A Review and Implications of Industrial Spatial Transformation Research Under the Trend of Machine Substitution

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Abstract：With the advent of the digital-intelligent era, the human-machine relationship is undergoing structural reorganization, giving rise to a new paradigm of human-space relationship. This transformation is reshaping both technological and social spatial frameworks, and is particularly prominent in the development and evolution of industrial space. From a techno-industrial perspective, this study systematically reviews the evolutionary trajectory of human-machine relationships. It argues that when machines acquire spatial agency, their geographical distribution will exhibit scenario-specific patterns, thereby necessitating adjustments to urban industrial spatial order. Contemporary research frontiers primarily focus on the spatial implications of machine substitution regarding employment displacement and regional pattern evolution, the transformation of industry-city relationships, and the intelligence of industrial space. However, a critical gap remains in the systematic thinking about emerging spatial paradigms. In response to technological trends and practical needs, this research proposes establishing a collaborative spatial analysis framework integrating the dimensions of "human—machine—land—industry," and identifies three priority research directions: Investigating human-mach

Keywords: human-machine relationship; machine substitution; industrial spatial transformation; spatial paradigm

Technological progress exerts complex and far-reaching impacts on urban spatial development. Whenever new technologies emerge and achieve large-scale industrial application, the relationship between humans and machines undergoes adjustment and reorganization through the bidirectional interaction between technological systems and social systems, projecting onto the intrinsic organization and external morphology of urban space. Early urban theorists such as Mumford [1] integrated technological progress with urban development research, arguing that "the true technological revolution lies not in machine innovation, but in reconstructing the organic connection between technology and humanity," providing an important "technological history perspective" for examining urban development history. Today, new-generation information technologies, artificial intelligence, and other technologies are pushing human society to the critical point of production system transformation, with human-machine relationships once again facing major adjustments. While new technologies significantly enhance productivity, they also give rise to intelligent production spaces [2] and trigger strong social concerns about "machine substitution" (i.e., machines replacing human job positions). Faced with new production modes, labor mobility trends, and spatial characteristics of industrial chains, there is an urgent need for new spatial supply and adaptation strategies [3]. Therefore, taking machine substitution as an entry point to review relevant research on the evolutionary trends of industrial space is an important perspective for exploring the spatial organization principles and mechanisms of future cities driven by new technologies.

1. Background: Technological Trends and Spatial Challenges of Machine Substitution

1.1Technological Spectrum and Stage Characteristics of Machine Substitution

The Industrial Revolution marks the starting point of modern human economic and social structure, initiating the systematic and large-scale replacement of human labor by machines. From a historical perspective, the substitution of machines for humans can be broadly divided into four stages.

(1) Tool enhancement stage (pre-Industrial Revolution): In agricultural societies, mechanical devices existed as physical extensions of human organs, where humans designed and controlled mechanical apparatuses or borrowed natural forces such as wind and water to amplify certain physiological functions such as physical strength or endurance. Although the complexity of different mechanical devices varied, their essence was fundamentally no different from the lever invented and used by Archimedes.

(2) Power substitution stage (first and second Industrial Revolutions): The invention of steam engines and electrical systems enabled human social production to break through the ceilings of human power, animal power, and natural energy. The shortcomings of insufficient human and animal power were compensated, and the defects of insufficient sustained and stable natural energy were overcome. On this basis, mechanical systems obtained independent power sources, and the energy value of human labor was almost completely replaced by machines. The value of humans shifted more toward technical domains, marking the first emergence of a relatively clear division of labor between humans and machines.

(3) Information control substitution stage (third Industrial Revolution): The invention of vacuum tubes and electron tubes provided the possibility of "controlling strong currents with small voltages" [4]. Supported by the von Neumann architecture [5], machines could not only complete standardized operation processes according to preset instructions, but also achieve direct information interaction between machines and machines. Among the human labor force, the demand for blue-collar workers declined, and they increasingly shifted from operator roles to monitor roles.

(4) Thinking and decision-making capability substitution stage (artificial intelligence technology stage): Driven by technologies such as big data analysis and deep learning, machines broke through the capability limitation of operating along human-set programs and began participating in cognitive-level information processing, forming human-machine collaborative decision-making capabilities through real-time interaction with humans. The division of labor between humans and machines began to tilt further toward machines. With the development of technologies such as brain-computer interfaces, it is not excluded that in the future a state of deep integration of biological intelligence and artificial intelligence will be formed.

Overall, the technological logic of machine substitution can be divided into two dimensions: first, the substitution of machines for humans gradually progresses from muscle strength substitution to mental substitution, with some scholars [6] thereby dividing it into "the first machine revolution" and "the second machine revolution"; second, the evolution of human control modes over machines, from manual control of machinery to control through program instructions to gradually developing to control through language and consciousness, with some scholars [7-8] proposing concepts such as "the third cognitive revolution" and "the Turing revolution" from the perspective of human cognition. See Figure 1.

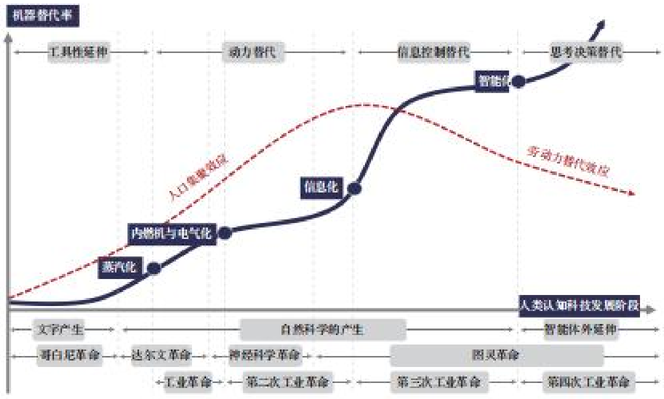

Fig.1 The overall historical process of machine substitution

1.2Evolutionary Trends of Human-Machine Division of Labor from the Perspective of Technology Philosophy

The human-machine relationship has generally experienced several developmental stages: instrumental theory, partnership theory, and symbiosis theory. In the instrumental theory stage, machines were viewed as extensions of tools used by humans. In the human-machine partnership theory stage, machines were no longer seen as completely passive tools, but rather had capabilities surpassing humans in certain aspects and formed a division of labor with humans, such as the proposal of technical concepts like "human-machine collaborative computing" [9]. Currently, artificial intelligence has successfully crossed the technological inflection point from "unusable, not easy to use" to "usable" [10] and entered the technological form of intelligent machines [11]. Intelligent machines not only imitate human behavior but can also simulate human thinking and consciousness, causing the boundary between "human" and "human-like" to become further blurred [12]. Norbert Wiener, the founder of cybernetics [4], believed that the relationship between humans and machines should not merely be human control over machines, but rather mutual collaboration and symbiosis, pointing out that the most important relationship in human society would become the relationships between humans and machines, between machines and machines, and between humans and humans.

However, whether one holds an optimistic or pessimistic attitude toward the development of artificial intelligence technology [13], machine substitution is almost an irreversible trend. As the subjects of labor division expand from a single subject of humans to the collaborative division of labor of human-machine dual subjects, human-machine division of labor has become an important manifestation of the fourth major social division of labor [14]. In the process of human-machine division of labor, two paradoxical effects (also known as "co-opetitive symbiosis" effects) of "machine replacing humans" and "machine augmentation" (also known as "human-machine mutual assistance") often coexist [15]. Overall, compared with the direct binary opposition between humans and machines in the era of large-scale machine industry, intelligent mechanical devices indeed play an important role as "liberators," to a certain extent liberating "humans," but workers at any time face the risk of being replaced by intelligent machines [16].

1.3Necessity of Spatial Turn in Machine Substitution Research

Large-scale machine industry constitutes the productivity foundation of modern urban development and has also played a decisive role in constructing urban planning thoughts and patterns and shaping spatial morphology. Generally speaking, industrial zones are spatial venues where machine substitution is most prominently concentrated. However, when machines lack autonomous capabilities, the agglomeration of machines and the agglomeration of industrial population occur synchronously. Therefore, for a considerable period of time, although machines had a certain substitution effect on humans (mainly power substitution), they also created more job positions in the process of industrialization, and the impact on society was relatively controllable.

When machine systems can conduct mutual information feedback and control, human labor begins to leave the blue-collar frontline of production, and the substitution effect of machines on humans begins to surpass the employment population agglomeration effect brought by large-scale machine industry. The explosion of artificial intelligence technology has further exacerbated this trend: in the industrial field, human labor has gradually separated from the production frontline, generating scenarios such as unmanned factories, unmanned terminals, and unmanned mines; in the service field, unmanned logistics, unmanned driving, and other technologies are also at the critical point of large-scale popularization and application. Consequently, machine substitution may for the first time squeeze human labor out of the employment space that humans have been accustomed to since the formation of industrial civilization, and link up to bring about fundamental changes in spatial organization patterns. It is evident that machine substitution is no longer an implicit philosophical, technological, or social relationship proposition, but is gradually rising to become an explicit spatial proposition.

Relevant scholars in urban and rural planning have realized the potential spatial impact brought by the new techno-economic paradigm [17], with emerging technologies represented by information technology being able to greatly change the physical spatial morphology and operation modes of cities [18]. However, current discussions mostly unfold from the "technology-space" dimension, such as discussing the relationship between virtual and real spaces [19-20], the decentralization and flattening of urban functional networks [21], and functional integration [22], with relatively less attention paid to the relationship between the "human" replaced by machines and space. Yang Yongchun et al. [23] believe that the intervention of new technologies will make the urban human-land relationship shift from human-land coordination to virtual interaction. Xu Wenbo et al. [24] proposed the human-machine spatial allocation mode of cities under deep human-machine collaboration (Figure 2), but specific empirical research on this mode is currently still lacking. Overall, disciplines with spatial attributes such as geography and urban and rural planning must pay attention to the cutting-edge machine substitution spatial practice, filling the research gap in key issues facing future urban development through interdisciplinary theoretical research and systematic spatial empirical studies.

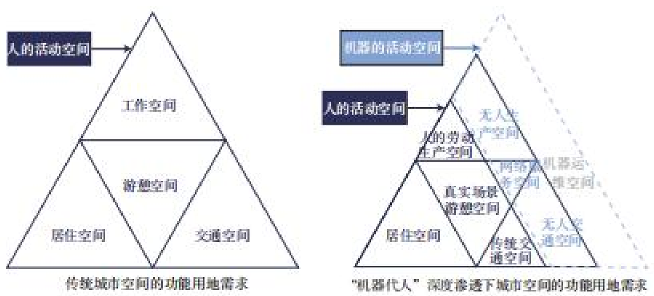

Fig.2 Assumption of human-machine space allocation and evolutionary trend of urban land composition

2. Progress in Industrial Space Research Under the Trend of Machine Substitution

Manufacturing is the industry with the earliest intervention of robots, the largest application scale, and the most significant impact, and the transformation of industrial space with manufacturing functions as the core is undoubtedly the key area of focus in the current stage of machine substitution research. In recent years, various regions have been advancing the construction of smart factories and "dark factories," promoting industrial parks toward intelligence and unmanned development, triggering differentiated spatial effects at various spatial scales including regions, cities, parks, and factory areas. Relevant research can be mainly summarized into the following three aspects.

2.1Macro Level: Focus on Industry and Regional Differences in Employment Substitution Effects

The substitution of machines for human employment is the core factor affecting regional and urban spatial changes. Historically, concerns about machines replacing humans originated with Ricardo and John Barton, who believed that machines would crowd out workers and cause a surplus of human labor [25]. In the early 19th century, the famous Luddite movement emerged in Britain, where workers, fearing that production machines would replace their jobs, launched a large-scale movement to smash production machines to oppose new technology applications. Generally, the impact of technological progress on industrial and social development is overall neutral [26], and the impact of machines on labor employment has both "displacement effects" and "creation effects"①. Acemoglu et al. [27] believe that by improving productivity, the substitution effect of machines on labor can be offset, creating new jobs suitable for human labor. However, there are also views [28] that automation is beneficial for growth but detrimental to equality. Overall, the impact of artificial intelligence intervention on labor employment is structural, particularly significantly increasing employment demand for high-skill and low-skill workers, while medium-skill workers face the highest degree of substitution [29], leading to the phenomenon of employment "polarization" [30]. From the perspective of labor skill types of job positions, machine substitution will lead to a coexisting trend of "technological upgrading" and "labor downgrading"② in some labor positions [31], but positions based on "tacit knowledge"③ are the least likely to be replicated and replaced by robots [32].

From international experience, the improvement of industrial production automation and digitalization levels will indeed directly replace a portion of labor. In research on US manufacturing, although the enrichment of information technology capital largely improves labor productivity, its employment level also declines faster [33], and may lead to wage decline and labor surplus. In Japan, approximately 55% of job positions are in a state that can be relatively easily replaced by computers [34]. Although China is a latecomer industrial country compared to Europe, the United States, and Japan, and has advantages in labor costs, significant phenomena of machine replacing humans have also appeared in regions such as the Pearl River Delta and the Yangtze River Delta, and in manufacturing enterprises there is also a significant negative relationship between enterprise automation levels and labor demand [35].

Regarding the regional differences of machine substitution, overall, China's manufacturing population has already shown a "demographic decline" trend, but from the perspective of "industry—population—space" linkage, China has not fallen into the "excessive deindustrialization" trap but is in a technology-driven benign deindustrialization [36]. Due to the "polarization" characteristics of manufacturing labor employment, traditional industrial workers have experienced "technological unemployment" [37], and labor factors no longer play a decisive role in regional industrial transfer. After the development of medium-technology manufacturing matures, it no longer prioritizes transfer to inland regions with lower labor costs [38]. The current simultaneous existence of machine replacing humans and labor transfer between industries and regional return in China indicates that the dual structure between urban and rural areas in China still exists, and the labor market still has certain regional characteristics [39]. Some research [40] shows that industrial intelligence has a more significant promotion effect on enterprise output value in higher-level cities. Some research conducted from the enterprise perspective can also prove the above judgment: in intelligent environments, the geographical pattern of enterprises is often dominated by large-scale enterprises, and technology investment barriers will make enterprises "the strong get stronger, the weak get weaker" [41]; the application of new technologies can enable enterprises to effectively offset the cost impact of rising labor prices and reduce the probability of enterprise relocation [42].

Machine substitution also demonstrates significant differences among different industries. According to research by Professor Li Xun's team [43], the labor substitution rate in the Pearl River Delta is approximately 10%, with Dongguan City's machine substitution rate at approximately 16%. The industries with the highest substitution rates are general equipment manufacturing, metal product manufacturing, and rubber product manufacturing (Figure 3). In research on Shunde District, Foshan City, the machine substitution rate of typical enterprises such as Midea is approximately 22%, the substitution rate of machines for labor in the household appliance industry in Shunde District is approximately 11.15%, and the average substitution rate of machines for labor in the manufacturing industry of the entire district is approximately 7.72% [44].

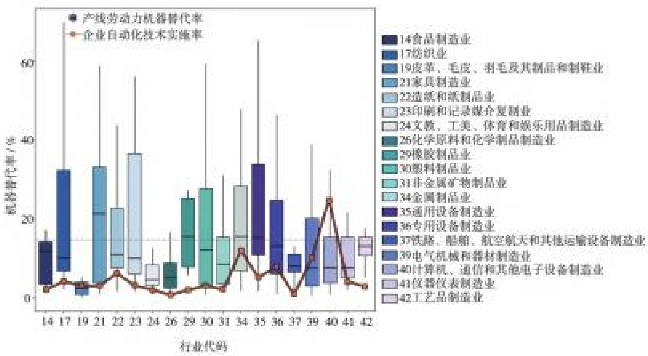

Fig.3 Machine substitution levels by manufacturing sub-sector in Dongguan city (2014-2016)

In recent years, research in disciplines such as industrial economics, labor economics, and population resources and environment has also paid attention to the impact of industrial intelligence on labor employment in the manufacturing field, measuring and explaining the impacts on employment scale, structure, mobility, income levels, and stability. This type of research mainly measures the level of industrial intelligence through indirect data on population, economy, industry, and innovation, and verifies the correlation between multiple factors through economic models and explains their mechanisms of action, but lacks summarization and explanation of spatial phenomena.

2.2 Meso Level: Focus on Changes in Industrial Location Selection and Reconstruction of Industry-City Relationships

The continuous deepening of the machine substitution process has somewhat reduced the explanatory power of traditional industrial location theory for current industrial spatial layout. Upgrades in transportation and logistics modes, as well as the demographic decline of industrial space, have led to major changes in the relationship between production—city spaces. Research by Professor Huang Jingnan's team [45] believes that the layout of industrial space will evolve into two patterns: transportation-oriented and technology-oriented. Other research [46], starting from industrial categories, believes there will be several patterns: "service-oriented" layout for light industry, "transportation-oriented" layout for heavy industry, and "technology-oriented" layout for creative industry. Overall, the role of labor costs in industrial space location selection is continuously weakening, while the influence of factors such as transportation costs, land costs, business environment, and innovation networks is continuously increasing. Research on Shenzhen [47-48] shows that different segments of the industrial production process present differentiated characteristics in spatial distribution, with industrial production activities distributed in a "polycentric contiguous" pattern on the outskirts of the central urban area, and industrial R&D activities distributed in a "monocentric scattered" pattern in the central urban area.

Regarding changes in the industry-city spatial relationship, intelligent manufacturing has a development trend toward flexibility and will promote the networked transformation of production organization, giving rise to integrated spaces matching new business formats [22]. Post-Fordist production methods have caused manufacturing space to shift from agglomerative layout to distributed and edge layouts at the macro level [49]. Some scholars [50] have divided domestic intelligent manufacturing industrial clusters into three layout patterns: park-type, urban-type, and regional-type. Some scholars have focused on industrial spatial evolution analysis at the metropolitan area scale and discovered similar characteristics: the suburban areas of metropolises overall show a trend of employment population outflow, while the employment population in the central urban area continues to densify [51], especially spatial sectors dominated by manufacturing functions presenting characteristics of human-land scale imbalance [52-53]. Other scholars [54], through observation of professional towns, found that the implementation of "machine replacing humans" can promote the extension of industrial chains toward service industries, enabling the spatial transformation of town areas toward integration.

2.3 Micro Level: Focus on Microscopic Spatial Organization of Intelligent Factories and Parks

Technological progress directly affects the spatial functions and morphology of factory buildings and factory areas, thereby leading to changes in industrial park spatial layout. Since the release of "Made in China 2025," research on smart factories in China's industrial community has been continuously emerging, gradually clarifying the overall architecture of smart factory construction [55-56]. However, limited by professional backgrounds, these research projects mainly focus on production technology and process flows, providing relatively limited guidance for industrial spatial planning and construction.

In the fields of urban planning and architecture, some scholars have already noted the development trends of industrial space utilization modes toward high efficiency, intensification, and flexibility under the influence of new technologies [57], believing that compared with traditional industrial space, intelligent industrial carriers have varying degrees of changes in form, land occupation, span, floor height, and load-bearing capacity, which will generate new requirements for industrial land division scales and layout in parks [22]. Among these, Chen Jiaping et al. [58] analyzed the industry characteristics and land occupation area of 46 "lighthouse factories" in China, with the average land area of each factory being 1.03 km², showing that the scale of factories is generally large, but this study did not conduct a horizontal comparison between "lighthouse factories" and traditional manufacturing factories. Zhu Kai et al. [59], through research on Hangzhou's future factories, believe that industrial space will form intensive business models, incubation R&D models, integrated network chain models, and factory-type manufacturing models at the microscopic scale. Research by Professor Wei Cheng's team [60] believes that new intelligent production systems pose certain challenges to traditional industrial space planning models and will have far-reaching impacts on industrial space from multiple aspects including functional integration, environmental quality, carrier intelligence, and land use organization optimization. Overall, planning researchers mainly conduct analysis from the level of park and factory area spatial patterns, with research mostly pointing to land use layout, functional organization, factory scale and morphology, internal production streamline organization, and infrastructure supporting facilities, serving the planning and design of physical space.

2.4Research Characteristics and Deficiencies

From the perspective of the disciplinary fields, spatial scales, and research focuses of existing research, machine substitution as an important variable affecting economic and social development has already attracted the attention of relevant disciplines. Many scholars have proactively paid attention to the potential impacts of new technology applications on future industrial space, attempting to make corresponding scientific proposals in terms of theory construction, pattern deduction, and planning practice. However, because new technologies such as artificial intelligence are still in their infancy and rapid growth stages, with spatial response relatively lagging and observable spatial phenomena still relatively scarce, current research on the spatial dimension still has deficiencies in theory construction and empirical research. In-depth research is relatively lacking on spatial evolution processes and mechanisms, spatial demand and supply matching, and production—city—human collaborative effects, and there is an urgent need to construct new explanatory frameworks. See Figure 4.

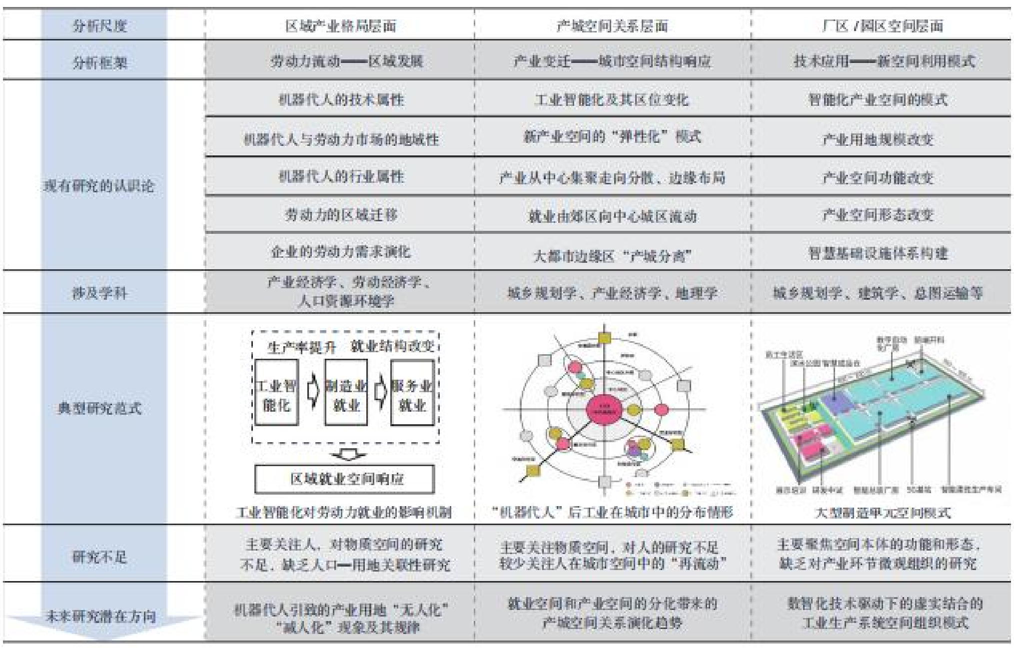

Fig.4 Summary of the existing research framework on machine substitution in industry space

(1) At the regional level, existing research mostly unfolds from the perspective of evolution characteristics of labor factors at the macro regional scale, mainly focusing on human scale increases or decreases and spatial distribution changes but relatively ignoring scale and structural changes of industrial land use, with insufficient research on the correlation between population and land use. Future research can continue to focus on the "unmanned" and "demographic decline" phenomena of industrial land use induced by machine substitution and their patterns.

(2) At the city level, there is relatively more research on industrial spatial transformation and urban structural evolution, but it mainly focuses on changes in location, scale, function, and morphology of material spatial carriers such as industrial parks, while relatively ignoring changes in employment choices of human labor under machine substitution and their "re-mobility" patterns within urban internal spaces. Subsequent research must note the differentiation between employment space (workplaces of human labor) and industrial space (venues with production functions), and use this as an entry point to rethink the evolutionary trends of industry-city relationships.

(3) At the micro spatial level of parks and factory areas, existing research has already noted changes in material spatial functions and morphology of new industrial space, but there is a relative lack of research on the intrinsic organizational logic of industrial space driven by digital-intelligent technology, particularly insufficient research on the combination patterns and "micro-location" selection of enterprise management, R&D, manufacturing, and sales segments in space. There is a need to re-excavate spatial laws starting from the intrinsic organizational mode of industrial production systems.

3. Research Implications: Industrial Spatial Paradigm Transformation Under Human-Machine Collaboration

3.1Reconstruction of Machine Spatial Subjectivity: From Instrumental Substitution to Behavioral Activity Substitution

In fields such as technology, literature, and film, humans have always been envisioning the emergence of "silicon-based life" with intelligence similar to humans. As early as 1950, in the work "I, Robot" by American science fiction writer Isaac Asimov [61], the famous "Three Laws of Robotics" were proposed and called "the cornerstone of modern robotics." Today, robots can already autonomously generate some behaviors through "behavioral computing." Although they are essentially still electromechanical devices, they have become machines with "human-like" qualities [62]. In the future stage of biological robots, with the improvement of intelligence levels, robots are likely to integrate more deeply into society as "other humans" [63].

Although this autonomous capability of robots is achieved based on human-set algorithms and sensor systems, they have still obtained the ability and authority to make "on-the-spot decisions" in many spatial scenarios. In the legal field, experts have already pointed out that humanoid robots can be included within the scope of legal responsibility subjects and proposed a basic legal governance framework [64-65]. From the interactive history of technological development and urban evolution, the subjects of space development and use will undoubtedly expand from a single human subject to "human-like subjects," and robots will shed their sole instrumental attribute and possess a certain degree of independent spatial actor attribute. Particularly in industrial space, machine occupation and use of space will largely exceed that of humans, and "exclude" and "crowd out" humans in space.

Consequently, human-machine interaction no longer merely occurs at the functional level but becomes a ubiquitous spatial scenario in future cities. Although this spatial "exclusion" and "crowding out" is based on the purpose of liberating humans and improving productivity, it will in fact lead to changes in the geographical spatial distribution of humans and machines, bringing about adjustments to urban spatial order. This is the core logic by which the evolution of human-machine relationships affects industrial spatial organization patterns.

3.2 Changes in Spatial Resource Allocation Logic: From "Human-Land Coupling" to Partial "Decoupling of Human and Land"

Theoretically, when robots simultaneously possess functional substitution and spatial substitution for human labor, the coupling relationship among productivity development, population agglomeration, and land expansion becomes unstable, which will promote the dissolution of the "production—city—human" development logic formed since the industrial civilization, and urban spatial resource allocation will shift from "human-land coupling" to "decoupling of human and land." The core of this transformation lies in: the close association between traditional urban space and human labor distribution under the background of industrial civilization is broken, and technology has reorganized the relationships among population, industry, and spatial organization at both virtual and physical levels across regions, thereby triggering profound changes in urban morphology, functional layout, and land use. Taking the specific development mode of cities as an example, assuming a city with industrial production as its main function achieves a high degree of "demographic decline" in the physical manufacturing segment, industrial scale expansion loses the effect of agglomerating population and promoting urbanization. In reality, we have already observed this trend in some cities, such as Yancheng, Changzhou, and other cities with developed physical manufacturing, or some resource-based cities, where the phenomenon of "decoupling of human and land" featuring population contraction and spatial growth has appeared. Some cities driven by modern service industries, cultural creativity, and consumption may simultaneously experience population growth and spatial contraction, which seems to imply that urbanization and industrialization can also be decoupled under certain circumstances.

The emergence of this new trend has brought significant impacts to current urban planning concepts and technologies. One-sided "population-based land allocation" equalitarianism may not be adaptable to the spatial development needs of all cities, or at least cannot objectively reflect the needs of productivity development. Particularly at the macro regional level, the allocation of spatial resources will become more complex, and the long-standing isomorphic relationship between industrial locations and urban locations will also loosen. In extreme cases, we can even imagine the emergence of a new type of "unmanned city" dominated by "unmanned manufacturing," "unmanned mining," and "unmanned port" functions. Therefore, under the new human-machine relationship, it is necessary to establish a "human—machine—land—industry" collaborative evolution analysis framework, viewing both humans and intelligent machines as subjects participating in social division of labor and using urban space: both re-examining industrial spatial carrying capacity under machine-dominated production backgrounds and continuously optimizing environmental quality with a human-centered approach; both considering the productivity improvement brought by machine substitution and balancing social effects after labor substitution; while also scientifically guaranteeing industrial space supply and layout to improve spatial efficiency. See Figure 5.

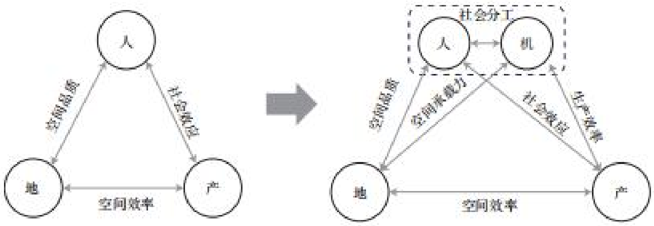

Fig.5 Spatial logic transformation from "human-land-industry" to "human-machine-land-industry"

3.3Construction Thinking of New Industrial Spatial Modes Under Human-Machine Collaboration

3.3.1Spatial Reallocation Under Machine Subjectivity Reconstruction

Machines are not humans; machines only serve humans. However, there is no doubt that when machines possess certain behavioral activity capabilities similar to humans, they also need to occupy space like humans. Since not all machines can enter human society in a low-impact manner, the large-scale application of some machines will inevitably form pressure on human activity spaces. Analogous to evolutionary laws in the biological world, as intelligent machines intervene as a "new species" in the industrial spatial order originally dominated by humans, the human-machine relationship is bound to experience different stages such as substitution, adaptation and commensalism, and symbiosis, generating the "rejection response" of spatial organisms through interactive gaming and gradually reaching a new human-machine symbiotic spatial order. For planning practitioners, coordinating the spatial relationship between humans and machines may be an implicit condition in future urban planning and industrial spatial planning work: from the organization of regional production networks and logistics networks, coordination of port-city and industry-city relationships, to the planning and construction of supporting facilities in industrial parks, coordination of architectural functional morphology with human/unmanned logistics systems, and coverage and maintenance of digital infrastructure, all must simultaneously consider the differentiated spatial needs of humans and machines.

3.3.2 Industry-City Rebalancing Under Demographic Decline in Manufacturing Space

For a long time, industrial space and employment space have been two different expression dimensions of the same type of space: the space carrying industrial functions is the space absorbing employment. However, as the trend of machine substitution becomes increasingly clear, we find that the meanings of this pair of concepts have undergone subtle changes: industrial space with manufacturing as the core does not necessarily centrally bear employment, while employment space with business offices and R&D as the core in cities is demonstrating "distributed" and "atomized" characteristics, and industrial space and employment space have become decoupled. Industrial parks have sparse human and vehicle traffic, while food delivery riders and Didi drivers have become new reservoirs for accommodating employment. Consequently, as large-scale commuting between industry and city disappears, industrial space and urban space also need to achieve a new balance. Both industry-city integration and "industry-city separation" trends are potential directions for future evolution.

3.3.3 Correlation and Collaboration Between Physical Production Space and Virtual Production Space

Traditional industrial space planning work mostly targets physical space, with industrial type guidance, functional zoning, traffic organization, morphological design, and supporting facility layout being the basic means for planners to handle this type of space. However, with the full arrival of the digital-intelligent era, industrial space has also entered a new stage of digital and intelligent development. Beyond tangible physical spaces such as factory workshops, headquarters, R&D laboratories, and sales terminals that can be seen and touched, virtual spaces spawned by technologies such as industrial cloud, industrial internet, and industrial big data are equally important components of the production system. This type of production network built on information flows and computing power creates conditions for cross-regional organization and distributed distribution of different segments including enterprise management, R&D, manufacturing, and sales in space. Against the general trend of industrial production spatial layout developing toward "distribution," code and algorithms cannot directly transform physical space, but will to a certain extent reconstruct the underlying logic of industrial spatial distribution and operation, determining the behavioral activities of human individuals and robots in the industrial production system. Therefore, human-machine spatial collaboration occurs not only in concrete industrial space in the traditional sense but also in digitized spaces. The planning community has already noted the important role of artificial intelligence and algorithms in spatial organization and spatial governance [66]. The planning and design of industrial space by planners needs to carry more "cloud-based" thinking, focusing on chain-like and networked organizational characteristics of space [67], promoting industrial space planning research to deepen from relatively static industrial category, cluster, and enterprise layouts toward dynamic production organization modes, production segments, process flows, and human-machine division of labor and ratios, more precisely matching differentiated spatial needs of different industrial categories and production segments.

4. Conclusion

Machines themselves possessing intelligence is a major variable that has not appeared in any previous historical stage. As the historical wave of digital-intelligence and "machine substitution" surges, intelligent machines, while enhancing human social productivity, inevitably "demand" corresponding space and become important users of industrial space. The human-machine relationship is no longer merely related to philosophical and ethical domains but will transform into a concrete spatial issue.

The research finds that many experts and scholars are paying attention to the spatial transformation brought by new technologies such as artificial intelligence, and there is no shortage of research views with both theoretical depth and imagination, providing important research support for industrial spatial development in the era of artificial intelligence. However, the research also finds that because technology development is advancing rapidly, current research exploration is mostly still built upon traditional spatial analysis frameworks, lacking systematic theoretical thinking about the latest technological trends and application scenarios. Technological determinism remains the mainstream direction, with relatively insufficient systematic thinking about social spatial systems driven by technology, particularly insufficient attention to the space of people replaced by machines. Admittedly, this study has only conducted limited review and interpretation of future industrial spatial development trends and planning concepts from the new perspective of human-machine relationship evolution. Future work will conduct more in-depth research on industrial spatial theory construction and spatial development empirical studies under human-machine relationship evolution based on this, aiming to propose new ideas for future urban development and planning in the digital-intelligent era.

Notes

① "Displacement effect" refers to machines directly replacing human positions in repetitive work (such as production line workers), leading to unemployment of some workers; "creation effect" refers to new job positions spawned by new technology applications, including mechanical engineers, algorithm engineers, data analysts, etc.

② Technological upgrading refers to machines improving production efficiency through intelligence, while labor downgrading is the process where workers' skills are broken down into simple operations, gradually becoming auxiliary roles or even being replaced.

③ Tacit knowledge in industrial production refers to the experience intuition and situational skills accumulated by workers through long-term practice that are difficult to encode, such as precision hand-feel, fault intuition, or the "knacks" for solving complex problems, constituting the core advantage of humans relative to machines.

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