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Article

Space Efficiency of Transit-Oriented Station Areas: A Case Study from a Complex Adaptive System Perspective

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Abstract: Transit-oriented development (TOD) has been widely adopted in urban planning to alleviate traffic congestion, urban sprawl, and other problems. The TOD metro station area, as a dynamic and open spatial system, presents typical complex features. To improve urban planning by understanding the complex features of metro station areas, this study proposes a comprehensive evaluation method using complex adaptive system theory (CAS) to assess space efficiency and the use of an evaluation method like COWA (continuous ordered weighted averaging) operator and cloud model to show efficiency. Factors include external relevance, internal coordination, and environmental adaptation. This study uses Museum Station of Harbin Railway Transportation as the case study, and the results show that the space efficiency of Harbin's TOD metro station areas are lacking in internal coordination and environmental adaptation. The proposed evaluation method not only identifies areas of space inefficiencies in urban rail transit station areas but also provides valuable insights for informed decision-making and future urban development initiatives.

Keywords: TOD; complex adaptive system; metro station area; space efficiency; cloud model

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1. Introduction

In the context of rapid urbanization, the people's demand for transportation and travel is gradually growing. This is accompanied by more and more serious problems such as urban sprawl, low land use, traffic congestion, and exhaust pollution. Consequently, many cities are accelerating the construction of rail transit systems and promoting public transportation-oriented development (TOD) to achieve a deeper integration of urban transportation and land use. TOD is a planning approach that maximizes the availability of residential, commercial, and recreational spaces within a certain walking distance from transit nodes [1]. Peter Calthorpe first proposed the public TOD in 1993 [2]. Since then, the definition of TOD has evolved from a theory about land use and site planning to practical applications like reducing car dependence. However, the rapid construction of TOD has exposed the following problems: Uncertainty about new station development ridership may result in lower development revenues and transit operating burdens [3]. Large concentrations of people and facilities from TOD projects may cause congestion and the deterioration of traffic conditions near the site in some urban areas [4]. Furthermore, land premiums can result in gentrification and social exclusion of low-income groups, particularly due to a lack of affordable housing near transit stations, raising significant social equity concerns [5]. The difficulties in obtaining data on population characteristics and the absence of a quantitative assessment framework for refining TOD complicate the formation of needs assessments and tailored response strategies for TOD.

In light of these challenges, researchers have increasingly focused on the space efficiency of TOD metro station areas to explore the potential for site development [6]. The term "TOD station area" refers to the geographic region surrounding a TOD station. In the disciplines of architecture and planning, "space efficiency" is evaluated in different ways and with different emphasis due to differences in research scope, cognitive perspectives, and environments, and it is complex and multifaceted [7–9]. Scholars often select specific urban areas to investigate spatial efficiency; for instance, some focus on the correlation between "behavioral activities" and the "physical environment" in central commercial districts, leading to the construction of space efficiency models for pedestrian environments [10]. With the rapid expansion of rail transit lines and the development of the areas around the stations, scholars at home and abroad have conducted studies to evaluate the space efficiency of these areas from various perspectives including transportation [11], society [12], economy [13], and environment [14,15]. Furthermore, scholars are utilizing nonlinear programming [16] and latent class analysis methods [6] to evaluate TOD's spatial and potential efficiency. Evaluating the space efficiency of TOD metro station areas involves studying space efficiency factors and understanding their interrelationship.

The introduction of complex adaptive systems (CAS) theory into urban research has provided valuable insights into theoretical urban system studies, emphasizing self-organization mechanisms and simulating urban system evolution. Although research on urban railways has been limited, the incorporation of CAS theory has laid the groundwork for empirical studies and the development of theoretical models. This paper develops a method for evaluating the space efficiency of Harbin's TOD system using CAS theory. This study aims to clarify the fundamental characteristics of the complex system surrounding transit-oriented development (TOD) station areas. We first summarize the basic characteristics of the complex system of the TOD station area; on this basis, we construct the framework of the complex system of the TOD station area from three aspects of internal coordination, external correlation, and environmental adaptation, summarize the comprehensive evaluation indexes of spatial efficiency of the TOD station area, propose the evaluation method combining the COWA (continuous ordered weighted averaging) assignment and the cloud model, and then generate the comprehensive cloud diagram, which visually shows the level of spatial efficiency of TOD station area, and take the Harbin City Railway Museum station area as a case study to apply the index method and test it. Using the Harbin City Railway Museum station area as a case study, we apply the proposed method to test and validate the spatial efficiency of the station area. This approach not only enhances our understanding and evaluation methods but also expands research on TOD metro station area assessments, providing new insights into urban rail transit development.

The structure of this study is as follows: Section 1 introduces the background of the research; Section 2 is the literature review; Section 3 is the methodology of this paper, including the conceptualization and deconstruction of complex adaptive systems, and modeling; Section 4 is the results of evaluating the space efficiency of the model with real case data brought into the model. Section 5 is the conclusion of the study and suggestions for optimization strategies.

2. Literature Review

2.1. Space Efficiency of TOD Stations

Peter Calthorpe first proposed the public TOD in 1993 [2]. Since then, the definition of TOD has evolved from a theory on land use and site planning to practical applications like reducing car dependence. This is achieved by emphasizing diverse land use, internal functional organization, and road network construction. The development experience of developed countries and regions has shown that the TOD model can speed up the process of multi-center urban construction, ease the overlapping functions and overcrowding in the core area, relieve traffic congestion and reduce air pollution, and has significant economic and social benefits [17–19]. The TOD concept is widely used in urban planning practice. Cervero and Kockelman, based on Calthorpe's research, proposed the "3D" principle, i.e., density, diversity, and design, which is utilized to provide more varied travel choices for different groups of people, to reduce the use of small cars [20]. Cervero added "Distance" and "Destination Accessibility" to the "3D" principle to expand it to a "5D" dimensional principle approach, which has been widely recognized [21].

TOD originated in the 1950s, when it was called PTOD (public transport-orientated development) and began to appear in the Nordic countries [22]. But it stopped until the 1980s, when it was formally used on the basis of linkages with the urban structure and transportation infrastructure [23]. By the 1990s, TOD continued to receive attention from researchers and attracted the interest of influential international organizations, such as the World Bank, which was responsible for applying TOD to urban planning [22]. The definition of TOD has expanded to multiple criteria related to physical, transportation, and socio-economic characteristics, but the premise of the model is to promote the use of public transportation by creating mixed-use, dense, and walkable neighborhoods around transit nodes that provide positive characteristics for urban rail transit (URT) development [1].

However, the rapid construction of URT under the TOD concept has exposed the following problems: Uncertainty about new station development ridership may result in lower development revenues and transit operating burdens [3]. Large concentrations of people and facilities from TOD projects may cause congestion and deterioration of traffic conditions near the site in some urban areas [4]. Land premiums lead to gentrification and the social exclusion of low-income groups, such as the lack of sheltered housing within the immediate vicinity of stations, which in turn raises social equity issues [5]. Due to the limitation of obtaining data on population characteristics and the lack of a quantitative assessment framework for TOD refinement, it is often difficult to form a needs assessment and a refined response strategy for TOD.

Therefore, scholars have gradually begun to pay attention to the space efficiency of TOD metro station areas in order to explore the potential of TOD site development [6]. In the disciplines of architecture and planning, "space efficiency" is evaluated in different ways and with different emphasis due to differences in research scope, cognitive perspectives, and environments, and is complex and multifaceted [7–9]. Scholars select a certain type of area in the city to explore spatial efficiency. For example, they take "behavioral activities" and "physical environment" in the outdoor walking environment of the city's central commercial street area as the main research object, analyze the correlation between the two, and construct a space efficiency model of the walking environment [10].

With the rapid expansion of rail transit lines and the development of the areas around the stations, scholars at home and abroad have conducted studies to evaluate the space efficiency of these areas from various perspectives including transportation, society, economy, and environment. In the transportation perspective, Qiang Du [11] uses a geographically weighted regression method to study the impacts of a new rail transit line and its interactions on space efficiency. Rupali Khare [12] developed a DEA (Data Envelopment Analysis) model to evaluate the efficiency of urban planning by measuring the coordinated relationships between BRTS and land use. Liwen Liu [24] proposed a conceptual framework for planning corridor TOD in order to enhance the application of TOD. Scholars such as Ding Yong, Sun Guibo, and John Zacharias used field surveys and questionnaires to measure metro riders' satisfaction with the internal environment [14,15]. Their findings suggest that improved connectivity, pedestrian-friendly designs, and higher building coverage near metro stations could enhance walking access efficiency and attract more riders. In the social dimension, scholars are increasingly exploring the societal benefits of TOD, often assessing its efficiency from the perspective of passenger safety [25,26]. As green transportation gains traction, Simar Wilson's two-stage approach considers an integrated subway, bus, and shared-bicycle system [27]. Furthermore, scholars are utilizing nonlinear programming [16] and latent class analysis methods [6] to evaluate TOD's spatial and potential efficiency. Evaluating space efficiency of TOD metro station areas involves studying space efficiency factors and understanding their interrelationship. However, research exploring the complexity of space efficiency factors and their interrelations in evaluating the space efficiency of TOD metro station areas remains relatively sparse.

Recent empirical studies have emphasized key factors affecting TOD efficiency and provided important insights for future planning practices. A case study on Tehran's metro stations identified critical features that define TOD and developed an index for measuring its effects, employing various spatial measurement units to assess the efficiency of TOD station areas [13]. The results highlighted the importance of tailored planning interventions that consider the unique characteristics of each TOD. Liu et al. [28] discovered, through machine learning methods, that transportation-related built environment factors are more significant during the early stages of a station's lifecycle, while land use factors become increasingly prominent as the station develops. This research underscores the necessity of formulating stage-specific planning strategies based on the evolving context of TOD areas. Robillard et al. developed a bicycle-oriented TOD typology, using Montreal's public transportation as an example, combining cycling indicators with traditional land use and transportation metrics [29]. This study demonstrated that incorporating cycling considerations into the TOD framework can enhance the overall effectiveness of public transit stations and promote active transportation modes. Abdullah et al. applied multi-criteria decision tools to evaluate the performance of Jakarta's rapid rail stations, finding significant differences in standard weights among different expert groups, highlighting the need for continuous monitoring and data collection concerning passenger volumes and TOD metrics to ensure effective planning [30].

When assessing the spatial efficiency of TOD, the range of the influenced area is a crucial factor, typically defined as the area surrounding the TOD location or station, within which land use and site design significantly impact TOD accessibility and walking behavior [31]. Some authors define it differently depending on the geographic context of the city and how people travel. Calthorpe [2] defines an 800 m zone of influence. Dittmar and Ohland [32], on the other hand, define the zone of influence as the 800 m area from the hub station. Cervero and Dai [33] consider the range of 500 m–1000 m as the optimal access distance. Higgins and Kanaroglou [6] used a 10 min walk access time instead of a distance definition to define the area of influence of a station in terms of a 10 min walk circle. There are several categories of research on TOD, some of which are summarized in the following Table 1.

Table 1. Category of TOD research.

Category	Key Studies	Focus/Findings
Foundational Concepts of TOD	Calthorpe (1993) [2], Cervero and Kockelman [20], Cervero [21], Dittmar and Ohland [32]	Evolution of TOD from theory to practice; emphasis on mixed-use, high-density, walkable neighborhoods; introduction of "3D" and "5D" principles.
Historical Development of TOD	Ibraeva et al. [9], Cervero and Dai [33]	Historical context of TOD; its application in urban planning; expansion of TOD definitions over time.

Table 1. *Cont.*

Category	Key Studies	Focus/Findings
Challenges of TOD Implementation	Yang et al. [3], Zhang and Ming et al. [4], Paderio et al. [5]	Identifies issues such as uncertainty in ridership, traffic congestion, and social equity challenges due to land premiums.
Spatial Efficiency Evaluation	Qiang Du [11], Rupali Khare [12], Ding Yong et al. [14], Liu [24]	Various methods to evaluate spatial efficiency; use of geographically weighted regression and DEA models; focus on rider satisfaction and connectivity.
Societal and Environmental Aspects	Yang, X. et al. [25] Wu et al. [26], Tamakloe et al. [27]	Increasing focus on societal benefits of TOD; integration of active transportation modes; assessment of safety and environmental impacts.
Recent Empirical Studies	Liu et al. [28], Robillard et al. [29], Abdullah et al. [30]	Identification of key factors affecting TOD efficiency; development of measurement indices; emphasis on tailored planning and monitoring.
Influence Area Definitions	Calthorpe [2], Dittmar and Ohland [32], Cervero and Dai [33], Zidong Yu [34], Higgins and Kanaroglou [6]	Different definitions of the influence area surrounding TOD stations; variations based on geographic context and accessibility measures.
Complex Adaptive Systems (CAS)	Holland [35], Qiu Baoxing et al. [36], Wu Liangyong and Zhou Ganzhi [26]	Introduction of CAS theory to urban studies; focus on self-organization and system evolution; relevance to understanding TOD interactions.

2.2. Complex Adaptive Systems

CAS (complex adaptive systems) research is based on the theory of systems science, which has evolved over time to provide people with a basic understanding of complex systems and the realization of their importance. From the 1970s to the 1980s, the study of systems science entered a period of complex research, from which CAS theory is the continuous development of the complex system theory. It was formally proposed by Professor J. H. Holland at the tenth anniversary of the Santa Fe Institute, and it quickly attracted widespread academic attention [37,38]. The study of complexity is also valued by Chinese scholars, who have introduced CAS theory to urban studies [39]. Inspired by academicians Wu Liangyong and Zhou Ganzhi, Qiu Baoxing et al. [40] conducted exploratory research combining theory and technology on urban planning in terms of urban boundaries, urban resilience, urban renewal, development modeling, spatial evolution, and smart cities [41,42]. Once CAS theory was incorporated into urban studies, it focused on theoretical research on urban systems, emphasizing self-organizing mechanisms and the simulation of urban system evolution. While research on urban rail remains limited, it has laid the groundwork for empirical research and theoretical models.

This study effectively captures the complexity of urban rail transit systems using CAS theory, incorporating complex systems theory to assess the spatial efficiency of TOD subway station areas and developing practical research methods. Despite the significant contributions made by existing literature in enriching TOD research, there remains a gap in understanding the complex interactions between TOD characteristics and urban systems. This highlights the importance of CAS theory. CAS theory provides a framework for analyzing how various components within urban systems interact and adapt. By applying CAS theory to TOD, researchers can better capture the dynamic characteristics of urban environments and the multifaceted relationships between transportation infrastructure, land use, and community needs. This theoretical perspective facilitates a more nuanced understanding of how TOD evolves in response to external pressures and internal dynamics. While existing research has made significant contributions, it often overlooks the interactions between TOD and broader urban resilience and adaptability. Integrating CAS theory into TOD research can help fill this gap by emphasizing self-organization and adaptive responses within urban systems.

In conclusion, the empirical studies reviewed highlight the critical factors influencing TOD efficiency and underscore the need for a comprehensive understanding of the interactions within urban systems. By incorporating CAS theory, this research aims to contribute to the ongoing discourse on TOD, providing insights that can guide future urban planning efforts.

3. Methodology

Usually station space efficiency can be defined as the effectiveness of urban spatial resource allocation, with the interaction of all kinds of spatial elements and behavioral activities in the station area of the rail transit hub as the main feature, and the spatial utilization of the rail transit station area is judged by whether the elements are organized at the spatial level in a high degree of spatial matching with the requirements of contemporary development. In this study, in order to explore the relationship between spatial matching and spatial function configuration between the city and transportation, and the most efficient spatial layout under the maximum satisfaction of people's use, CAS theory is introduced, so as to establish the evaluation system of space efficiency for the framework in turn.

3.1. CAS Theory and Its Characteristics

The CAS research has a rich connotation, the concept of subject is not enough to be fully expressed, so with the subject as the core concept, Holland [35] followed up with other important concepts of CAS theory such as aggregation, nonlinearity, flow, diversity, marking, building blocks, and internal model. The seven characteristics of the CAS theory are presented in Figure 1.

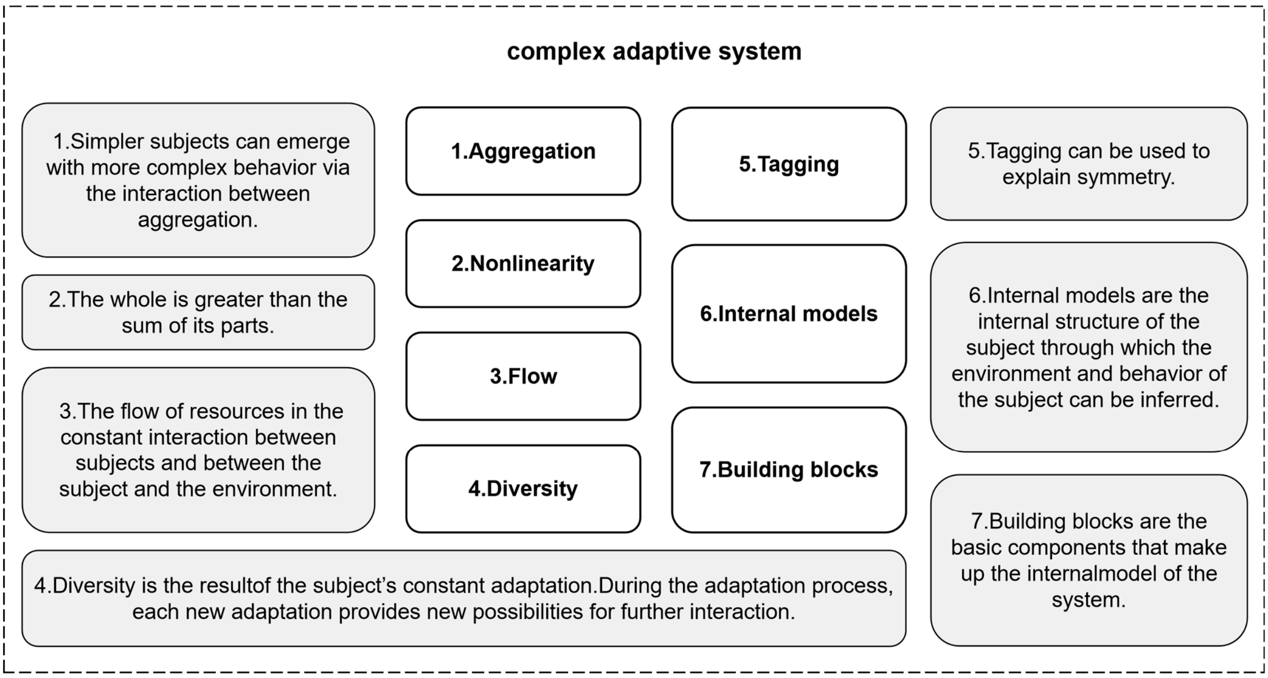

Figure 1. CAS theory and its characteristics.

If the TOD metro station areas are referred to as the TOD system centered on the TOD site, CAS theory can better describe urban systems (see Table 2). Introducing complex systems theory to assess the TOD system allows for the exploration and development of research methods.

Table 2. Characteristics and mechanisms of complex adaptive system of TOD metro station areas.

Characteristics	Mechanism	Notes
Aggregation	Emergence	TOD involves complex planning and coordination among multiple departments. Its spatial aggregation characteristics can be utilized to achieve efficient and cost-effective operations.
Nonlinearity	Interaction, feedback	The TOD system's evolution is influenced by unforeseen events like natural disasters, but controllable factors (like policy factors, management planning) outweigh non-controllable ones. For example, urban residents use TOD station areas more due to convenience and accessibility, leading to increased pedestrian flow. Therefore, TOD metro station areas have less significant nonlinear characteristics compared to cities, communities, and natural spaces [35].
Flow	Cycle	The TOD system is influenced by intense material flow, energy flow, capital flow, information flow, and human flow, which are vital for the station area's vitality [41]. Reduced "mobility" leads to decreased activity and abandonment by users.
Diversity	Coordination	The TOD system excels in diversity of space elements, space function, space users, and the user needs and behavior.
Tagging	Selection	The adaptive evolution of system elements in TOD system based on usage needs is precisely the process of different functional spaces emphasizing their own identity. This recognizability can be translated into urban spatial tendency factors that are conducive to the decision-making of station residents [41]. Strengthening spatial identity at the micro-spatial level helps to better identify unique characteristics, while at the overall level, the TOD system needs to strengthen their own identities to highlight their unique spatial characteristics.
Internal models	Foresight	The internal modeling mechanism can be seen as a spatial behavioral mechanism that supports and guides resident behavior by connecting TOD system elements to station area resident behavior in a suitable manner.
Building blocks	Combination	Understanding the hierarchy of residents' different needs, satisfying the transportation function is a basic need for the TOD system, while satisfying advanced needs such as pleasure and comfort.

Due to the use of different groups for different purposes of use in the TOD station area into the elements to meet the objective passengers' traffic and non-transportation demands, and at the same time to meet the group subjectively on the evaluation of the TOD station area of this urban public space, the station area must continue to play its basic function of transportation, but also daily life functions in the coordinated coupling. Therefore, in order to evaluate the space efficiency of the TOD station area, the combination of the subjective and objective evaluation must be used in order to reflect the realization of the station area's dual objectives of function and humanization.

3.2. Forming CAS Framework of TOD Metro Station Areas

The general significance of the model of complex adaptive systems is that the subject adjusts its own "reaction rules" by constantly and actively adapting to changes in external stimuli, thus realizing the integration and optimization of internal elements. Introducing the CAS helps understand TOD metro areas. From the perspective of the design and development of TOD metro station areas, and combining the seven basic characteristics of a CAS, the framework of complex adaptive systems of TOD metro station areas are summarized in Figure 2.

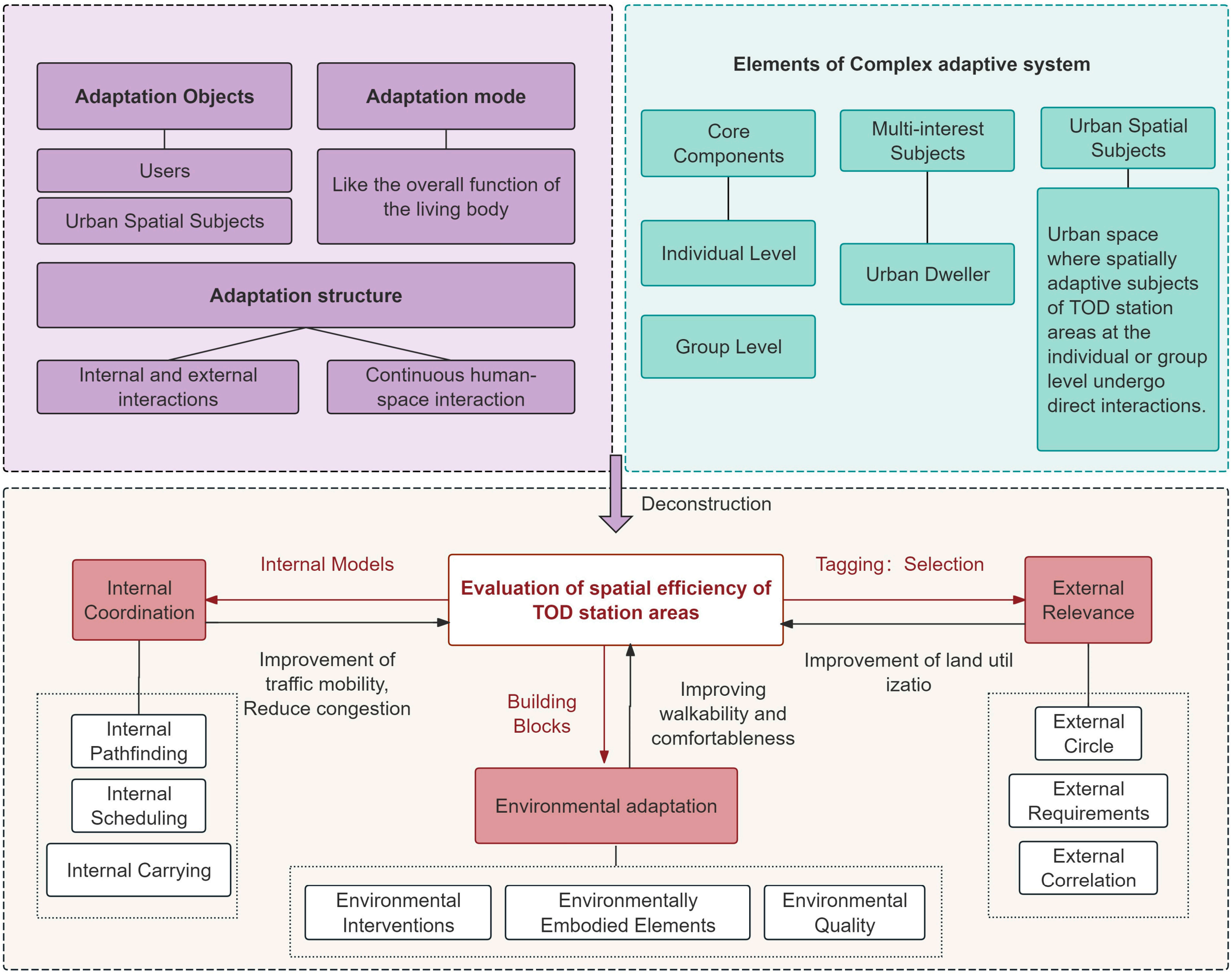

Figure 2. CAS framework of TOD system.

Under the guidance of CAS theory, the TOD metro station area is taken as the research object, the concept of adaptive subject is introduced, and the core constituents of the TOD station area system are clarified:

(1) Core components: Adaptable individuals in TOD metro station areas come from diverse backgrounds. These adaptable individuals can come together to create new adaptable groups, with the size of the group depending on the differences in how they are grouped together.

(2) Other components: People are the most crucial dynamic element in the system, including the government, developers, designers, residents, and many other stakeholders. This study focuses on the space efficiency of TOD metro station areas for urban residents, who are specifically the user subjects.

(3) Adaptation objects: Elements interacting with the TOD metro station's adaptive subject are its adaptive objects. Limited ecological niche influences only the constituent elements in the immediate environment, which are classified as adaptive objects. Study on micro-scale space efficiency identifies two types: The users of the TOD metro station areas (including commuters, residents, and those who engage in activities in the area) and the subjects of the urban space.

(4) Adaptation structure: The urban environment interacts with the TOD metro station areas, creating an adaptive structure for users.

(5) Adaptation method: If the TOD metro station area is like a living body, it is the heart, transporting users and facilitating movement to other urban areas. Other components, like organ organization and venous blood vessels, traffic flow, and style, are also crucial for its function.

(6) Adaptation routes: On the one hand, the comprehensive development of the rail transit line needs to be addressed from the beginning, while on the other hand, the changes in the surrounding environment due to urban development need to be faced. The adaptive path essentially consists of two types of design: planning-type design and new design.

In 1996, Bertolini introduced the node-place model in TOD research. This model suggests that TOD systems [42] are interconnected and significant in the broader urban context, representing important facets of urban life. Within the city, TOD, as a central urban space, includes transportation buildings, public spaces, and localized urban areas, reflecting the complex interplay of social relations. The various functional spaces within the TOD system interact, necessitating a dynamic and comprehensive perspective. It is crucial to view the TOD system as a whole, rather than a static, objective existence.

These consolidated indices seek to measure or describe "the degree to which a particular project is intrinsically oriented toward transit". Renne and Curtis [43] pioneered this research area by proposing a list of TOD success factors related to: (1) built environment (e.g., density); (2) travel behavior (e.g., the number of transit boardings or availability of parking); (3) economy (e.g., the number of retail establishments); and (4) social diversity/quality (e.g., public perception). Researchers globally evaluate different TOD or transit corridors using these categories.

Several articles have attempted to develop more accurate indices. One of the most cited is by Singh et al. [1]. Singh et al. based their selection on eight rules or principles of TOD. However, most studies ignore that the TOD metro station area is a comprehensive and complex system. Therefore, this study combines the internal and external aspects of the TOD system to analyze it as a whole, and for how to evaluate the space efficiency of the TOD system, in terms of the system composition, the TOD system consists of three parts: internal coordination, external relevance, and environmental adaptation.

The TOD system's flow function is crucial for reconfiguring urban life patterns. This function aligns with the initiative and autonomy of the adaptive subject. Space production involves various economic flows (economic flow, material, energy, financial, information, and human flow, etc.) [44]. This means that units in the metro station are no longer isolated. Therefore, in the internal coordination, internal path-finding, internal scheduling, and internal carrying are selected as the infrastructure of this part.

The TOD system supports diverse people from different areas for various purposes. Behavioral activities in the station area have multiple origins [45]. The TOD system needs to maintain dynamic stability while coping with a great variety of usage behaviors, reflecting the adaptive subjective stress. The development process includes ephemeral aspects and evolves through interactions. Therefore, in the part of external correlation, this paper selects the three parts of the external circle, external requirements, and external correlation as the basis of the factor system.

The sociality of a TOD system is influenced by users' demographics and spatial production, shaping different social needs. Social needs are the driving force of space production, creating a complex network that serves a public function. The environment of a TOD system does not only refer to its internal greening and cultural environment, but also its social and economic environment, all of which must be adapted. Therefore, the part of environmental adaptation can be divided into environmental interventions, environmental embodied elements, and environmental quality.

3.3. Interrelationship of Variables

Based on the analysis of the TOD station as an adaptive subject in the previous section, it can be seen that the process of coordinating the internal elements of the station is the process of aggregation of its components according to a certain way, and the aggregation is to give play to the predictive ability, and it is not difficult to see that this is very similar to the concept of spatial layout and organization in the field of design, so it can be said that the combination of the internal coordination of the station is adjusted to the combination of the relationship between the elements, and it can be implemented into the practice. The layout organization of TOD is a process of internal elements gathering and interacting with each other. Therefore, this paper extracts the prototype of TOD station internal coordination as layout organization. After research and comparative analysis from multiple perspectives, we can find that the influence of station layout organization on people mainly lies in walking behavior. Specifically, the level of walking-friendliness has an impact on the decision of whether to travel by URT, while some indicators of the built environment have an impact on how to use the TOD station areas, and similar conclusions have been verified in numerous environmental behavior studies. It can be seen that there are two stages of things during a single walking behavior; one is the Decision, i.e., whether or not the walking behavior will take place, and the other is the Progress [46,47]. In addition, there are two main branches in the development of walking behavior; one is closely related to the objective use level such as walking efficiency, and the other is closely related to the subjective feeling level such as walking experience. Along with the walking behavior and the end of the walking behavior, there also exists the evaluation of the walking behavior and experience accumulation, and the process of repetitive walking behavior forms a dependence relationship, which is called the loyalty in management science. Walking behavior "loyalty" sometimes affects the efficiency of walking (e.g., too much or too little foot traffic). Walking efficiency also affects the walking decision. It can be said that internal scheduling is the objective manifestation of the efficiency of station design, and internal wayfinding is the subjective manifestation of the efficiency of station design, which are intertwined and interact with each other to determine the internal carrying. Based on combing the system structure relationships related to the walking situation in TOD station areas, this study proposes the hypothesis that the micro-design of TOD station areas plays an important role in the dynamic equilibrium of complex systems.

The External Relevance is both similar and different compared to the internal. The similarity lies in the fact that both can be abstracted as interaction processes and outcomes. In the interaction of adapting to external urban subjects, the TOD station area is more in the form of a point in the larger adaptive category, which is well explained by the mechanism of "Tagging" in the theory of complex adaptive systems, i.e., TOD stations are selected and identified with the urban subjects only through specific "Tagging", which leads to interaction (aggregation or exclusion), i.e., TOD stations are selected and identified with the urban subjects only through specific "Tagging". In other words, the design of a TOD station specifies its outward "Tagging" in the city through the overall positioning of the TOD station's role in the city's larger context, and its outward "Tagging" in the city is determined by its outward "Tagging" in the city. Its outward "Tagging" in the city is determined by its external demand. When there are many residential areas outside the station area, the TOD station area needs to strengthen the efficiency of walking to meet the travel needs of users; when there are many business districts outside the station area, the TOD station area needs to set up more public places to attract more people for entertainment and consumption activities. External supply can be divided into material and non-material supply, with material supply referring to the objective construction of the station area and non-material supply referring to the products and services provided by the station area. The issue of supply and demand is one of the core issues in economics, and when the supply and demand have problems, it is very unfavorable to both the supply side and the demand side. For example, when supply exceeds demand, it results in resource wastage on the supply side, whereas when the supply is less than demand, it leads to customer dissatisfaction and a potential loss of business. This illustrates that the relationship between the external demand and the functional supply involves ongoing interactions with various external stakeholders. Furthermore, in the context of survival environment adaptation—which is also considered part of the external environment—the complex adaptive nature of the TOD station area means that the survival environment does not simply remain outside the boundaries of the TOD area. Rather, the influences from the survival environment can penetrate these ambiguous boundaries and significantly affect the station area dynamics. This underscores the importance of considering both external factors and their interconnections with the operational framework of the TOD station area. This permeable influence due to the fuzzy boundaries makes the TOD station not only rely on the "sign" to respond to the outside world, but also need to be mobilized in a wider range and with more levels to complete the external adaptation to the living environment, this process is the station in the urban environment to shape the body of the urban environment through the interaction process. Therefore, this paper extracts the external adaptation between the TOD station and the environment as quality creation. Environmental quality is the result of the joint action of the urban space outside the station, the transition space inside and outside the station, and the articulation space inside the station, and the environmental creation of TOD station areas is to meet the perceived needs of urban residents in terms of subway travel. When there are problems with the environment, it will not only have an immediate short-term impact on the users of the space in terms of physical and mental aspects, but will also bring indirect long-term impacts with the prolongation of the space use, poor environmental quality, exacerbating the burden of the public to walk in the station area, and exacerbating the impacts of the loss of personnel.

In the face of the Environmental Adaptation, due to the fuzzy boundary of the complex adaptation system of the TOD station area, the Environmental Adaptation will not ideally stay outside the TOD station area, as if the space itself is a vacuum body, so the influence of the Environmental Adaptation on the station area space will break through the fuzzy boundary and affect the subject inside. This permeable influence, due to the fuzzy boundaries, makes the TOD station not only rely on the "Tagging" to respond to the outside world, but also need to be mobilized in a wider range and with more levels to complete the external adaptation to the living environment. This process involves the station in the urban environment shaping the body of the urban environment through the interaction process. Therefore, this paper extracts the external adaptation between TOD station and environment as quality creation. Environmental quality is the result of the joint action of the urban space outside the station, the transition space inside and outside the station, the articulation space inside the station, and the environmental creation of TOD station areas is to meet the perceived needs of urban residents in terms of subway travel. When there are problems with the environment, it will not only have an immediate short-term impact on the users of the space in terms of physical and mental aspects, but will also bring indirect long-term impacts with the prolongation of the space use, with poor environmental quality, exacerbating the burden of the public to walk in the station area, and exacerbating the impacts of the loss of personnel (see Figure 3).

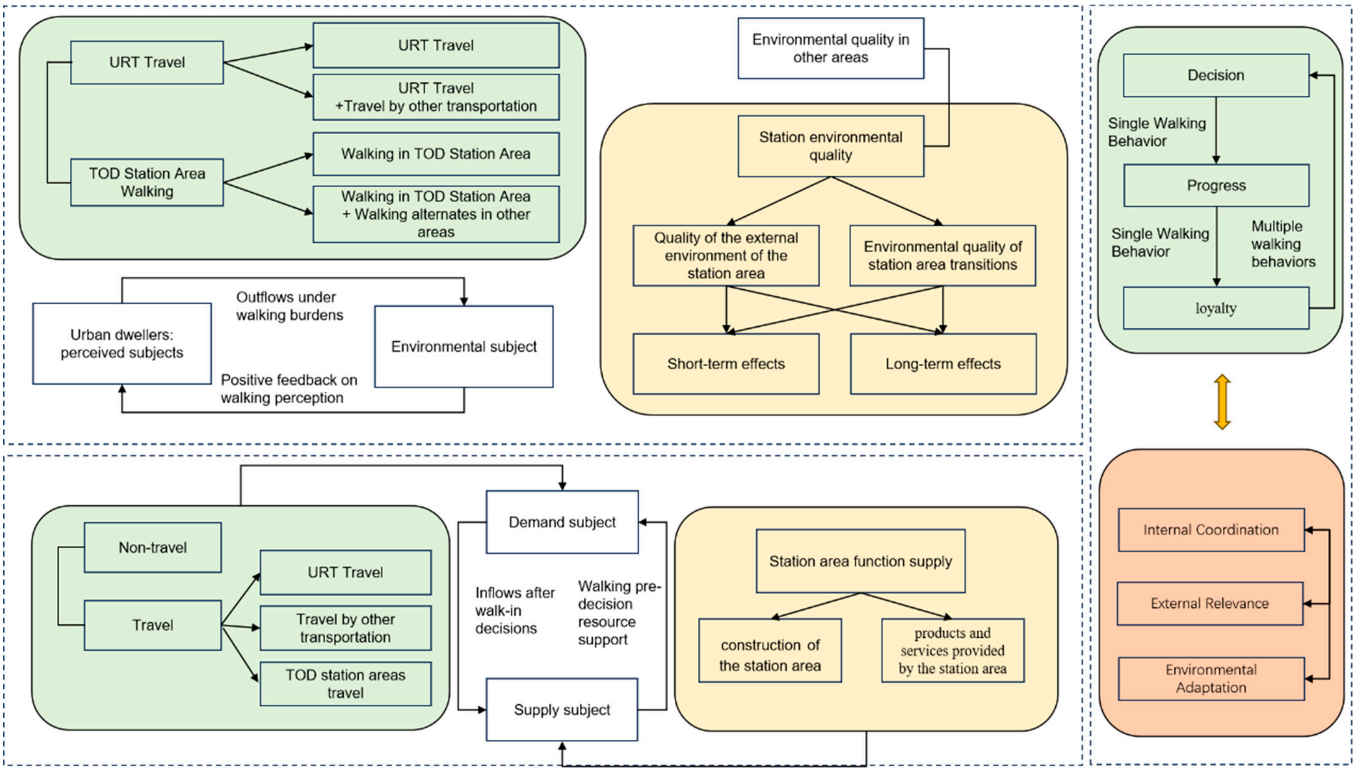

Figure 3. Analysis of multiple internal and external interactions.

3.4. Selecting Factors

Existing research shows that TOD metro station areas have significant development values in various fields, which is an emergent phenomenon in itself. These values can be summarized as the value of individual health brought by a good slow-moving environment, the value of social stability brought by a comfortable and convenient gathering space that enhances the quality of life, the value of environmental protection brought by low-carbon transit-oriented travel, and the value of economic revitalization brought by the stimulation of urban vitality under sustainable development.

For the TOD metro station areas, (1) the reconfiguration of the external city circle through its flow function is its fundamental functional attribute and a prerequisite for its establishment. The station's flow gives rise to the entire area. (2) Space production in the station involves various flows like economy, energy, finance, and human interactions. Consequently, within the station, internal scheduling and coordination ensure that the constituent units are no longer solitary and isolated. Social dynamics stem from the station's service space users, encompassing individuals of different genders, ages, specific family structures, and other social relations. Social needs drive space production, influencing and promoting social needs. (3) The TOD metro station area's environmental adaptive relationship highlights its public function, showing a close connection with the external environment. This interaction with the city and its population allows it to better adapt to the urban residents' needs and the city's development. Simultaneously, the external environment can also impact the station's development, encompassing both natural and socio-economic environments.

According to current TOD-related studies, the circular area of 400–800 m around a TOD site is generally taken as the TOD impact area, and this study combines the actual level of service of transportation facilities, land use, and other factors in Harbin, and determines it to be within the range of 600 m (walking scale of 8–10 min) [35]. Through the aforementioned analysis, combined with the literature review, the preliminary determination of the spatial efficiency evaluation index set and index description for the TOD metro station area can be established. This is depicted in the following, where quantitative factors can be obtained through field or data research, and qualitative factors can be derived through questionnaire research.

(1) Internal coordination

For a metro station, it is essential to have three sets of spatial clusters—origin-destination, path, and area—available at the same time to support travel behavior. The TOD station uses a traffic-centered approach to categorize node sites into three types based on traffic relationships: Internal Scheduling (C11), Internal Pathfinding (C12), and Internal Carrying (C13). The establishment of the internal coordination indexes is to evaluate the congestion problem of the station area. The accurate assessment of the external environment of the station area enables developers to provide more accurate public services to the target population of the station to promote social equity. The detailed level of description in the TOD station allows for the effective assessment of travel from origin to destination. This descriptive clarity highlights the need for spatial guidance, especially for experienced users navigating the station. Factors such as Public Space Visibility (D121), which reflects how visible and accessible public spaces are within the TOD area and enhances safety perceptions, User-Friendliness of Intelligent Facilities (D122), measuring how easily users can interact with smart technologies at stations, Manual Service (D123), which evaluates the effectiveness of human assistance available at transit locations, Clarity of Broadcasts (D124), gauging the effectiveness of information dissemination at stations, and Walking Effectiveness (D125), which assesses how effectively walking routes contribute to station access, all indicate a demand for timely information and must align with the station's characteristics. Factors such as Public Space Visibility (D121), User-Friendliness of Intelligent Facilities (D122), Manual Service (D123), Clarity of Broadcasts (D124), and Walking Effectiveness (D125) all indicate a demand for timely information and must align with the station's characteristics.

Additionally, elements such as Traffic Interference, Intersection Density (D111), which indicates a more integrated street network facilitating easy access to transit modes, Branch Network Density (D112), reflecting the complexity of the local transportation network, Average In–Out Distance of Stations (D113), measuring the average distance commuters must travel to access metro stations, Pedestrian Route Directness (D114), indicating how direct pedestrian paths are to transit hubs, and Walking Environment (D115), assessing the quality of the pedestrian experience, significantly influence traffic scheduling at the station. Furthermore, stopover behavior greatly affects the transition space, reflected in metrics like Metro Travel Sharing Rate (D131), measuring the percentage of users sharing metro services, Congestion Delay Index (D132), evaluating average delays experienced during peak congestion times, and Load Capacity of Passenger Flow (D133), assessing how well the transit system can accommodate passenger volumes.

(2) External Relevance

Although walking is the main mode of transportation in the TOD station area, it does not operate in isolation. Walking interacts with various elements within the station. This paper classifies the interactions in the TOD station area into three types: interactions among different station areas, interactions between station areas and the city, and interactions between station areas and city residents. These correspond to External Circle Elements (C21), External Related Elements (C22), and External Demand Elements (C23). The External Demand Elements (C23) in the external correlation index assess external demand, which aims to reduce the uncertainty of the passenger volume of the station development. It is crucial to clarify the Compactness of Land Use within the Station Area (D221), which assesses how closely land parcels are clustered. This metric supports efficient public transport systems by minimizing travel distances and promoting vibrant communities. These correspond to External circle elements C21, External related elements C22, and External demand elements C23. The external demand elements C23 in the external correlation index is an assessment of external demand, which is intended to reduce the uncertainty of the passenger volume of the station development. It is important to clarify the compactness of land use within the station area (D221). The connection between the TOD station domain and the city can be measured by the average number of entrances at block interfaces (D222), public transport integration (D223), and the average distance for transfers (D224). Additionally, understanding the surrounding population and resource distribution is essential for enhancing interactions with residents.

The connection between the TOD station domain and the city can be measured by the Average Number of Entrances at Block Interfaces (D222), indicating the number of entrances available to stations which can enhance access and reduce congestion; Public Transport Integration (D223), evaluating how well different transport modes connect and interact, ensuring seamless transitions between options; and Average Transfer Distance (D224), measuring the average distance users need to transfer from one transit line to another. Shorter transfer distances contribute to user convenience and may enhance ridership, thereby promoting equitable access to transit.

Additionally, the Density of Resident Population (D231) indicates the proportion of residents living close to transit stations, as higher densities typically lead to increased transit use and support a vibrant urban environment. The Disposable Income (D232) of residents reflects the economic capacity to utilize transportation services, where a higher disposable income can correlate with increased transit usage and investments in transit facilities. Finally, Off-Street Parking Supply (D233) measures the availability of off-street parking options, as adequate parking can support transit use by accommodating drivers transitioning to public transport. The Site Location (D234) refers to the geographical placement of the station within the urban fabric, which is vital in influencing ridership and overall spatial efficiency.

(3) Adaptation to the environment

In subway station areas with ample walking space, the term “path” refers to all linear spaces. However, in cold cities, the impact of the harsh climate means that pedestrian traffic in these linear spaces varies significantly and cannot be generalized. This complexity requires viewing the adaptive system as continuously evolving. The TOD station area must navigate three distinct environmental stages: the built environment, the native environment, and the living environment of residents.

The built dimension, Environmental Intervention Elements (C31), encompasses the interaction between the TOD station area and the modified environment created by human intervention in the cold city. Unlike the direct environmental stimuli of the primary dimension, this dimension focuses on the psychological effects that the built environment has on users.

The native dimension, known as Environmental Embodied Elements (C32), refers to the interaction between the TOD site and the natural conditions of a cold city. The influence of the native environment is primarily seen in how climate affects users, categorized into three types of protection: from cold winter winds, from snow and ice, and from temperature variations both internally and externally.

The living environment of residents, Environmental Quality Elements (C33), involves the overall interaction between the TOD site and the current conditions of the cold city. This includes both the immediate identity of individual users at a material level and their long-term values at a non-material level. In the environmental adaptation section, the Percentage of Footpaths with Shade and Rain Protection (D311) and Exposure of Street

Connectivity (D312) are crucial indicators for the city of Harbin, given its status as a high-latitude cold city. These indicators assess the provision of shelter on walking paths and measure how well streets connect various urban elements, respectively. Improved comfort encourages walking, especially in inclement weather, and high connectivity enhances movement options and transit access.

In the environmental adaptation section, the Percentage of Footpaths With Shade and Rain Protection (D311) and Exposure of Street Connectivity (D312) are very important in the city of Harbin because the city, in this case, is a high-latitude cold city, and these two indicators are not of high importance in arid areas, although the demand for sunshade exists, but it is not as rigid as the need to block rain and snow. In addition to cold cities, the Exposure of Street Connectivity (D312) is also important in humid and rainy areas, but is not as important in dryland cities. For example, an attempt could be made to replace the "air-conditioned area" indicator in TOD assessments for cities with hot and arid climates. Therefore, when this framework is used to evaluate other cities, the indicators in the environmental adaptation section should be changed according to the local context, which is also in line with the conclusion that the process of adaptation of environmental agents is an interactive process in which the station area shapes the agents that are responsive to the urban environment within the larger urban environment. The system of evaluation indicators established is shown in Table 3.

Table 3. Evaluation factors for space efficiency of TOD metro station areas.

Dimension	Mechanisms		Description
Internal Coordination B1	Internal scheduling C11	Intersection density D111	Number of station crossings/area of station site
		Branch network density D112	Total length of feeder roads/total station area
		Average in-out distance of stations D113	Walking distance from the exit gate to the entrance/exit of the hub's above or below ground articulated urban space
		Pedestrian route directness D114	Actual walking distance from the main entrance or exit to the inner planes of the station space/ideal distance in a straight line
		Walking environment D115	Though the scale questions on questionnaire
	Internal pathfinding C12	Public space visibility D121	Though the scale questions on questionnaire
		User-friendliness of Intelligent facilities D122	Though the scale questions on questionnaire
		Manual service D123	Though the scale questions on questionnaire
		Clarity of broadcast D124	Though the scale questions on questionnaire
		Walking effectiveness D125	Though the scale questions on questionnaire
	Internal carrying C13	Metro travel sharing rate D131	Share of trips using rail in total urban motorized trips
		Congestion delay index D132	Time spent during congested periods/time spent during smooth periods
		Load capacity of Passenger flow D133	Rail passenger capacity/total line length
External Relevance B2	External circle elements C21	The functional mix of the areas surrounding stations D211	Ratio between residential and non-residential functions (excluding parking areas)
		Service coverage D212	Percentage of buildings within walking distance of schools, medical facilities or pharmacies, fresh food supplies
	External related elements C22	Land use compactness D221	Ratio of total built-up area to site area within the station area
		The average entrance number of the block interface D222	Number of stores, building entrances, and pedestrian entrances included per 100 m-long block interface, on average.
		Public transport cohesion D223	Number of each public transportation travel option within walking distance.
		Average transfer distance D224	Walking distance to the nearest public transportation stop.
	External demand elements C23	Density of resident population D231	From Harbin City 2022 Statistical Yearbook
		Disposable income D232	From Harbin City 2022 Statistical Yearbook
		Off-street parking supply D233	The proportion of the total station site area occupied by all off-street spaces used for parking.
		Site Location D234	Location of the station area in relation to the city center

Table 3. *Cont.*

Dimension	Mechanisms		Description
Environmental Adaptation B3	Environmental intervention elements C31	Percentage of footpaths with shade and rain protection D311	The total number of walkway segments with adequate shade and rain protection is divided by the total number of walkway segments.
		Exposure of street connectivity D312	Though the scale questions on questionnaire
	Environmental embodied elements C32	Spatial functional diversity D321	Though the scale questions on questionnaire
		Comfort D322	Though the scale questions on questionnaire
	Environmental quality elements C33	Greening landscape construction D331	Though the scale questions on questionnaire
		Cultural atmosphere D332	Though the scale questions on questionnaire

3.5. Developing Composite Cloud Model

The cloud model, proposed by academician Deyi Li, is based on the probability theory and fuzzy mathematics. It achieves the mutual transformation of qualitative concepts and quantitative numerical values through a cloud generator [8]. Unlike other evaluation methods, the cloud model evaluation method does not have an explicit function representation. Instead, it utilizes the expectation, entropy, and hyperentropy of the cloud, effectively integrating fuzzy and stochastic characteristics. This approach addresses the limitations of traditional evaluation methods, which struggle to accurately evaluate and fully represent the entire evaluation process. It demonstrates excellent adaptability [46]. Therefore, the use of the cloud model evaluation method can reduce the number of evaluations affected by ambiguity and uncertainty arising from subjective reasons ultimately enhancing the credibility and validity of the final conclusion. This paper employs the cloud modeling algorithm to evaluate the spatial efficiency of TOD metro station areas. It takes into account the randomness and fuzzy nature of data acquisition, making it suitable for data collection. By using the cloud model algorithm to represent variable characteristics, it can incorporate all errors affecting algorithm accuracy. The thickness of the cloud map provides visualized information, reflecting the varying degrees of variable dispersion. With low computational complexity, the cloud model allows for comparing cloud maps of different variables over time to analyze their changes.

The assignment of weights to indicators can be categorized into three main methods: subjective, objective, and hybrid approaches. Subjective methods, such as the Analytic Hierarchy Process (AHP), expert surveys, and ordinal relationship analysis, are straightforward and easily accessible, relying on the decision-maker's judgment. However, they often lack objective elements, which can limit their applicability by introducing bias. On the other hand, objective methods calculate weights based on sample data, resulting in stronger objectivity. These include methods like the entropy method, coefficient of variation, and principal component analysis. While objective methods provide unbiased results, they typically rely heavily on the specific problem domain, limit decision-maker involvement, and can be complex in execution.

Given the strengths and weaknesses of both subjective and objective methods, the COWA operator emerges as a hybrid approach that combines the advantages of both to derive optimal weights. The COWA operator minimizes the influence of extreme values by redistributing weights based on combinations of the data, leading to more objective results compared to AHP. The improved COWA operator enhances this process by integrating weights with combinations, thus mitigating the impact of subjective evaluations while still incorporating the decision-makers' insights. Consequently, this method enhances the accuracy, rationality, and simplicity of calculations.

There are also many evaluation methods for the space efficiency of TOD, such as the AHP method, fuzzy comprehensive evaluation method, gray correlation evaluation method, Delphi method, etc. The cloud model evaluation method has also been applied in the fields of urban renewal project efficiency evaluation, green retrofit risk evaluation, and green building sustainability evaluation. The cloud modeling algorithm is a method from quantitative processing to qualitative analysis expression, which fully considers the randomness and fuzzy changes in the data acquisition process, and is more in line with the characteristics of data collection in practical situations. By establishing the cloud model algorithm to represent the variable characteristics, it can include all the errors that affect the accuracy of the algorithm, and the information of the thickness of the cloud map, which is visualized through the graphics, can reflect the different degrees of dispersion of the variables. On this basis, based on the cloud model with low computational complexity, the comparison of cloud maps composed of different variables in different time periods can be visualized to analyze their changes.

Every evaluation method has its unique applicability, advantages, and limitations. For instance, the Delphi method often suffers from high subjectivity, particularly with larger expert panels, leading to difficulty in reaching a consensus and a lack of scientific rigor. The hierarchical structure of AHP may fail to capture the interrelations between evaluation indicators, resulting in subjective outcomes. While fuzzy comprehensive evaluation techniques hold some advantages, they can struggle with issues such as information redundancy and inadequate fuzzy matrices when multiple indicators are involved.

In contrast, the cloud model evaluation method does not rely on a fixed functional representation. Instead, it synergizes fuzziness and randomness through the integration of the model's expectation, entropy, and hyper-entropy, effectively addressing disadvantages of traditional evaluation methods that yield imprecise assessments. This method not only captures the complete evaluation process but also exhibits excellent adaptability, reducing subjective influences and ambiguity. Thus, the conclusions derived from using the cloud model evaluation method achieve a new level of credibility and effectiveness.

In this study, utilizing the cloud model algorithm for assessing the space efficiency of urban rail transit stations allows for a more scientific and reasonable evaluation while minimizing subjectivity and fuzziness.

3.5.1. Establishing Weights of Factors

In this study, the weighting method of COWA (continuous ordered weighted averaging operator) is used to calculate the weights of spatial efficiency indexes in TOD metro station areas, which lays the theoretical foundation for the establishment of cloud modeling.

(1) Collection and reordering of evaluation data. Invite m experts in the industry to score the importance of each factor, and the score obtained by the factor is proportional to its importance. Evaluation data is obtained as $A = \{a_1, a_2, \cdots, a_j, \cdots, a_m\}$. The evaluation data are rearranged in descending order to obtain $B = \{b_0, b_1, b_2, \cdots, b_j, \cdots, b_{m-1}\}$. $b_0 \geq b_1 \geq b_2 \geq \cdots \geq b_j \geq \cdots \geq b_{m-1}$.

(2) Calculate the weight α_{j+1} for b_j.

$$\alpha_{j+1} = \frac{C_{m-1}^{j}}{\sum_{k=0}^{m-1} C_{m-1}^{k}} = \frac{C_{m-1}^{j}}{2^{m-1}} \tag{1}$$

where i = 0, 1, 2, . . ., $m-1$, C_{m-1}^{j} is the number of combinations of j data from $m-1$ data $\sum_{j=0}^{m-1} \alpha_{j+1} = 1$

(3) Calculate the absolute weight of the factor $\overline{\omega}_i$ based on the obtained weighting vector α_{j+1}.

$$\overline{\omega}_i = \sum_{j=1}^{m} \alpha_j \cdot b_j \tag{2}$$

where $\alpha_j \in [0, 1]$, $i \in [1, n]$, n is the number of.

(4) Calculate the relative weight values of the ω_i.

$$\omega_i = \frac{\overline{\omega}_i}{\sum_{i=1}^{m} \overline{\omega}_i}, i = 1, 2, \cdots, m \quad (3)$$

3.5.2. Calculating the Numerical Characteristics

Each criterion is assessed and results in a series of comments. Based on the characteristics of fuzzy language and consultation with experts, the criteria were classified into five levels: Extremely inefficient (V), Inefficient (IV), Moderate (III), Efficient (II), and Extremely efficient (I). The data attributes corresponding to each criterion are transformed into a standard cloud using a forward cloud generator. The effective range of each factor assessment value is divided into several subintervals based on the set of criteria, and the numerical eigenvalues of the standard cloud for each subinterval are calculated using the following formula:

$$\begin{cases} Ex = \dfrac{V_{max} + V_{min}}{2} \\ En = \dfrac{V_{max} - V_{min}}{6} \\ He = K \end{cases} \quad (4)$$

Among them, the upper and lower limits are V_{max} and V_{min}, respectively. K is a constant value that varies with the ambiguity and vagueness of the variable itself, and Ex, En, and He represent expectation, entropy, and hyper-entropy, respectively.

Expectation: This represents the most typical point in the domain that embodies the qualitative concept. In the context of this study, Ex signifies the expected evaluation of spatial efficiency in the station area. A higher Ex indicates a more favorable perception of spatial efficiency.

Entropy: This quantifies the randomness and fuzziness in the evaluation scores. It reflects how dispersed the evaluations are around the expectation. A larger entropy value results in a wider distribution of cloud drops, indicating greater uncertainty in the evaluation of spatial efficiency.

Hyper-entropy: This represents the degree of uncertainty associated with entropy, illustrated by the "thickness" of the cloud drops. Greater hyper-entropy results in thicker cloud drops, suggesting higher variability in evaluations.

To enhance the clarity and intuitiveness of the cloud diagram, this study utilizes a ten-point system for dividing the index levels, enabling the determination of the range of change corresponding to each qualitative evaluation factor and its related description, as depicted in Table 4.

Table 4. Evaluating grade and numerical characteristics of cloud models.

Level of Space Efficiency	Description	Range of Values	Numerical Characteristics (Ex, En, He)
V	Extremely inefficient	[0, 4)	(2.00, 0.67, 0.10)
IV	Inefficient	[4, 6)	(5.00, 0.33, 0.10)
III	Moderate	[6, 7)	(6.50, 0.17, 0.10)
II	Efficient	[7, 9)	(8.00, 0.33, 0.10)
I	Extremely efficient	[9,10]	(9.50, 0.17, 0.10)

After extensive adjustments, we determined the value of He to be 0.1. Utilizing the evaluation levels established previously, we can construct a standard cloud model to assess the spatial efficiency of TOD metro station areas. This model will allow us to visually and quantitatively represent the spatial efficiency, enabling stakeholders to better understand the performance and effectiveness of development strategies in these areas. This cloud consists of five levels of information. The numerical characteristics of the cloud in Table 4 are utilized to write code and draw the standard cloud diagram of evaluation using MATLAB R2023a software. Each variable, Ex, En, and He, is defined for five different evaluations. These parameters represent the expected value, entropy, and hyper-entropy for different evaluations of space efficiency. A loop iterates N times (N = 3000) to generate cloud drops. For each iteration: Random values for entropy are generated using a normal distribution. Cloud drops (representing evaluation values and their corresponding membership degrees) are calculated based on Ex and the generated entropy values. The resulting membership degree is derived using an exponential function that measures how closely each evaluation corresponds to the expected value, creating a concentrated distribution around Ex.

The following MATLAB code snippet generates the cloud map based on the specified parameters:

```
N = 3000;
% Define parameters for cloud drops
Ex1 = 2; En1 = 0.6667; He1 = 0.1;
Ex2 = 5; En2 = 0.3333; He2 = 0.1;
Ex3 = 6.5; En3 = 0.1667; He3 = 0.1;
Ex4 = 8; En4 = 0.3333; He4 = 0.1;
Ex5 = 9.5; En5 = 0.1667; He5 = 0.1;

% Preallocate array for cloud drops
CloudDrp = zeros(2,N);

% Generate cloud drops
for i = 1:N
    % Generate drops for each parameter set
    E_n1 = normrnd(En1,He1,1,1);
    CloudDrp(1,i) = normrnd(Ex1,E_n1,1,1);
    CloudDrp(2,i) = exp(−(CloudDrp(1,i) − Ex1)ˆ2/(2*E_n1ˆ2));

    E_n2 = normrnd(En2,He2,1,1);
    CloudDrp(3,i) = normrnd(Ex2,E_n2,1,1);
    CloudDrp(4,i) = exp(−(CloudDrp(3,i) − Ex2)ˆ2/(2*E_n2ˆ2));

    % Repeat for other expectation values
    E_n3 = normrnd(En3,He3,1,1);
    CloudDrp(5,i) = normrnd(Ex3,E_n3,1,1);
    CloudDrp(6,i) = exp(−(CloudDrp(5,i) − Ex3)ˆ2/(2*E_n3ˆ2));

    E_n4 = normrnd(En4,He4,1,1);
    CloudDrp(7,i) = normrnd(Ex4,E_n4,1,1);
    CloudDrp(8,i) = exp(−(CloudDrp(7,i) − Ex4)ˆ2/(2*E_n4ˆ2));
    E_n5 = normrnd(En5,He5,1,1);
    CloudDrp(9,i) = normrnd(Ex5,E_n5,1,1);
    CloudDrp(10,i) = exp(−(CloudDrp(9,i) − Ex5)ˆ2/(2*E_n5ˆ2));
end
```

After generating the cloud drops, the following code visualizes the cloud map:

```
% Plotting the cloud map
plot(CloudDrp(1, :), CloudDrp(2, :), '.', 'Color', [0.5 0.5 0.5])
gtext('V', 'FontSize', 22, 'FontWeight', 'bold')
hold on
plot(CloudDrp(3, :), CloudDrp(4, :), '.', 'Color', [0.5 0.5 0.5])
gtext('IV', 'FontSize', 22, 'FontWeight', 'bold')
% Repeat for remaining parameters...
```

xlabel({'Evaluation Value'}, 'FontSize', 22, 'FontWeight', 'bold')
ylabel('Membership'}, 'FontSize', 22, 'FontWeight', 'bold')

The plotted cloud drops illustrate the distribution of evaluations with respect to their membership levels. Each distinct grouping corresponds to a different evaluation scenario (labeled I to V) based on the defined *Ex* values. The concentration of cloud drops near specific Ex points suggests a higher level of agreement among evaluators regarding the spatial efficiency of the station area. Conversely, a wider spread indicates greater variability and uncertainty in evaluations. By utilizing this step-by-step process and visual representation, the cloud model succinctly captures qualitative evaluations of spatial efficiency, providing clear and interpretable results. The standard cloud diagram shown in Figure 4 is obtained.

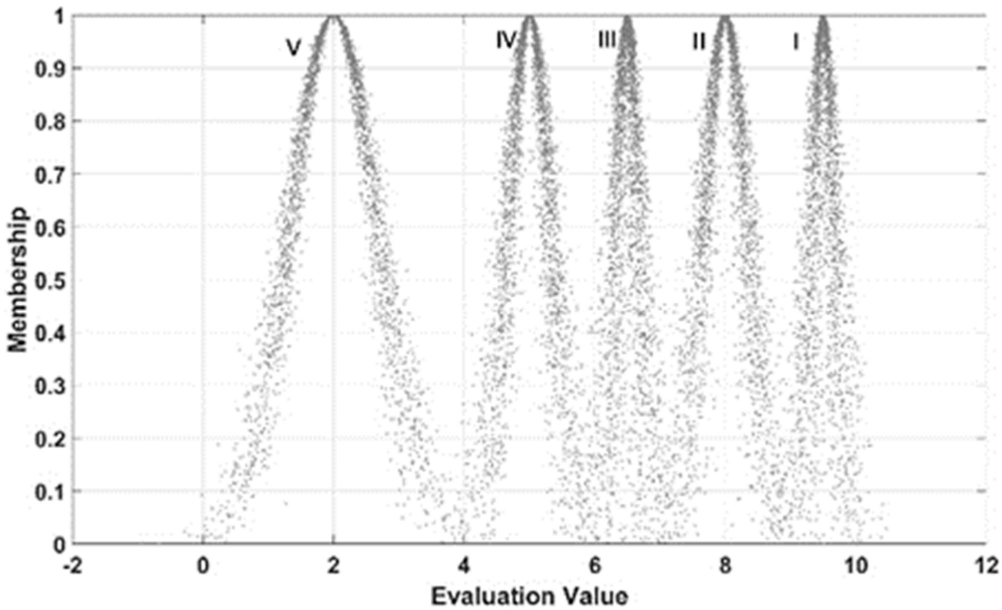

Figure 4. Concept diagram of the standard cloud model.

3.5.3. Developing Comprehensive Evaluation Cloud Model

The evaluation factor cloud is created by calculating the value of each professional scoring result, and then applying the two-way restriction of the factor at each level to determine the highest and minimum scores. After summarizing and analyzing the statistics, the scores of each factor are input into the reverse cloud generator, as shown in Figure 5, to produce the minimum and maximum values of the numerical characteristics.

$$\begin{cases} Ex = \overline{X} \\ En = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum_{i=1}^{n}|x_i - Ex| \\ He = \sqrt{S^2 - En^2} \end{cases} \quad (5)$$

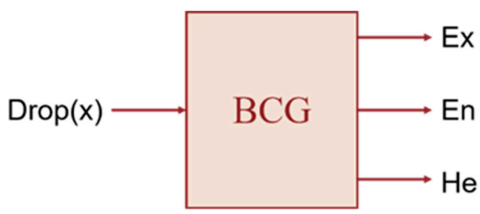

Figure 5. Reverse cloud generator.

Qualitative factors directly calculate numerical characteristics based on questionnaire scores; quantitative factors obtain numerical characteristics after determining their grades according to Table 5. Quantitative factors are determined by summarizing the parameter values of TOD metro station design and the literature, and determining the recommended criteria for the grade of each factor [7,17,46–50].

Table 5. Standard of quantitative factors grades.

Factors	V	IV	III	II	I
D111	[0, 40]	(40, 60]	(60, 75]	(75, 90]	(90, 100]
D112	<4.0	[4.0, 6.0)	[6.0, 7.0)	[7.0, 8.0)	≥8.0
D113	>400	(300, 400]	(200, 300]	(100, 200]	(0, 100]
D114	>1.65	(1.50, 1.65]	(1.35, 1.50]	[1.20, 1.35]	<1.20
D131	[0, 1.0]∪(8.5, ∞) ≤15.9	(1.0, 1.5]∪(7.0, 8.5] (15.9, 23.3]	(1.5, 2.0]∪(5.5, 7.0] (23.3, 24.8]	(2.5, 3.0]∪(4.0, 5.5] (24.8, 33]	(3.0, 4.0] >33
D132	≥2.2	[1.8, 2.2)	[1.5, 1.8)	(1, 1.5]	1
D133	<0.2	[0.2, 0.5)	[0.5, 0.7)	[0.7, 2.2)	≥2.20
D211	[120, ∞)∪(−∞, 50]	(50, 66.7)∪(100, 120)	[66.7, 75)	[75, 85)	[85, 100]
D212	0	1	2	3	≥3
D221	<1.0	[1.0, 1.1)	[1.1, 1.15)	[1.15, 1.2)	≥1.2
D222	<3	[3, 4)	[4, 5)	[5, 6)	≥6
D223	0; 1	2; 3	4; 5	6; 7	≥8
D224	>400	(300, 400]	(200, 300]	(100, 200]	(0, 100]
D231	≤200	[201, 400)	[401, 500)	[501, 1000)	>1000
D232	8333	18,446	29,053	44,949	85,836
D233	≤40	[25, 40)	(20, 25]	(10, 20]	[0, 10]
D311	≤75	(75, 80]	(80, 85]	(85, 90]	>90

When seeking the cloud parameter of the target layer, the cloud parameter of the guideline layer needs to be calculated, and the cloud parameter of the guideline layer amount is calculated on the basis of the cloud parameter of the index layer, and it needs to be calculated layer by layer when seeking the integrated numerical characteristics, which is calculated by the formula:

$$Ex = Ex_1\omega_1 + Ex_2\omega_2 + \cdots + Ex_n\omega_n \tag{6}$$

$$En = \frac{\omega_1^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}En_1 + \frac{\omega_2^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}En_2 + \cdots + \frac{\omega_n^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}En_n \tag{7}$$

$$He = \frac{\omega_1^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}He_1 + \frac{\omega_2^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}He_2 + \cdots + \frac{\omega_n^2}{\omega_1^2+\omega_2^2+\cdots+\omega_n^2}He_n \tag{8}$$

The generation of cloud maps by forward cloud generator in order to make the error of Ex not greater than the set error value Δ, the number of cloud drops should be ≥9S2/Δ2 (S2 is the variance). Generate the cloud map of the evaluation results based on the integrated numerical characteristics to obtain the evaluation results.

4. Empirical Results

4.1. Research Area and Data

Urban construction driven by URT is typically found in newly developed urban areas like suburbs. However, in the extensive and intense built-up areas like urban centers, it is more necessary for URT to adaptively integrate into the city. This integration should evolve and perfect itself in overall integration and interaction with all aspects of the city, gradually improving the quality of life for urban residents and promoting the development of the urban city. With the deepening development of the science of habitat environment, refined urban design research is a new development trend for different research objects in different regions. Harbin, a high-latitude cold city, is subject to a cold climate and is dependent on

URT development. It serves as a new type of urban space for city residents, and urgently needs more targeted theoretical ideas to evaluate and guide the updated design research.

Since its opening in September 2013, Harbin has become the first city in China to have an alpine subway. As of September 2023, there are three subway lines in operation in Harbin, covering a total distance of 79.61 km and serving 66 stations. The subway has facilitated a total of 72.55 million passenger trips and features four interchange stations: Museum Station (see in Figures 6 and 7), Taipingqiao Station, Yidaeryuan Station, and Zhujiang Road Station.

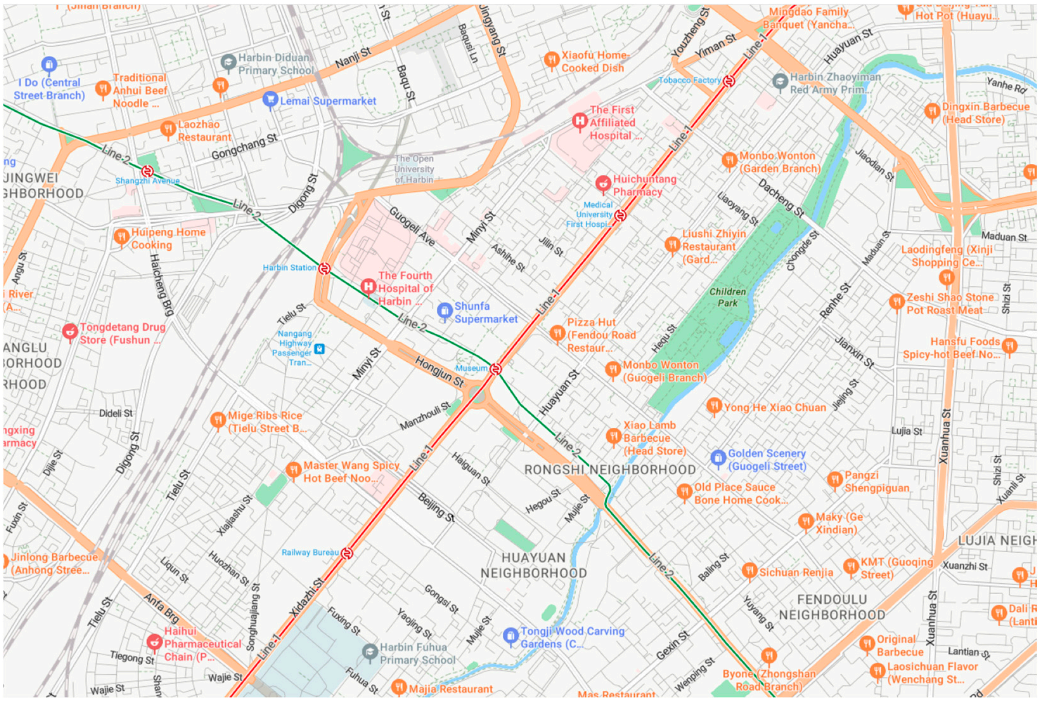

Figure 6. Map of Museum Station.

Overall, reasons for Selecting Harbin as a Case Study is as follows:

(1) Adaptive Integration of Urban Rail Transit (URT): Unlike newly developed suburban areas, urban centers like Harbin require URT systems to integrate adaptively into their existing urban fabric. This study emphasizes the importance of URT evolving in coordination with all aspects of the urban environment, aiming to enhance residents' quality of life.

(2) Focus on High-Latitude Cold Cities: Harbin, being a high-latitude city with a cold climate, presents unique challenges and requirements for URT development. The specific climatic conditions necessitate tailored theoretical approaches to evaluate and guide urban design, making it a relevant case for studying TOD spatial efficiency.

(3) Recent Development of URT in Harbin: Since the opening of its alpine subway in September 2013, Harbin has significantly developed its URT infrastructure. As of September 2023, the city operates three subway lines covering 79.61 km and serving 66 stations, making it a timely context for evaluating the impact of URT on urban space.

(4) Centralized Commercial Complexes: The presence of a large, centralized commercial complex near Museum Station supports mixed-use development, which aligns with TOD principles. This enhances the potential for station-city integration and underscores the station's relevance as a case study site.

(5) Research Trend in Urban Design: The study corresponds with the growing trend toward refined urban design research, which aims to address specific regional contexts.

Evaluating Harbin's TOD system fits into this broader research agenda by providing insights into adaptive urban design strategies.

(6) Extensive Data Availability: The availability of comprehensive data sources, including road networks, rail transit, public transportation, and land use, facilitates a robust analysis of spatial efficiency. These data enables the application of various analytical tools, such as ArcGIS, to derive meaningful insights.

Based on the station–city integration development potential of the site, the presence of a large, centralized commercial complex in the vicinity of Museum Station, and the trend toward mixed-use development, Museum Station was selected as a study site. Sample station profiles are detailed in Table 6 below.

Figure 7. Satellite map of Museum Station.

The data used in this study is primarily sourced from various datasets. The 2023 Harbin road network data, rail transit line data, public transportation data, and building census data are from Open Street Map. The land use base data of Harbin city comes from the vector data of 1:1 million national basic geographic database downloaded from the National Geographic Information Resources Catalog Service System. Population data information is from the *Heilongjiang Provincial Statistical Yearbook*. The required data were loaded in the ArcGIS (Version 10.8). The results of the calculation of the quantitative factors in Table 7 were obtained by the calculation in Table 3, and the qualitative factors are described in the Table 8. Some of the data are visualized as shown in Figures 8 and 9.

Table 6. The basic data of the research object.

Name	Type	Basic Information		Neighborhood
Museum Station	hybrid	Number of entrances and exits	6	Yuanda Shopping Center, Heilongjiang Provincial Department of Education, Hongbo Shopping Center, Heilongjiang Provincial Museum, Shangdu Shopping Plaza, Guomao Shopping Center, Children's Palace Art Center
		Entrance Name	1, 2, 3A, 3B, 4, 5	
		Number of complexes	5	
		Whether it is an interchange station	Yes	
		District/County	Nangang	

Table 7. Quantitative factors.

Quantitative Factors	Calculations of Quantitative Factors	Unit of Measurement
Intersection density D111	1.568	Percentage
Branch network density D112	6.000	km/km^2
Average in-out distance of stations D113	63.000	m
pedestrian route directness D114	1.386	Ratio
Metro travel sharing rate D131	0.036	Percentage
congestion delay index D132	1.579	Ratio
load capacity of Passenger flow D133	0.460	Ratio
The functional mix of the areas surrounding stations D211	2.170	Percentage
Service coverage D212	3	Count
Land use compactness D221	1.150	Ratio
The average entrance number of the block interface D222	3.375	Count
public transport cohesion D223	10	Count/Area
Average transfer distance D224	167	m
Density of permanent population D231	6319.7	Quorum/km^2
disposable income D232	48,190	Yuan
Off-street parking supply D233	0.025	Percentage
Percentage of footpaths with shade and rain protection D311	0.750	Percentage

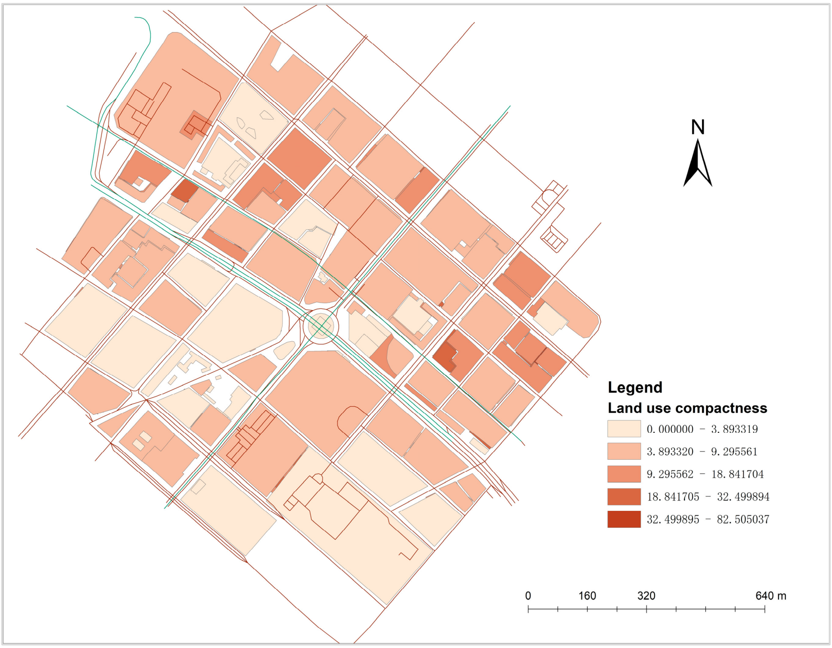

Figure 8. Land use compactness.

Table 8. Qualitative factors.

Qualitative Factors	Description
Walking environment D115	Comfort and convenience of transportation facilities and walking environment.
Public space visibility D121	Is it the best vision.
User-friendliness of Intelligent facilities D122	Does the use of intelligent facilities reduce the difficulty of use.

Table 8. *Cont.*

Qualitative Factors	Description
manual service D123	Whether the service system can quickly solve and meet the use dilemma.
clarity of broadcast D124	The clarity of the broadcast affects how well prompts and safety instructions can be heard.
Walking effectiveness D125	The coordination of walking facilities ensures their continuous function and aligns urban elements, like green spaces and buildings, with esthetic principles.
Site Location D234	Location relationship between station area and city center.
exposure of street connectivity D312	Are there climate protection features in the corridor transition space, entrance, exit, and external connections to shield against cold, ice, and snow.
Spatial functional diversity D321	Does it have diversity characteristics.
Comfort D322	Facilities like public rest seats, barrier-free toilets, space decoration materials, space functional zoning, lighting configuration, physical environment quality, color visual coordination, ground pavement anti-skid, protection device.
Greening landscape construction D331	How does the green landscape design contribute to both physical and mental comfort.
Cultural atmosphere D332	Is it combined with local cultural characteristics.

Figure 9. The functional mix of the areas surrounding stations.

4.2. The Factor Weight of the Evaluation Factors

A total of nine transportation engineering and other field experts and scholars were invited to form an expert panel. Five experts are in the field of urban rail transit, one's field of study is smart cities, and three have conducted research on TOD policies. They used the 0–5 scoring method and their professional knowledge and experience to score at all levels. A larger value indicates greater importance and influence on the spatial efficiency of the TOD metro station area. The results of the factor weights calculated by Formulas (1)–(3) are shown in Table 9.

Table 9. The factor weights of the evaluation system.

Dimensions	Weights	Secondary	Weights	Tertiary	Weights
B1	0.391347099	C11	0.357575758	D111	0.212140307
				D112	0.210249947
				D113	0.192816635
				D114	0.18168452
				D115	0.203108591
		C12	0.344848485	D121	0.202523916
				D122	0.202727458
				D123	0.19051496
				D124	0.19051496
				D125	0.213718705
		C13	0.297575758	D131	0.262622658
				D132	0.365566459
				D133	0.371810883
B2	0.335627663	C21	0.354566385	D211	0.325262481
				D212	0.345189629
				D221	0.329547889
		C22	0.308710668	D222	0.257667678
				D223	0.395517358
				D224	0.346814965
		C23	0.336722947	D231	0.24374289
				D232	0.194539249
				D233	0.242463026
				D234	0.319254835
B3	0.273025238	C31	0.32254073	D311	0.478283351
				D312	0.521716649
		C32	0.340070118	D321	0.465102465
				D322	0.534897535
		C33	0.337389152	D331	0.481283422
				D332	0.518716578

4.3. Calculating the Cloud Model

Through the questionnaire survey, to obtain the museum station passengers on the qualitative level of judgment. The questionnaire was distributed from 23 November 2023 to 23 December 2023, and the questionnaire was mainly a web-based questionnaire, which was generated through the "Questionnaire Star" app, and distributed by scanning the QR code in the vicinity of important stations (including the museum station) during the working hours of urban rail transit in Harbin City, so the main population who filled out the questionnaire were people of all ages who use or are using the subway for commuting, business and entertainment. Therefore, the main group of people who filled out the questionnaire were people of all ages who use or were using the subway in Harbin City for commuting, business, entertainment, and other purposes. The design of the questionnaire is shown in Table 10, and a total of 338 questionnaires were issued. Out of these, 268 were recovered, and after screening, 253 effective questionnaires were obtained, resulting in an effective rate of 94.4%. Most of the passengers are aged between 18 and 50 years old, and the purpose of traveling is mainly for work and leisure shopping, which is in line with the characteristics of the main land around the museum site. The quantitative data obtained from the field survey are used to determine the class and its corresponding numerical characteristics. Based on the questionnaire survey, the cloud parameters of each evaluation were calculated using the inverse cloud generator Formula (5) and the contents of Table 8, as shown in Tables 11–13. The comprehensive evaluation of the cloud was then calculated using Formulas (6)–(8) and then transformed into an evaluation cloud diagram using the forward cloud generator programmed in MATLAB software, as depicted in Figure 10.

Table 10. Questionnaire design details.

	Content	No. of Questions	Type of Questions
Part I	Basic information such as age, occupation, length of residence	4	single-selected questions
Part II	Satisfaction with station space efficiency	16	scale questions

Table 11. Numerical characteristics of the third-grade factors.

	Ex	*En*	*He*	Weights
D111	9.5000	0.1667	0.1000	0.2121
D112	6.5000	0.1667	0.1000	0.2102
D113	9.5000	0.1667	0.1000	0.1928
D114	6.5000	0.1667	0.1000	0.1817
D115	5.2846	1.4252	0.0597	0.2031
D121	6.3014	0.8400	0.0361	0.2025
D122	7.4002	0.8511	0.3786	0.2027
D123	7.0820	0.8150	0.1810	0.1905
D124	4.7045	2.0898	0.3685	0.1905
D125	3.5435	0.6814	0.4796	0.2137
D131	2.0000	0.6667	0.1000	0.2626
D132	6.5000	0.1667	0.1000	0.3656
D133	5.0000	0.3333	0.1000	0.3718
D211	2.0000	0.6667	0.1000	0.3253
D212	8.0000	0.3333	0.1000	0.3452
D221	8.0000	0.3333	0.1000	0.3295
D222	8.0000	0.3333	0.1000	0.2577
D223	9.5000	0.1667	0.1000	0.3955
D224	8.0000	0.3333	0.1000	0.3468
D231	9.5000	0.1667	0.1000	0.2437
D232	8.0000	0.3333	0.1000	0.1945
D233	9.5000	0.1667	0.1000	0.2425
D234	5.5257	1.6574	0.0944	0.3193
D311	2.0000	0.6667	0.1000	0.4783
D312	2.7875	1.0095	0.0876	0.5217
D321	2.8676	1.4803	0.0610	0.4651
D322	4.9805	1.5740	0.5157	0.5349
D331	3.0010	1.5860	0.3224	0.4813
D332	7.4032	1.5188	0.3381	0.5187

Table 12. Numerical characteristics of the second-grade factors.

Secondary	*Ex*	*En*	*He*	Weights
C11	7.4680	0.4254	0.0917	0.3576
C12	5.7792	1.0280	0.2939	0.3448
C13	4.7605	0.3354	0.1000	0.2976
C21	6.0484	0.4391	0.1000	0.3546
C22	8.5933	0.2573	0.1000	0.3087
C23	7.9394	0.7801	0.0978	0.3367
C31	2.4109	0.8529	0.0933	0.3225
C32	3.9978	1.5336	0.3199	0.3401
C33	5.2845	1.5499	0.3308	0.3374

Table 13. Numerical characteristics of the first-grade factors.

Tertiary	*Ex*	*En*	*He*	Weights
B1	6.0799	0.6153	0.1656	0.3913
B2	7.4708	0.5029	0.0992	0.3356
B3	3.9201	1.3268	0.2529	0.2730

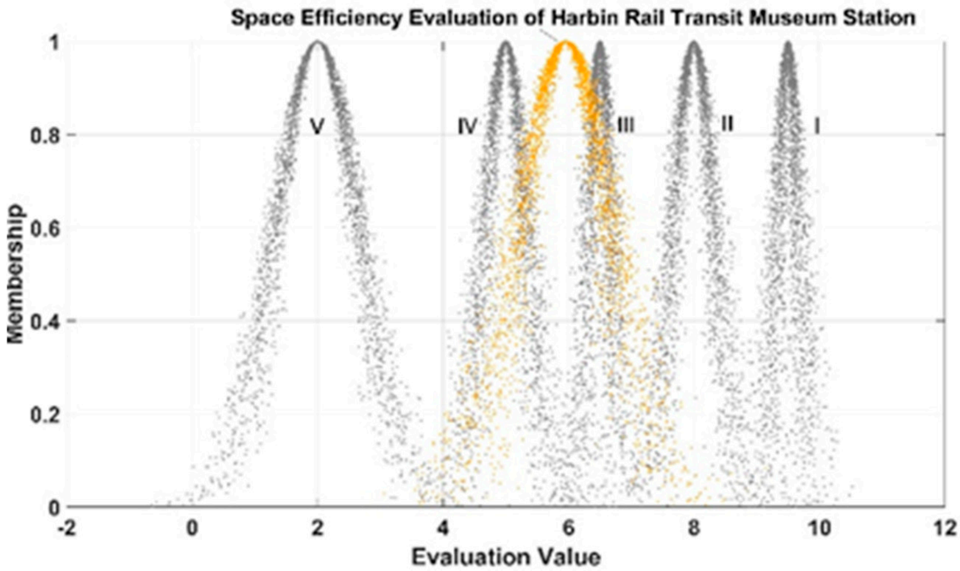

Figure 10. The concept diagram of comprehensive evaluation cloud.

4.4. Results Analysis

The numerical characteristics of each evaluation are entered into the forward cloud generator, and the evaluation cloud map of the dimension is plotted in Figure 10.

In comparing the concept diagram of comprehensive evaluation cloud with the standard cloud diagram in Figure 4, it is evident that the comprehensive cloud model of the Museum Station area falls within the range of "III" to "IV". The cloud droplets are concentrated at 5.96, indicating a probability score of 5.96, corresponding to "moderate". As the distance from 5.96 increases, the cloud droplets become more scattered, signifying a gradual increase in error. Moreover, the cloud thickness also gradually increases. This score reflects the challenges faced by urban rail transit (URT) systems in built-up environments, which is consistent with the observations of Sara M. Ibrahim et al. [9] and Hossein Khosravi et al. [13], who noted that high land use intensity typically complicates the integration of transit infrastructure with adjacent development, but that all but the land use criteria were significantly associated with the utilization of the TOD station area.

Figure 11 reveals that the External Relevance of the Museum station area achieves the highest score, ranging between "II" and "I", with cloud droplets gathering at 7.47, indicating a score close to "efficient" and "extremely efficient". The Internal Coordination gathers at 6.07, denoting an "efficient" rating. The lowest score for the Environmental Adaptation is 3.92, falling within the range of "V" to "IV". Museum station is a comprehensive TOD station located in the center of various types of infrastructure. It is surrounded by public facilities, commercial areas, residential areas, and transportation hubs. However, the constraints on land use diversity are more obvious here, resulting in looser transportation land. The layout of transport arteries lacks systematic scientific planning, which negatively impacts URT construction in the context of TOD requirements.

Regarding the evaluation results, the development of External Relevance in the museum station area is balanced due to the diverse land use. The bus transfer station's density has helped promote the TOD mode to meet commuting needs. There are residential neighborhoods and supporting spaces in the area to enhance work–life balance and city quality. However, the External Coordination element indicates that the external diversity does not perfectly match the population size.

In the Internal Coordination dimension, since the station is in the busy part of the old city, there is the phenomenon of over-concentration of urban functions, so the setting of the URT station has the function of easing traffic congestion. In order to realize convenient transfer, the entrances and exits of the station are generally closely integrated with commercial complexes, and some of them are directly connected to the interior of the buildings. The density of transit interchanges around Museum Station promotes a TOD model that meets commuting needs while supporting a balanced integration of residential, commercial, and public facilities. This result is consistent with previous findings, such as those of the scholar Ruoyu Wang [51] who emphasized the importance of diverse land uses to improve the connectivity and operational efficiency of urban transportation hubs. Changes in accessibility due to TOD strategies may affect areas closer to metro stations more. However, the URT does not essentially solve this problem in the Museum Station area. The area with the business office industry functions of the agglomeration, the tidal traffic increases, the walking distance is farther and farther away from the station, and the problem is becoming more and more prominent. In addition, the station should have more escalators or barrier-free facilities and services in the interior space to improve walking continuity.

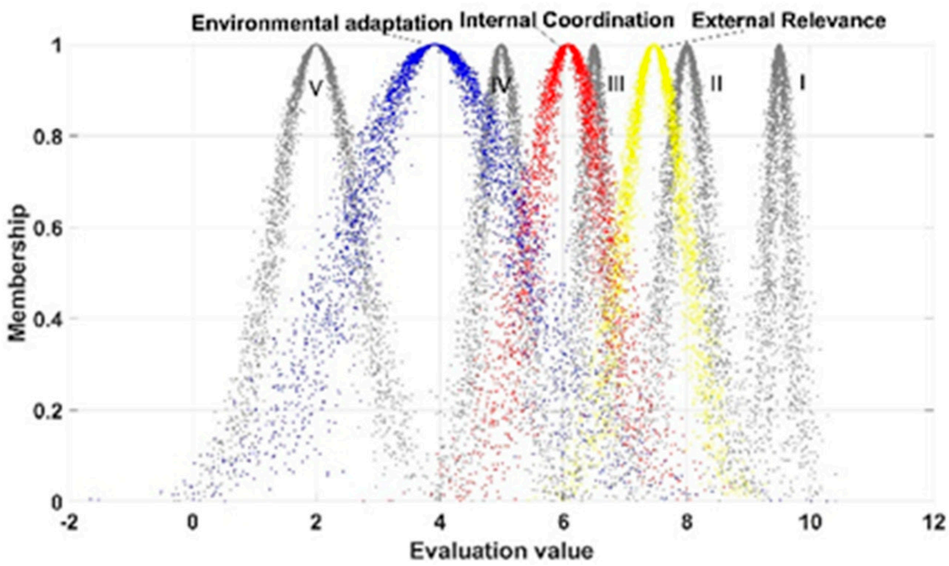

Figure 11. Concept diagram of dimension evaluation cloud.

The analysis revealed a significant difference in the Internal Coordination element, with a score of 6.07. This score, categorized as "efficient", suggests that the overconcentration of urban functions in the older city center poses a challenge, despite efforts to connect transit options to the business district. Past research, including that of Xiang Liu [28], has highlighted similar problems in historic urban centers, where transit stops are not adequately designed to accommodate surging commuter volumes, thus exacerbating traffic congestion. The age of the built environment has a significant impact on patronage. Thus, Yingying Xu's findings also confirm that the addition of escalators and accessibility can make it easier for the elderly and disabled to get around [52], improve the human inclusiveness of the city, and that better infrastructure can support more foot traffic.

Harbin is a cold city with long winters and a lot of rain and snow. In terms of Environmental Adaptation, the station focuses on the cultural exploration of regional characteristics, but the comfort in rain and snow needs to be further improved. The low score of 3.92 for the Environmental Adaptability dimension suggests that the station design suffers from significant deficiencies in addressing Harbin's unique climatic challenges. While the incorporation of regional cultural characteristics in station design is commendable, peer studies have shown that passenger comfort in adverse weather conditions is often overlooked. At the same time, Chuan Ding et al. [53] argue that the integration of public transportation with a highly walkable greenway network will increase the utilization of public transportation.

These results suggest that Museum Station, as a central commercial TOD station, has a high external correlation index, followed by internal coordination, and the lowest score for environmental adaptation. Overall, the spatial efficiency of the museum station is slightly low, indicating a need for improvement in creating a more human-centered and comfortable station environment in the cold city of Harbin.

4.5. Improved Advice

For a complex adaptive system, the subject must constantly and actively adapt to changes in external stimuli in order to achieve the integration and optimization of internal elements by adjusting its own "reaction rules". After evaluating the space efficiency of TOD metro station areas, the following improvements are necessary:

(1) Enhance Internal Coordination: Firstly, improve Vertical Connectivity. Install more elevators and escalators to better connect different levels of the station and commercial areas, maximizing the use of vertical space. Secondly, redesign Circulation Paths. Create clearer pathways that facilitate the movement of pedestrians from the commercial areas to the station. This can be achieved through better signage and intuitive design layouts. In addition, the walkways are too narrow and lack escalators, reducing capacity. To improve this, increase the capacity and manage the flow. In high-traffic areas, add escalators to ease congestion. Create zones with signage to control flow. Figures 12 and 13 are taken in the museum station by the author.

(2) Capitalize on External Relevance: Firstly, integrate with Surrounding Infrastructure. Strengthen connections to nearby public transport options, encouraging seamless transfers and improving overall user experience. Secondly, promote Mixed-Use Developments. Support the development of more mixed-use spaces around the station to foster a vibrant urban environment. Coordinate with local businesses to enhance commercial offerings around Museum Station.

(3) Improve Environmental Adaptation: The cold city of Harbin needs to upgrade its Public Facility Infrastructure. Modernize outdated public and transportation facilities to improve functionality and comfort. This includes ensuring heating systems and insulation are adequate for cold weather conditions. Introduce environmentally friendly facilities that help mitigate the effects of harsh weather, such as windbreaks, covered walkways, and heated waiting areas. Street trees, greening, street furniture, and soft separation interfaces can enhance the walking environment and provide a sense of comfort. Ensuring sufficient scale and smoothness of the walking net area is crucial for accommodating people with suitcases in the cold metro station space. Given the expansive nature of the Museum Station area and the limited integration of the current construction, many pedestrians inevitably experience prolonged exposure to cold outdoor conditions while navigating the station. In winter, the extreme weather in Harbin severely limits walking time. Therefore, the performance of the walking corridor in terms of wayfinding efficiency is crucial. Wayfinding efficiency hinges on legibility and continuity. To maintain high wayfinding efficiency during winter, adjustments should be made to align with winter line-of-sight marking habits. This entails setting line signs closer to sidewalks and other core areas and reinforcing line signs in the near-ground range while supplementing appropriate wayfinding guidance.

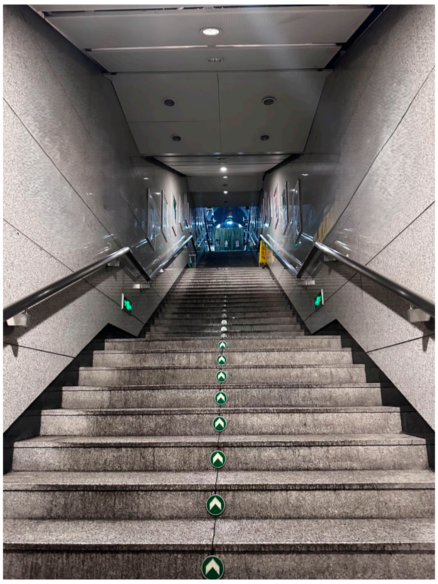

Figure 12. Upstairs without escalator.

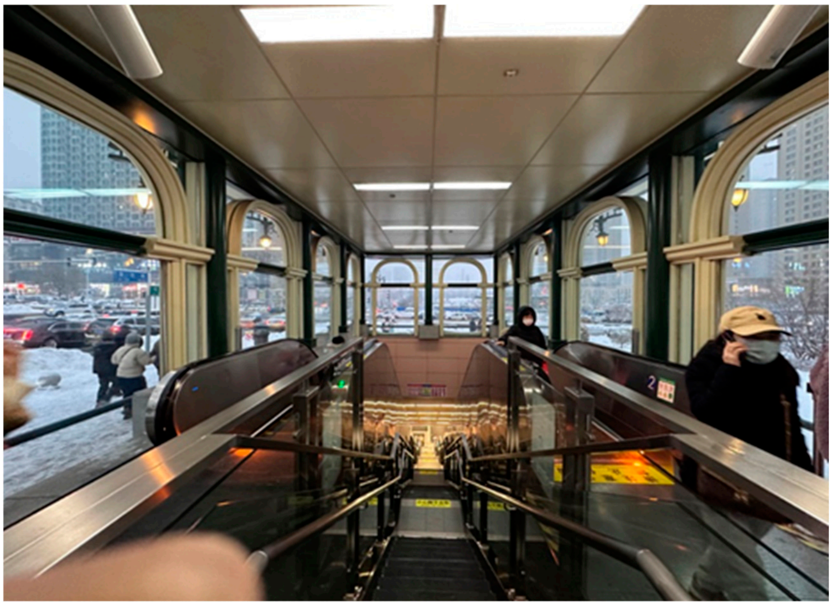

Figure 13. Access with up and down escalators.

5. Conclusions

This study explores the characteristics of transit-oriented development (TOD) and spatial efficiency through the lens of complex adaptive systems. By introducing the concept of the TOD metro station area as a complex system based on seven characteristics of complex adaptive systems, we summarize its fundamental features, deconstruct it, and construct a framework that includes Internal Coordination, External Relevance, and Environmental Adaptation. We design an evaluation system for the spatial efficiency of station areas and propose a novel evaluation method that combines the continuous ordered weighted averaging (COWA) operator and cloud model. In this approach, qualitative factors are quantified as evaluation clouds, with results presented in terms of expectation, entropy, and super entropy.

Using the Museum Station of Harbin as a case study, we evaluate its spatial efficiency, providing valuable insights for TOD metro station planning and facilitating future updates and strategic positioning of each station area. The findings reveal several key aspects of the Museum Station's performance: (1) the Internal Coordination evaluation result of the museum metro station corresponds to the grade of "efficient". The commercial complex has less connection with the underground of the station, the utilization rate of vertical three-dimensional space is low, and the accessibility of slow walking is low, leading to poor spatial and economic efficiency of the station area. (2) The evaluation result of the External Relevance is "extremely efficient". The commercial and business space in the station area of the Museum Station is extended horizontally, the transportation environment and functional configuration are perfect, and the spatial efficiency of the external connection dimension is high. (3) The evaluation result of the Environmental Adaptation is moderate. The site of Museum Station is located in the center of Harbin, the public service facilities in the station area are perfect, and the accessibility of the station area is high. However, the public facilities and transportation facilities in the station area are old, and there is a lack of environmentally friendly facilities for avoiding cold winds, rain, and snow in the cold environment, resulting in low efficiency of environmental adaptation, so the following improvements are essential:

(1) **Enhance Internal Coordination**:

Vertical Connectivity: Add more elevators and escalators to connect different levels of the station and nearby commercial areas.

Redesign Circulation Paths: Create clearer and wider pathways for pedestrians, with better signage to guide movement and reduce congestion.

(2) **Capitalize on External Relevance**:

Integrate with the Surrounding Infrastructure: Strengthen links to nearby transport options for smoother transfers.

Promote Mixed-Use Developments: Encourage the growth of mixed-use spaces around the station to create a lively urban environment.

(3) **Improve Environmental Adaptation**:

Upgrade Public Facilities: Modernize the station's facilities to ensure comfort in cold weather, including adequate heating and shelter.

Enhance the Walking Environment: Introduce features like windbreaks and green spaces to improve comfort for pedestrians.

Focus on Wayfinding Efficiency: Position signage closer to pedestrian pathways to aid navigation and visibility during winter.

Combined with the station types, the evaluation results are generally in line with the actual functional positioning of the TOD station area, but there are parts that need to be optimized.

(1) Limited Scope of Case Study: The research focuses solely on the Museum Station, which restricts the generalizability of the findings. Future work should consider a comparative evaluation involving multiple key interchange stations to provide a broader context.

(2) Lack of Comparison with Other Evaluation Methods: The findings are not contrasted with results from other evaluation methods due to insufficient data. This limitation prevents a comprehensive understanding of how the proposed method performs relative to established approaches.

(3) Insufficient Data for Other Indices: The study relies on data that may not fully capture all relevant evaluation indices, limiting the depth of the analysis and insights provided.

Overall, the results of this study are not compared with other evaluation methods because more data need to be obtained for other evaluation methods. They only illustrate the advantages of this method compared with a single method, which can be combined with other cases to conduct in-depth research. Only one site was selected for this study, and a comparative evaluation of the space efficiency of multiple key interchange sites will be considered in the future.

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