This cyclical movement reflects changes in the dominant drivers of industrial development across different historical stages. In the early 20th century, railway construction functioned as the primary organizing framework of industrial expansion. During the period of intensive resource exploitation in the socialist industrialization phase, large-scale mining and energy projects temporarily reoriented industrial development toward resource-rich zones. With the deepening of reform and industrial restructuring, transportation accessibility again became a decisive factor, leading to a renewed concentration along railway corridors. Before the 20th century, the center of industrial heritage distribution in Northeast China was located in areas such as Liaoning Province, which are closer to the central part of China. In the early 20th century, with the growth of colonial industry, the Middle East Railway and South Manchuria Railway were progressively constructed. A large-scale railway network was developed in Northeast China, along with the construction of many associated industrial facilities, such as railway-affiliated factories and locomotive repair plants. As a result, railway corridors acted not only as transportation infrastructure but also as spatial anchors for industrial clustering, shaping the long-term linear distribution pattern of industrial heritage in Northeast China. Later, with the establishment of the People's Republic of China, the government took over the railway network in Northeast China and leveraged the existing industrial base to develop heavy industries such as machinery and automobile manufacturing, building the industrial base for the new China. Between 1958 and 1965, China engaged in large-scale economic construction, and Northeast China saw signs of economic overheating, with resource development, led by the Daqing Oilfield, booming. During this period, a large number of petroleum and mining industries emerged, causing the center of industrial heritage distribution to shift slightly toward resource-rich areas. Later, with the deepening of reform and opening-up, technological exchanges became increasingly frequent, and the advantages

of transportation in industrial development were once again emphasized. The center of industrial heritage distribution shifted back to the railway corridor areas.

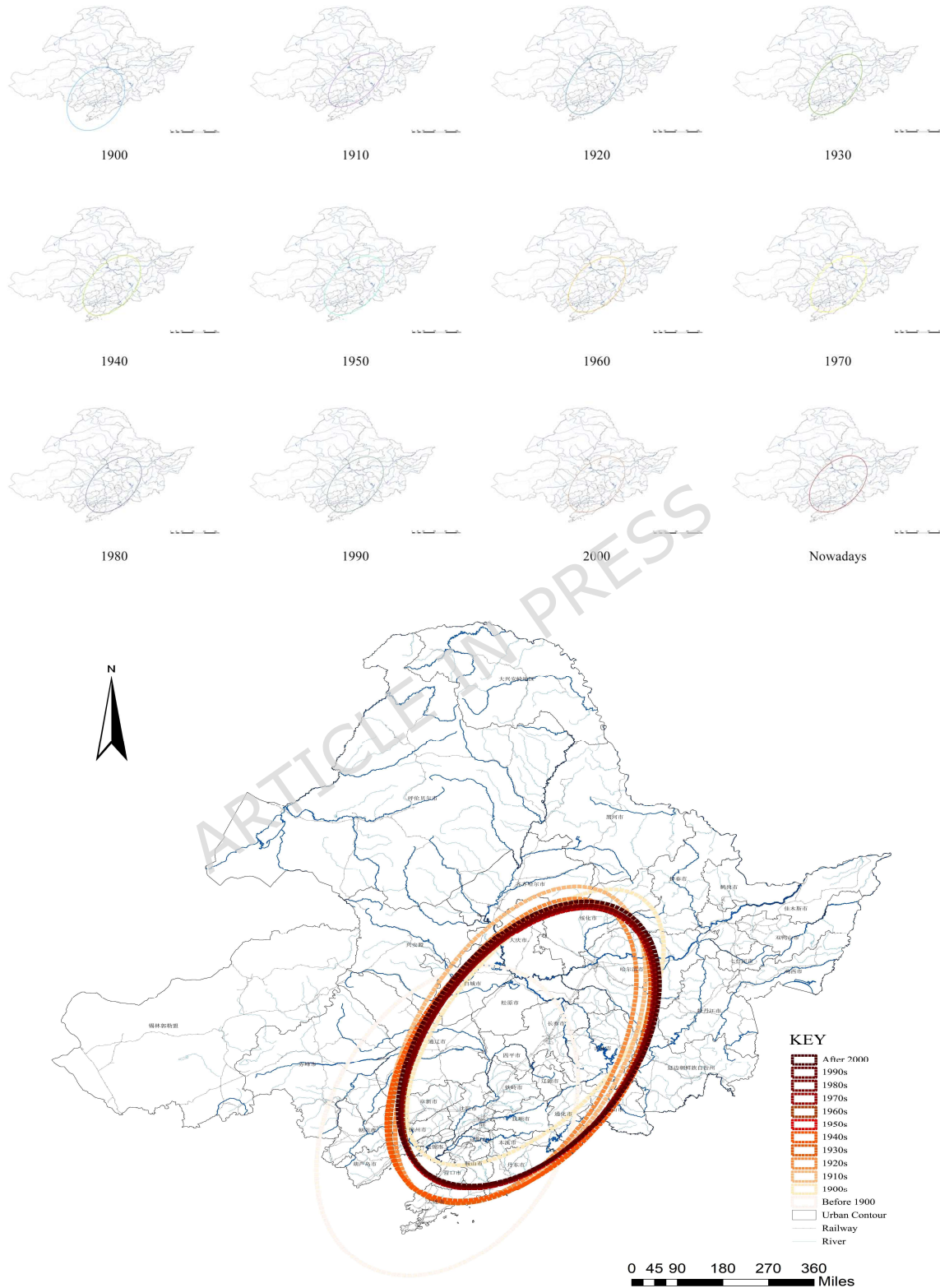


Figure 3. Standard Deviation Ellipse Analysis of Industrial Heritage in Northeast China

3.2.3 Spatial Distribution Characteristics

The surface fitting results of the spatial distribution trends of industrial heritage in Northeast China over different time periods are shown in Figure 4. The X-axis represents the east-west direction, with the positive direction pointing east. The Y-axis represents the north-south direction, with the positive direction pointing north. The Z-axis represents the analysis variable. The curve on the XZ plane illustrates the distribution trend of the analysis variable in the east-west direction, while the curve on the YZ plane shows the distribution trend of the analysis variable in the north-south direction. The observed spatial trends indicate a transition from dispersed, exploratory industrial development toward more centralized and functionally specialized industrial zones. This consolidation reflects the maturation of industrial systems, in which production efficiency, administrative coordination, and infrastructure integration increasingly outweighed frontier expansion and small-scale resource exploitation as dominant locational considerations. In the east-west direction represented on the XZ plane, the number of industrial heritage sites in the eastern region was much higher than in the western region, which is closely tied to the historical background at that time. Afterwards, the number of industrial heritage sites in the western region increased, but by the early 21st century, it remained significantly fewer than in the eastern region. The variation in the number of industrial heritage sites in the north-south direction is quite pronounced. Before 1900, industrial heritage sites were more concentrated in the northern and southern parts of the region, reflecting early industrial development driven by border trade, colonial penetration, and resource-oriented activities along peripheral zones. From 1900 to 1950, the curve on the YZ plane showed a concave shape, indicating that during this period, the number of industrial heritage sites in the central region was fewer than at the northern and southern ends. Between 1900 and 1910, the number of industrial heritage sites in the central region increased significantly, reducing the gap with the northern and southern regions. Although still fewer in number, the gap was no longer as large as before. By 1950, the number of industrial heritage sites in the central region was almost on par with the north and south. By 1960, the central region even surpassed the others in terms of quantity. From 1960 to 2000, the convex pattern along the north-south axis indicates the emergence of central dominance, suggesting a shift toward internally integrated regional development. Central areas with stronger administrative capacity, labor concentration, and infrastructural connectivity became the core zones of industrial accumulation during this stage. This trend was most evident between 1960 and 1980, before it weakened, and the numbers of industrial heritage sites in the north, center, and south became more balanced.

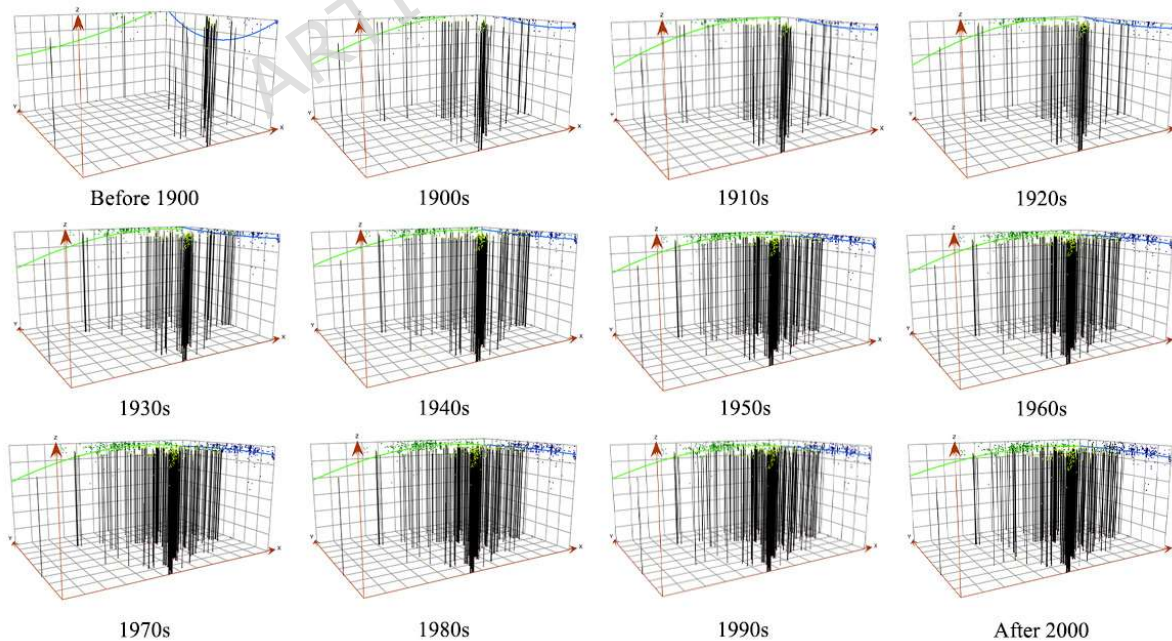


Figure 4. Trend Surface Analysis of Spatial Distribution of Industrial Heritage in Northeast China

3.3. Evolution characteristics of industrial heritage distribution in the dimension of industrial classification

The industrial heritage in Northeast China shows significant differences in industrial types across different provinces (Figure 5). In this study, the industrial heritage types surveyed were categorized in detail. All industrial heritage sites were divided into five primary categories and seventeen secondary categories based on industrial differences. The five primary categories are: Mining and Metallurgy Industry, Civilian Manufacturing Industry, Storage and Transportation Defense Manufacturing Industry, Municipal Infrastructure Construction, and Other. The 17 secondary classifications are: Coal, Metal Mining & Metallurgy Industry, Non-Metallic Mining & Metallurgy Industry (excluding coal), Food & Beverage Industry, Textile Industry, General Manufacturing Industry, Building Materials Manufacturing Industry, Chemical Industry, Bioindustry, Vehicle Manufacturing, Transport Lines, Military Defense, Supporting Facilities, Urban Energy, Urban Water Supply, Urban Telephone Inquiry, and Living Facilities. This classification system is scientifically sound and effectively encompasses the diverse industrial forms of industrial heritage. An analysis of the industrial heritage by province shows that, overall, Liaoning Province, as China's heavy industrial center, has abundant heavy industry resources and a considerable amount of industrial heritage in metal mining and metallurgy. Heilongjiang Province primarily features industrial heritage from the coal, petroleum, and transportation sectors, while Jilin Province is known for automotive manufacturing (such as FAW) and chemical industries. In contrast, the eastern part of Inner Mongolia, having been developed later, mainly holds remnants of transportation and energy industries. The regional differences in the industrial heritage structure are shaped by historical factors, resource distribution, national policies, and geographical and transportation conditions. This demonstrates the dual logic of resource-driven and cultural orientation, where natural resource endowments determine the leading industrial types in each region. For instance, the mining heritage in Heilongjiang and Liaoning is particularly rich, making up a significant proportion of their industrial heritage, owing to Heilongjiang's coal and oil resources and Liaoning's iron ore deposits. Historical backgrounds and corresponding policy directions further differentiate the industrial heritage structures across regions. The coal, steel, and railway networks established during the Russo-Japanese colonial period in Northeast China played a key role in shaping the industrial structure of each province. After the establishment of the People's Republic of China, national strategies reinforced industrial concentration and heritage preservation, designating Northeast China as a heavy industry base. Key national strategic projects such as Anshan Steel in Liaoning, FAW in Jilin, and Daqing Oilfield in Heilongjiang reaffirmed the industrial heritage structure in the region. Building on this, geographical location further shapes the differentiated characteristics of specific sectors. Liaoning, with its proximity to the Bohai Bay port, fostered the development of metallurgy, military industries, and international trade infrastructure. Jilin, located in the heart of Northeast China, boasts abundant agricultural resources, sustaining numerous food, beverage, and light industrial heritage. As an automotive industry hub, Changchun has developed a concentrated cluster of vehicle manufacturing heritage. The eastern part of Inner Mongolia, with its vast, sparsely populated land and rich resources, focused on energy production during modern development, resulting in a high concentration of heritage in railway and urban energy facilities. These multidimensional factors have jointly shaped the current industrial heritage structure of Northeast China.

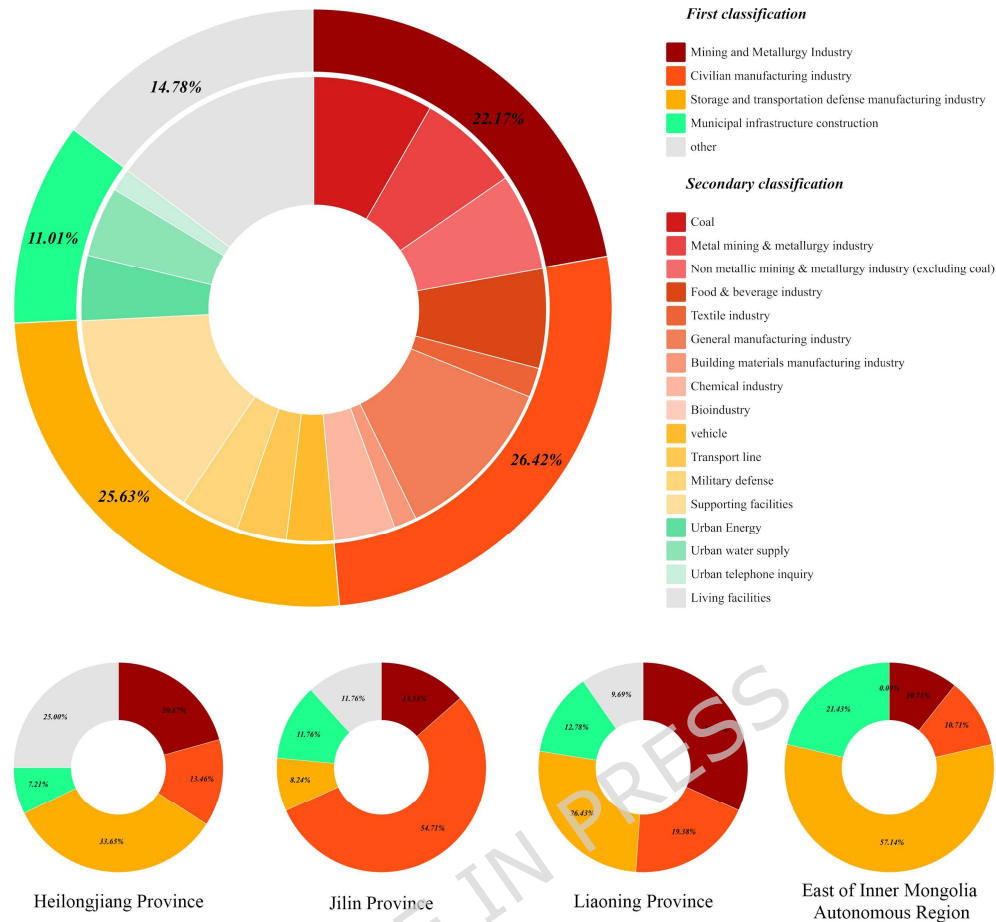


Figure 5. Variations in Industrial Heritage Composition by Sector Across Provinces in Northeast China

Overall, the spatiotemporal patterns revealed by the GIS analyses demonstrate that the distribution of industrial heritage in Northeast China is not the result of random accumulation. Instead, it reflects successive shifts in dominant industrial drivers, including transportation infrastructure, resource exploitation, and state-led policy interventions. These drivers interacted differently across historical stages, producing distinct phases of spatial expansion, concentration, and stabilization.

4. Discussion

Based on the collected industrial heritage data of Northeast China, and employing ArcGIS spatial analysis techniques, the spatial-temporal distribution patterns of industrial heritage in this region were analyzed, resulting in the following analysis findings:

(1) In the temporal dimension, the emergence and evolution of industrial heritage in Northeast China can be broadly divided into five periods. Industrial heritage from the late Qing Dynasty to the Republic of China was significantly influenced by the Japanese and Russian colonial rule. After the establishment of the People's Republic of China, the government took over the industrial sector in Northeast China, focusing on the development of heavy industries such as machinery and automobile manufacturing, leading to a significant surge in industrial heritage. During the Great Leap Forward and the subsequent adjustment period, large-scale economic construction generated a vast amount of industrial heritage related to petroleum and chemicals. Political movements in later years, however, disrupted some industrial development. With the gradual deepening of reform and opening-up and after structural adjustments, the industrial heritage pattern of Northeast China took shape.

(2) In the spatial dimension, from the aggregation characteristics, after 1900, industrial heritage in Northeast China began to show clustering, with this phenomenon becoming more pronounced over time. The analysis of directional trends strongly

supports the idea that the spatial distribution center of industrial heritage shifted noticeably across different historical stages, displaying a movement from the railway lines to resource-rich areas, and then back to the railway lines. As for the spatial distribution features, industrial heritage in Northeast China displays a more in the east, less in the west pattern along the east-west axis, while the north-south direction experienced a transition from more in the south and north, less in the center to less in the south and north, more in the center, finally forming the current pattern where the central region has slightly more industrial heritage than the north and south.

(3) Regarding the types of industrial heritage, Liaoning Province, as China's heavy industrial base, boasts significant industrial heritage in metal mining and metallurgy, thanks to its resource advantages and transportation accessibility. Heilongjiang Province is primarily characterized by industrial heritage in coal, petroleum, and transportation industries. Jilin Province, located in the heart of Northeast China, is abundant in agricultural resources, which supported a large number of food and beverage and light industry heritage. Industrial heritage in the eastern part of Inner Mongolia is mostly related to transportation and energy industries.

The observed spatiotemporal and typological patterns are closely associated with multiple factors, including resources, transportation, policy, climate, and topography.

The Impact of Resource Factors on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

Northeast China has long been recognized as the cradle of China's modern industrialization. According to the distribution of mineral resources and industrial heritage in Northeast China (Figure 6), the distribution of industrial heritage is highly correlated with the region's abundant natural resources. According to statistics (Figure 7), 116 industrial heritage sites are located within 5,000 meters of mineral resource areas, accounting for over one-sixth of the total, which further confirms the aforementioned conclusion. From the late 19th century to the mid-20th century, the coal, iron ore, and petroleum resources in Northeast China played a key role in the rise of heavy industries, including steel, machinery, and energy. Specifically, Anshan developed an advanced iron-making industry due to its iron ore resources, while the discovery of the Daqing Oilfield significantly accelerated the development of China's petroleum and petrochemical industry system. Resource endowments played a significant role in shaping the selection of industrial city locations. As resources were progressively discovered, industrial heritage became increasingly concentrated in resource-rich areas. In the late 20th century, the exhaustion of resources caused some traditional industrial areas to decline, but the remaining mines, smelting plants, and other facilities became the key carriers of industrial heritage. Currently, the industrial heritage of resource-based cities exhibits the characteristics of point clustering and strip extension. For example, the Liaozhongnan Industrial Corridor concentrates a large number of coal and steel-related industrial heritage sites, reflecting the historically resource-oriented logic of industrial development.

Figure 6. Distribution of Mineral Resources and Industrial Heritage in Northeast China

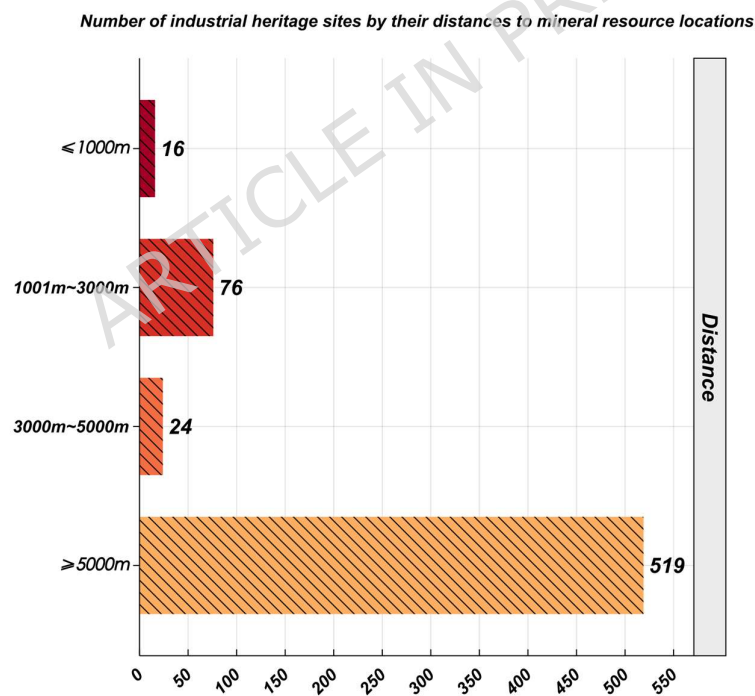


Figure 7. Number of industrial heritage sites by their distances to mineral resource locations

The Impact of Climate Factors on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

An analysis of the regional average annual temperature and the distribution of industrial heritage clearly shows that the harsh climate in Northeast China has had a profound impact on the spatiotemporal distribution of industrial heritage (Figure

8). The long winters (with an average of 6 months of subzero temperatures) and extreme cold (below -30°C) forced early industrial construction to implement special designs, including dense steam heating networks, enclosed factory structures, and underground transport tunnels (such as those in the Fushun Coal Mine), which became common features. Climate conditions also led to seasonal characteristics in industrial production, such as the clustering of industries relying on coal for heating (e.g., power generation and smelting) during winter. Cities such as Harbin preserved many characteristic industrial buildings due to the cold-resistant construction techniques derived from Russian architecture. Additionally, low temperatures may have contributed to slower material degradation processes, which could partially explain the relatively good preservation of some early 20th-century industrial facilities. However, this interpretation remains hypothetical and requires further material-based investigation. However, freeze-thaw cycles have also exacerbated the deterioration of some outdoor facilities, leading to the characteristic distribution of heritage in which indoor facilities are better preserved than outdoor equipment. Climate represents both a constraint on heritage preservation and an important contextual factor contributing to the distinctive characteristics of industrial heritage in Northeast China.

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Figure 8. Distribution of Annual Mean Temperature and Industrial Heritage in Northeast China (2000)

The Impact of Topographical Factors on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

As illustrated in Figure 9, the topographical configuration of Northeast China, with three mountains encircling a central plain, has shaped the distribution pattern of industrial heritage. The Changbai Mountains, Xiao Xing'an Mountains, and other mountain ranges create natural barriers, compelling early industrial development to spread along river valleys and plains. The flat terrain of the Songnen Plain provided ample space for large-scale industrial complexes, such as the automobile manufacturing facilities in Changchun, while the hilly topography of the Liaodong Peninsula led to the formation of stepped mining systems, represented by the Benxi Iron Mine. The Trans-Siberian Railway, in order to surmount the topographical challenges of the Greater Xing'an Mountains, used a zigzag design to ascend the slopes, resulting in a unique collection of railway-related industrial heritage along its route. Mountainous terrain also promoted a resource-driven industrial layout. In the forests of the Greater Xing'an Mountains, the timber processing industry developed along the foothills, creating numerous unique industrial heritage sites. It is also worth noting that in the low-lying Liaoh

Plain, an area vulnerable to flooding, many industrial heritage sites were constructed on artificially compacted high platforms, resulting in a distinctive architectural landscape. In summary, topographical factors have led to the spatial layout of industrial heritage in Northeast China showing a concentrated on plains, dispersed in mountains pattern.

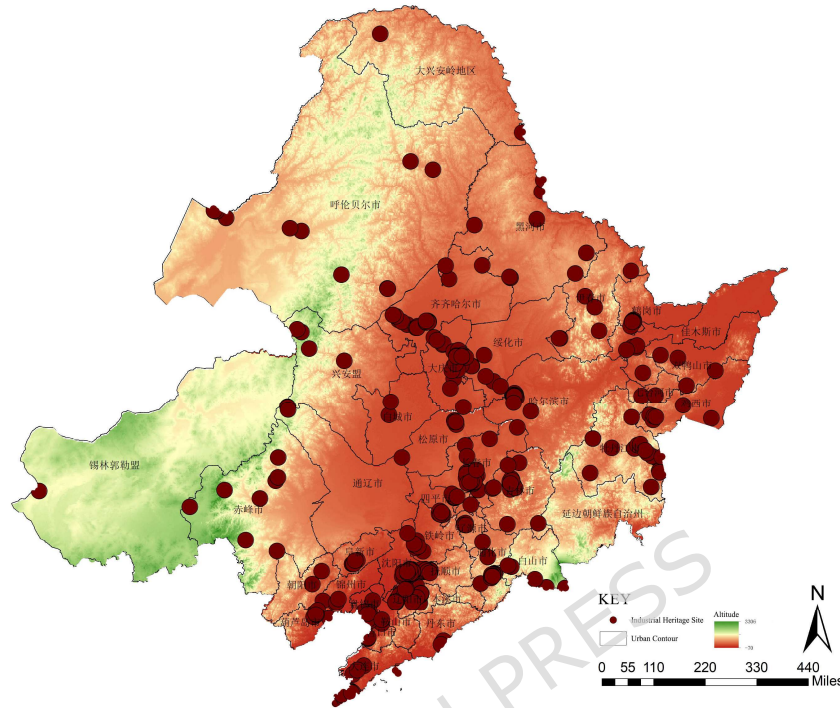


Figure 9. Distribution of Annual Elevation and Industrial Heritage in Northeast China

The Impact of Policy Factors on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

Policy direction has been a major driving force in the spatiotemporal evolution of industrial heritage in Northeast China. The immigration to the frontier policy in the late Qing Dynasty marked the beginning of modern industrialization, while the Manchukuo Iron and Steel system during the Japanese occupation formed the industrial foundation of Northeast China. In the 1950s, the First Five-Year Plan deployed 58 of its 156 key projects to Northeast China, creating iconic heritage sites such as the Shenyang Machine Tool and Changchun Automobile industries. During the planned economy period, the Third Front Construction promoted the spread of industry into the inland areas, resulting in many industrial relics in regions like Tonghua, Jilin. After the reform and opening-up, the restructuring of state-owned enterprises led to the abandonment of numerous factories, giving rise to a distinctive laid-off factory heritage type in the 1990s. In recent years, the Revitalization of Northeast China policy has facilitated the revitalization of heritage, with the Tiexi District in Shenyang developing an industrial heritage corridor through the East-to-West relocation strategy. The changing policies have resulted in a staged accumulation of heritage, with colonial, planned economy, and post-restructuring industrial heritage overlapping spatially. The Shenyang-Harbin-Dalian axis holds the concentration of industrial relics reflecting the imprint of policies from different periods.

The Impact of Water Systems on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

While Northeast China is not a water-rich region on a national scale, the hydrological network in this region has deeply impacted the distribution pattern of industrial heritage (Figure 10). Over half of the industrial heritage sites are located within 5 kilometers of rivers (Figure 11). Major rivers such as the Songhua River and Liao River provided water sources and transportation routes for early industries, leading to the formation of waterfront industrial clusters, such as the three

major power plants in Harbin and the Jilin Chemical Industrial Zone. The Fulao Hydroelectric Station (on the Songhua River) and its supporting power grid infrastructure, constructed during the Manchukuo period, have become key heritage sites. However, seasonal fluctuations in water levels forced factories to construct flood control embankments (such as at the Qiqihar Heavy Machinery Plant), resulting in the creation of a distinctive factory-city embankment system. Water system pollution has caused some heritage sites to shift their functions. For instance, following pollution control at Anshan Steel, the original coking plant area was transformed into an environmentally themed heritage park. The decline of inland waterway navigation has turned riverfront port facilities along the Songhua River (e.g., the Old Jiang Bridge in Harbin) into transportation heritage. Currently, industrial heritage belts along the Liao River-Hunhe River axis and energy heritage clusters along the Songhua River serve as evidence of the historical principle of production determined by water.

Figure 10. Distribution of Water Systems and Industrial Heritage in Northeast China

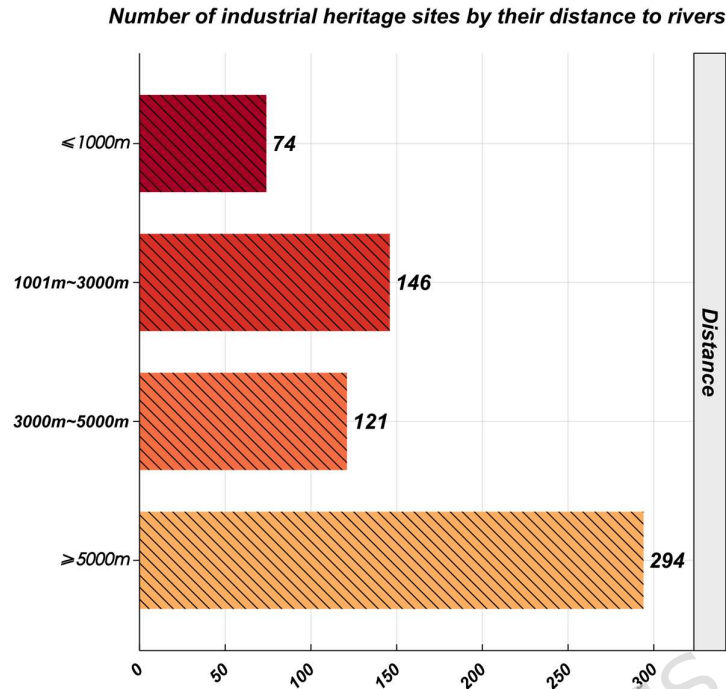


Figure 11. Number of industrial heritage sites by their distance to rivers

The Impact of Railway Transportation on the Spatiotemporal Distribution of Industrial Heritage in Northeast China:

Railway construction forms the core framework of the distribution of industrial heritage in Northeast China. The construction of the Central Manchuria Railway in 1898 marked the initiation of modern industrialization, giving rise to railway heritage like the Harbin Locomotive Depot and Dalian Locomotive Factory along the route. The colonial territory system of the South Manchuria Railway led to the creation of colonial industrial heritage, such as the Anshan Ironworks. The railway network (including the Harbin-Dalian Line, Binzhou Line, etc.) linked coal mines (Hegang), forestry areas (Yichun), and steel cities (Anshan) into industrial belts, with repair shops, freight yards, and other supporting facilities concentrated around the stations. The Soviet-style broad-gauge railway heritage (such as Suifenhe Port Station) bears witness to Sino-Russian industrial technology exchanges. After the founding of the People's Republic, the electrification of railways led to the preservation of steam locomotive depots (such as the Sujiatun Locomotive Depot in Shenyang), which have become unique heritage sites. According to the analysis of the relationship between railway transportation and industrial heritage distribution in Northeast China (Figure 12), it is evident that 89.6% of industrial heritage in the region is located within a 5-kilometer range of railway lines (Figure 13), forming a distinct corridor effect. The Harbin-Dalian railway heritage corridor has become a classic representation of linear cultural heritage.

Figure 12. Spatial relationship between railway networks and industrial heritage distribution in Northeast China

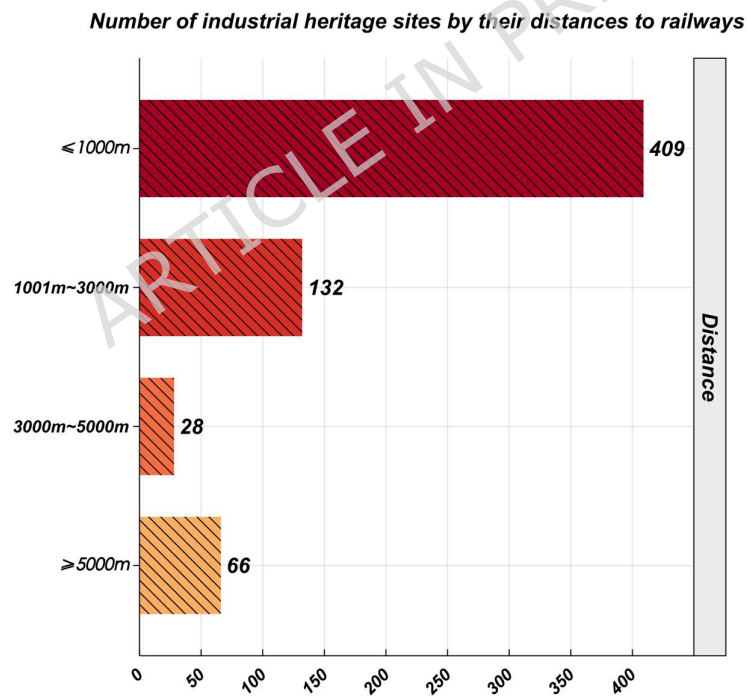


Figure 13. Number of industrial heritage sites by their distances to railways

This study examines the spatiotemporal distribution patterns and influencing factors of industrial heritage in Northeast China, partially addressing gaps in previous research and offering valuable insights for the future value assessment, scientific conservation, and rational use of industrial heritage in the region. However, there are some limitations to the

content. This research primarily relies on industrial heritage data certified by various levels of government in Northeast China, supplemented with industrial heritage data gathered from historical sources. The accuracy of these historical sources can influence the data collection process, and the potential heritage value of industrial heritage not certified within these materials has not been thoroughly evaluated. As a result, while the data is comprehensive, there may be redundancy. Regarding influencing factors, this study does not employ regression-based or geographically weighted statistical models. Given the historical nature of the dataset and the difficulty of reconstructing time-specific environmental variables, the analysis focuses on spatial association patterns and historically informed interpretation. Future research could integrate spatial statistical models to further test these relationships quantitatively. Therefore, we can only rely on existing industrial heritage data and relevant textual and visual information for research and interpretation, which is another limitation in terms of content.

5. Conclusions

Industrial heritage, though a relatively new type of heritage, is equally a valuable part of human history, containing profound historical and cultural significance, with unique artistic, academic, and social value. By observing the dynamic evolution of the geographic locations and industrial structures of industrial heritage in Northeast China during different historical periods, we can effectively reveal the spatiotemporal distribution patterns and influencing factors (Li, 2024). This has significant practical implications for applying and implementing industrial archaeology research projects, as well as for the scientific protection, rational development, and efficient management of industrial heritage in the region. However, over the past century, factors such as neglect in conservation, war-related destruction, and land transactions have caused varying degrees of damage to industrial heritage in Northeast China, with many valuable industrial heritage sites disappearing from history. Among the preserved industrial heritage, the existing trend of urban contraction in the era of limited resources makes rational use and effective updating an inevitable process. In recent engineering practices, despite the government's establishment of relevant protective measures and the introduction of a series of management approaches, the pursuit of economic interests and misalignment of development strategies still lead to over-commercialization, which further damages industrial heritage. Although the country has recognized the value of industrial heritage, started the evaluation and recognition of industrial heritage at the national and provincial levels, and introduced the National Industrial Heritage Management Regulations, establishing a relatively complete system for the protection and renewal of industrial heritage, regional policies for Northeast China remain inadequate. The current state of protection, management, and inheritance of industrial heritage in Northeast China is still dire. Therefore, based on the distinct characteristics and issues of the spatiotemporal distribution of industrial heritage in Northeast China, this study puts forward the following recommendations.

(1) Local governments need to improve industrial heritage evaluation and certification methods, establish more robust protection mechanisms and regulations, increase funding for industrial heritage protection and renewal, balance urban planning with heritage resources in the context of urban renewal, take into account both economic growth and cultural communication, cultivate highly skilled researchers and technical professionals, actively apply for heritage projects, and work to strengthen both domestic and international influence in the context of Northeast revitalization, ultimately creating a more comprehensive discourse framework for industrial heritage.

(2) Based on the results of kernel density analysis, trend surface analysis, and spatial clustering analysis of industrial heritage in Northeast China, industrial heritage resources in the region should be categorized into high, medium, and low-density areas. The development of heritage corridors should be promoted, with an emphasis on breaking regional administrative barriers. Through regional cooperation, the protection and renewal of industrial heritage can be synergized, with each province utilizing its unique industrial heritage advantages. The development of industrial heritage tourism routes will jointly promote industrial transformation and upgrading in Northeast China.

(3) The development of industrial archaeology should be strongly promoted, with the active application of advanced technologies such as multi-source data and XR to assist in the protection and renewal of industrial heritage in Northeast

China. An H-GIS industrial heritage database should be established to integrate various information sources, create digital archives, and set up expert platforms. These will propose development policies and renewal strategies based on the specific characteristics and challenges of industrial heritage in Northeast China.

Industrial heritage stands as a witness to China's industrial history and a gem of industrial culture. With the backing of the current Northeast revitalization policy, in the context of stock renewal, industrial heritage in Northeast China is playing an increasingly vital role in urban life and cultural dissemination. The research in this field has been abundant, and engineering practices are flourishing (Yao et al., 2024; Zhang et al., 2024b). However, we must acknowledge that when it comes to the protection and renewal of industrial heritage (Zhang et al., 2020b), as well as the construction of the discourse on China's industrial heritage, much remains to be done.

Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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Ethical approval and informed consent

This article does not contain any studies with human participants performed by any of the authors.

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