Space Gene: An Identification Approach

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Abstract: Research on space genes, which reveals the spatial organization laws of urban form, plays a crucial role in balancing ecological protection, cultural inheritance, and contemporary development, offering significant value for both research and practice. However, due to the absence of a systematic approach to identifying space genes, the objectivity, completeness, and reliability of findings are often questionable. Based on an in-depth understanding of space genes, this study proposes that the key to identifying space genes lies in the recognition of interactions between space, nature, and humans within urban characteristic spaces. The identification process is elaborated in five steps: summarizing urban characteristic spaces; gaining public recognition of characteristic spaces; clustering and filtering of spatial cognition features; abstracting the configuration relationships of spatial elements; and integrating a set of spatial organization rules. Accurately identifying space genes directly enhance the operational efficiency and accuracy of space gene analysis and its practical applications. This approach contributes effectively to planning and design for local sustainable development.

Keywords: space gene; spatial development theory; pattern of spatial organization; identification; extraction

Chinese Library Classification No.: TU984; Document Code: A

DOI: 10.16361/j.upf.202501003; Article No.: 1000-3363(2025)01-0018-07

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Funding: National Key R&D Program of China, "Research on Planning Technologies for the Protection and Renewal of Characteristic Towns and Villages" (Project No. 2019YFD1100700).

To address the destruction of natural environments and the rupture of historical and cultural continuity in urban development, Duan et al.[1] introduced the concept of the "space gene" and developed a technical system for its analysis and inheritance. Because space genes carry regional information and sustain harmonious relationships among space, nature, and culture, this system provides an operational pathway for achieving mutually reinforcing outcomes in environmental protection, historical and cultural inheritance, and urban development. Related studies have offered important technical support for maintaining local distinctiveness[2-4], inheriting Chinese city-building concepts[5-6], and activating local development momentum[7-8].

The technical system for space-gene analysis and inheritance consists primarily of three components: identification and extraction, analysis and evaluation, and inheritance-oriented guidance and control. Identification and extraction are the first step and provide the essential basis for subsequent analysis, evaluation, and guidance. Research on space genes, however, remains at an early stage. Neither the objects of identification nor the procedures and methods employed have yet been supported by objective, scientific, and systematic criteria. Most studies rely on abstract principles or conventional sociological and morphological methods, making the process excessively dependent on the abilities and experience of planners and designers. Subjective influences are therefore substantial, and practical work is prone to unclear, incomplete, or incorrect identification and extraction. At root, these problems arise from an inadequate understanding of the concept and mechanism of space genes:

without a scientific account of what a space gene is, how it operates, and why it operates in that way, an appropriate identification pathway cannot be established.

Whether the space genes within a study area can be identified completely and accurately directly determines the efficiency and precision with which space-gene analysis and inheritance technologies can be applied. Drawing on the conceptual meaning and operating mechanism of space genes, this article therefore proposes an identification and extraction pathway intended to provide methodological support for related work and to advance the complete construction of the technical system for space-gene analysis and inheritance.

1 Theoretical Basis and Approach to Identification and Extraction

1.1 Core Meaning and Operating Mechanism of Space Genes

The concept of the "space gene" was first proposed in 2019. It refers to "distinctive and relatively stable patterns of spatial organization formed through the interaction of urban space with the natural environment and the socio-cultural context." Space genes are products of the long-term, coordinated evolution of space, nature, and culture[1]. In 2022, their meaning and operating mechanism were further elaborated[9]. In summary, a space gene is a pattern of interaction among space, nature, and culture selected by local development conditions through the self-organization of a complex urban system. It has three characteristics: ① Materially, it appears in space as a specific configurational relationship among spatial elements. ② Hierarchically, it exists at multiple spatial levels, including the city, block, plot, and building. ③ Informationally, it contains urban information concerning the construction concepts adapted to local conditions of survival and development at a particular time. Its operating mechanism comprises three processes: coding, replication, and expression. First, spatial elements form a space gene according to specific coding rules and thereby carry urban information concerning harmonious local interactions among space, nature, and culture. Second, with the space gene as the medium, this information is replicated through synchronic and diachronic transmission. Finally, the space gene is expressed as a visible and accessible material form[9].

This discussion of the meaning and mechanism of space genes refines our understanding of the concept. On the basis of construction concepts conducive to local survival and development, a space gene encodes spatial elements into specific configurational relationships, storing, transmitting, and expressing urban information that embodies the construction concepts of a given place and time. In this way, it controls and influences the evolution and development of urban spatial form. An accurate understanding of this conceptual meaning and operating mechanism provides the basis for identifying and extracting space genes systematically and scientifically.

1.2 An Approach to Identifying and Extracting Space Genes

Research on the identification and extraction of biological genes commonly proceeds by comparing gene sequences across organisms displaying a particular "trait" and control cases without that trait, thereby determining the relationship between the gene and the trait. This approach also offers a clue for the identification and extraction of space genes. As the British architectural and urban morphologists B. Hillier and colleagues argued in The Social Logic of Space (1984)[10], although urban space and biological organisms differ fundamentally, they share essential properties, including mechanisms of information transmission, systemic evolution, and stability. The mechanism of searching for and extracting a "gene" from a "trait" is therefore also applicable to investigations of the organizational logic underlying urban spatial form.

If the physical or physiological characteristics of an organism are the traits expressed by biological genes[11], then the material form of a space and the feelings people experience within it can be understood as traits expressed by space genes. Identifying and extracting space genes is thus a spatial tracing of regional characteristics. Its core task is to identify the pattern of interaction among space, nature, and culture contained within a particular spatial characteristic - the expressed trait of a space gene, including spatial cognition and spatial form. This interaction pattern comprises both the configurational relationships among spatial elements at the material level and the construction concepts at the informational level. The process consists of five steps: ① inventory characteristic spaces; ② obtain public perceptions of the characteristics of these spaces; ③ cluster and screen the publicly perceived spatial characteristics to identify the expressed traits of space genes; ④ abstract these expressed traits into configurational relationships among spatial elements; and ⑤ screen the configurational relationships in light of the trait characteristics and the construction concepts they embody, combining them into a set of spatial organization rules that governs trait expression. See Fig. 1.

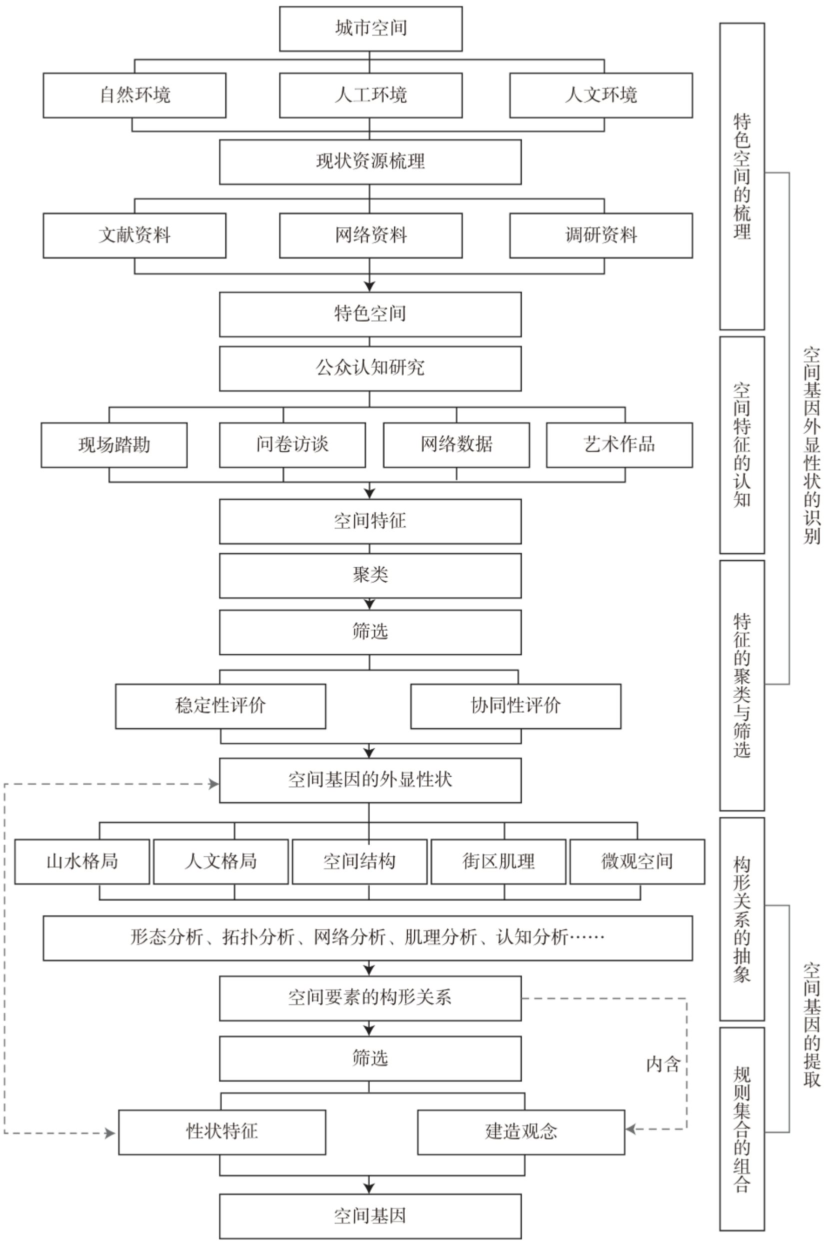


Fig.1 The identification process of space genes

2 Identifying the Phenotypic Traits of Space Genes

2.1 Inventorying Characteristic Spaces

The first step is to review existing materials and compile an inventory of locally characteristic resource spaces. In general, the distinctiveness of a city is manifested in three dimensions: the natural environment, the built environment, and the cultural environment. The inventory may draw on documentary sources, such as World Heritage lists, lists of protected cultural relics, and inventories of intangible cultural heritage; online sources, such as satellite images, street-view photographs, and documentaries; and field materials, such as local accounts and photographs and videos taken on site[12-14].

Each entry in the inventory must include both the name of the characteristic resource and its spatial carrier. Even characteristic resources in the cultural dimension are supported by corresponding spatial carriers, and these carriers become the material objects of subsequent research. Five-Ancestor Boxing, for example, is a national intangible cultural heritage practice widely found in southern Fujian. Xiamen is one of its places of origin, and the spatial layouts of traditional dwellings there have been influenced by this culture: spaces for martial-arts practice are deliberately arranged outside the houses. Such spaces constitute characteristic resource spaces of Xiamen's traditional dwellings.

2.2 Eliciting Public Perceptions of Characteristic Spaces

The second step is to connect characteristic resource spaces with public experience through studies of perception, thereby producing an inventory of perceived spatial characteristics. Public perception can be investigated through four principal channels: field observation, questionnaires and interviews, online data, and artistic works[14-17]. First, researchers must personally conduct field observation to obtain authentic perceptual information and avoid assumptions and conjecture. Second, online data, with their large volume, broad population coverage, and diverse content, help improve the objectivity and accuracy of public-perception research. Third, in areas where online data are difficult to obtain, and in order to ensure diversity among public respondents, conventional social-survey methods such as questionnaires, group discussions, and interviews remain among the most effective approaches. Finally, poems, paintings, songs, and other works created by artists from lived experience contain their perceptions and feelings regarding characteristic spaces and can inform researchers' judgments of spatial cognition.

Some public perceptions may be too broad to locate a corresponding material space and therefore require further refinement. Conversely, some spatial carriers underlying public perceptions may not have been identified during the initial inventory of characteristic resource spaces and can be added at this stage. "Beautiful Xiamen," for example, is a shared understanding among Xiamen residents, the municipal government, and experts①. At the outset of research, "beauty" might easily be treated as one of Xiamen's typical characteristics. Yet almost any spatial carrier can be associated with beauty, so the characteristic must be subdivided. More detailed investigation may refine Xiamen's beauty into such characteristics as a city where mountains and sea merge, elegant and romantic bays, and garden-like streets.

2.3 Clustering and Screening Spatial Characteristics

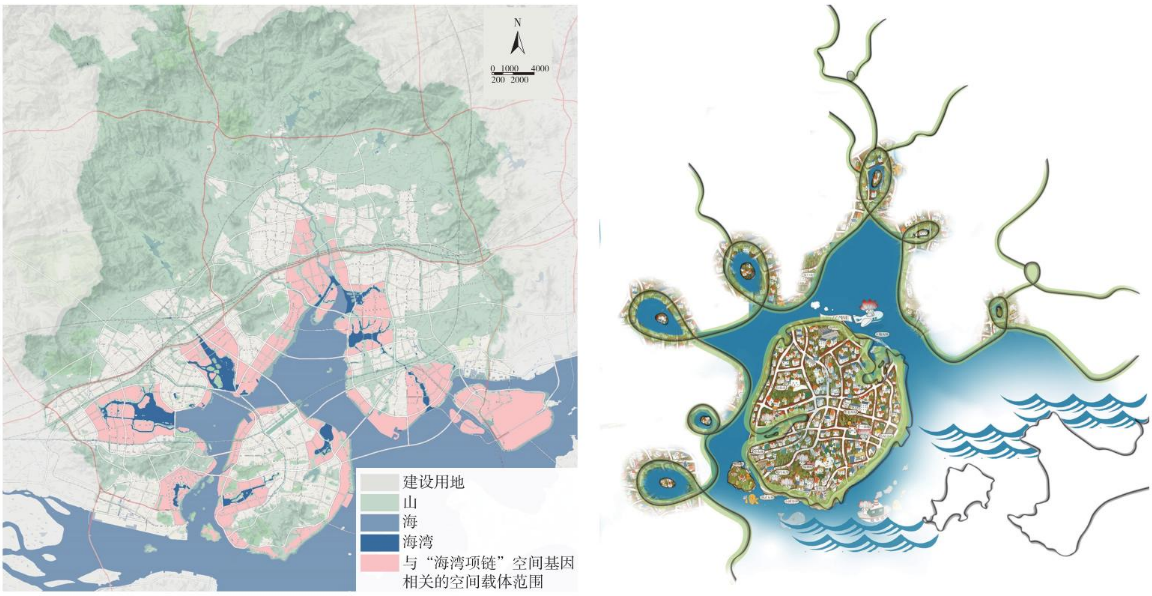
The third step is to screen the publicly perceived spatial characteristics in light of the basic definition of a space gene, identifying those spatial characteristics and carriers influenced by a particular space gene - namely, its expressed traits - and compiling an inventory of those traits. This means that not every characteristic identified in the preceding work necessarily contains a space gene.

Some may result from deliberate human intervention and may not have been selected through the operation of the spatial system. A spatial characteristic containing a space gene must satisfy the basic definition of a space gene: it must be distinctive, relatively stable, and based on harmonious interaction among nature, culture, and space. The spatial characteristics obtained in the previous step must therefore be evaluated for stability and synergy.

First, spatial characteristics may be clustered to improve screening efficiency. The replication mechanism of space genes indicates that genes spread synchronically, causing spatial characteristics to display regional similarity. Grouping similar characteristics therefore improves the efficiency of identification and extraction. Clustering may be undertaken with any of the many available algorithms or manually. Based on the hierarchical attribute of space genes, the clustering principle should assign spatial characteristics to the spatial level emphasized by the research. In a citywide study, for example, it is unnecessary to focus excessively on the detailed characteristics of a single building or place; instead, the general characteristics displayed by that type of building or place at the citywide level may be summarized.

Second, evaluations of stability and synergy analyze material spatial form using historical maps and records. Stability evaluation concerns the diachronic development of spatial form and asks whether abrupt structural changes have occurred. Synergy evaluation focuses on the factors shaping spatial form and asks whether their relationships are harmonious and sustainable. To determine whether the characteristic "romantic and elegant coastal space" contains a space gene, historical sources and maps may first be used to show that Xiamen's urban development - whether spontaneous construction or planned proposals - has consistently followed the pattern of "building around the sea and developing along bays"②. The characteristic must then be shown to arise from harmonious interaction among space, nature, and culture: deep bays provide safe and comfortable settings for waterfront production and everyday life, attracting service industries and concentrations of human activity③.

The spatial characteristics that satisfy the definition of a space gene can thus be selected as the expressed traits of a particular gene. At this point, the gene may be named with reference to spatial form or public cognition. The confirmed characteristic "romantic and elegant coastal space," for example, can be linked to its spatial carriers and named the "Bay Necklace" space gene. Ring-bay avenues connect a series of bays like a necklace set with pearls, together forming a uniquely romantic and elegant framework of coastal public space. See Fig. 2.



（a）空间载体　　　　　　（b）抽象结构

Fig.2 Material space (left) and abstract structure (right) of space genes

3 Extracting Space Genes

3.1 Abstracting Configurational Relationships among Spatial Elements

The fourth step is to abstract each selected expressed trait of a space gene - here, primarily material spatial form - into a number of configurational relationships among spatial elements. The coding mechanism of space genes indicates that, on the basis of construction concepts selected through interaction among space, nature, and culture and better suited to local survival and development, people arrange spatial elements so that specific configurational relationships emerge among them.

More than a century of research across multiple disciplines has examined how configurational relationships may be abstracted from material spatial form. Building on previous studies[10,18-22], these relationships can be grouped into five categories. The first concerns relationships between built-up areas and natural elements, such as landscape patterns. The second concerns citywide cultural-space nodes and landmarks and the relationships among them, such as cultural patterns. The third concerns integrated spatial structures, road systems, and movement networks, such as street-network and public-space structures. The fourth concerns the fabrics of different types of districts, including garden and courtyard relationships. The fifth centers on human perception and spatial relationships closely connected to everyday activity, including architectural space and street interfaces. At this stage, these categories provide clues for investigating their specific local manifestations through morphological, topological, network, fabric, cognitive, and other forms of spatial analysis[22-24].

To avoid omitting key configurational relationships, all spatial elements contained in each expressed trait may also be exhaustively combined to form a spatial-element matrix. The local manifestations of the five categories of configurational relationships, as identified through the analytical methods above, can then be associated with this matrix. Its systematic and open structure allows findings from multiple sources to complement and verify one another. Each expressed trait of a space gene can therefore generate a spatial-element matrix containing a number of configurational relationships abstracted from the trait.

The spatial elements involved in Xiamen's "Bay Necklace" gene include sea, island, bay, city, and trees. The resulting spatial-element matrix (Table 1) shows the following. In the relationship between the city and natural elements, historical maps reveal a "C-shaped large bay with bays within bays," a "city on the sea and sea within the city," and "islands within the bay" (site nos. 2, 3, and 18). Distance measurements based on satellite imagery provide ranges for bay depth and sinuosity (site no. 2). In terms of spatial structure, integration analysis of historical status maps and planning maps, together with point-of-interest data, identifies such relationships as the connection of the main island with offshore urban clusters and the use of bays as public centers (site no. 11). For movement routes, destination popularity rankings calculated from online comments and travel guides reveal highly valued scenic routes (site no. 11). At the micro-spatial level, tourist photographs and street-view imagery show that coastal areas are commonly planted with tall palms and other tropical vegetation; blue sky, white clouds, white sand, and green trees create vivid, romantic, and refreshing coastal colors (site nos. 4 and 7). The imagery also reveals the sequential relationship of "city-bay-sea-island" (site nos. 13, 21, 25, and 26). Satellite-based distance measurement further identifies layered depth relationships among mountains, sea, islands, city, and bays within the human field of view (site nos. 32, 41, and 47).

Tab.1 Relationship matrix of spatial elements of space genes

空间矩阵	海	岛	湾	城	树	湾/城	湾/树	城/树	湾/城/树
海		1	2	3	4	11	12	13	21
岛			5	6	7	14	15	16	22
湾				8	9			17	
城					10				
树									
海/岛			18	19	20	23	24	25	26

特征图示	位点编号:2 空间关系:海—湾 C型大海湾	位点编号:2 空间关系:海—湾 湾中有湾	位点编号:2 空间关系:海—湾 湾的曲折率(L/W)=3.12-5.22; 湾的进深度(d/W)=1.31-1.7
特征图示	位点编号:3 空间关系:海—城 城在海上,海在城中	位点编号:4 空间关系:海—树 滨海为热带植物	位点编号:4 空间关系:海—树 岛上有树
特征图示	位点编号:11 空间关系:海—湾—城 沿湾建设公共中心	位点编号:11 空间关系:海—湾—城 连续景观大道串联海湾	位点编号:11 空间关系:海—湾—城 本岛与岛外组团串联
特征图示	位点编号:13 空间关系:海—城—树 “城—树—海”的空间序列		位点编号:18 空间关系:海—岛—湾 湾中有岛
特征图示	位点编号:19 空间关系:海—岛—城 景深层次丰富,D_1=1-2 km,D_2=1-2 km		
特征图示	位点编号:21 空间关系:海—湾—城—树 “城—树—湾—海”的空间序列		位点编号:23 空间关系:海—岛—湾—城 环湾看岛
特征图示	位点编号:25 空间关系:海—岛—城—树 “城—树—海—岛—海—城”的空间序列		
特征图示	位点编号:26 空间关系:海—岛—湾—城—树 “城—树—湾—海—岛—海—城”的空间序列		
特征图示	位点编号:1 空间关系:海—岛 无明显特征关系	位点编号:5 空间关系:岛—湾 无明显特征关系	位点编号:6 空间关系:岛—城 无明显特征关系
特征图示	位点编号:8 空间关系:湾—城 无明显特征关系	位点编号:9 空间关系:湾—树 无明显特征关系	位点编号:10 空间关系:城—树 无明显特征关系
特征图示	位点编号:12 空间关系:海—湾—树 无明显特征关系	位点编号:14 空间关系:岛—湾—城 无明显特征关系	位点编号:15 空间关系:岛—湾—树 无明显特征关系
特征图示	位点编号:16 空间关系:岛—城—树 无明显特征关系	位点编号:17 空间关系:湾—城—树 无明显特征关系	位点编号:20 空间关系:海—岛—树 无明显特征关系
特征图示	位点编号:22 空间关系:岛—湾—城—树 无明显特征关系	位点编号:24 空间关系:海—岛—湾—树 无明显特征关系	

3.2 Combining Spatial Rules that Generate Phenotypic Characteristics

The fifth step is to screen the configurational relationships within each spatial-element matrix and combine them into a set of spatial rules that constitutes the necessary and sufficient conditions for the expression of the characteristic. In other words, the configurational relationships abstracted from an expressed trait do not all need to be retained unchanged; they can be merged and screened. Screening should be guided by the trait characteristic and the construction concepts it contains. If the configurational relationships in the proposed rule set are insufficient to support the formation of the trait, the trait must be analyzed again. Conversely, relationships that do not decisively influence the characteristic, or that embody construction concepts inconsistent with harmonious local interactions among space, nature, and culture, may be removed.

The informational attribute of space genes shows that, although a gene appears to be a pattern of spatial organization composed of multiple configurational relationships among spatial elements, in essence it is a comprehensive reflection of interactions between human activities and the natural environment under specific development conditions. Research limited to the material expression of elements is therefore inadequate. Only by uncovering the construction concept contained in each configurational relationship and checking it against harmonious interaction among space, nature, and culture can the genuine logic underlying spatial form be grasped. By investigating the construction information embedded in each relationship and combining the relationships into a necessary and sufficient set of spatial rules governing the expression of a space gene's phenotype, the complete meaning of the gene can be identified and extracted.

In the "Bay Necklace" space gene, for example, the core configurational relationships all revolve around bays: a C-shaped large bay containing smaller bays and islands; sinuous and relatively deep bay forms, with a sinuosity of approximately 3.12-5.22 and a depth ratio of approximately 1.31-1.70; urban public centers constructed along the bays; continuous scenic avenues connecting the bays; and tropical planting along the coast. Together these produce the spatial sequence "city-tree-bay-sea-island-sea-city" and a uniquely romantic and elegant coastal public space. All are concrete expressions of harmonious interaction among space, nature, and culture. By contrast, the configurational relationship "city on the sea, sea within the city" is only weakly connected with the bays, while "trees on islands" is excessively detailed; both may therefore be deleted. See Fig. 3.

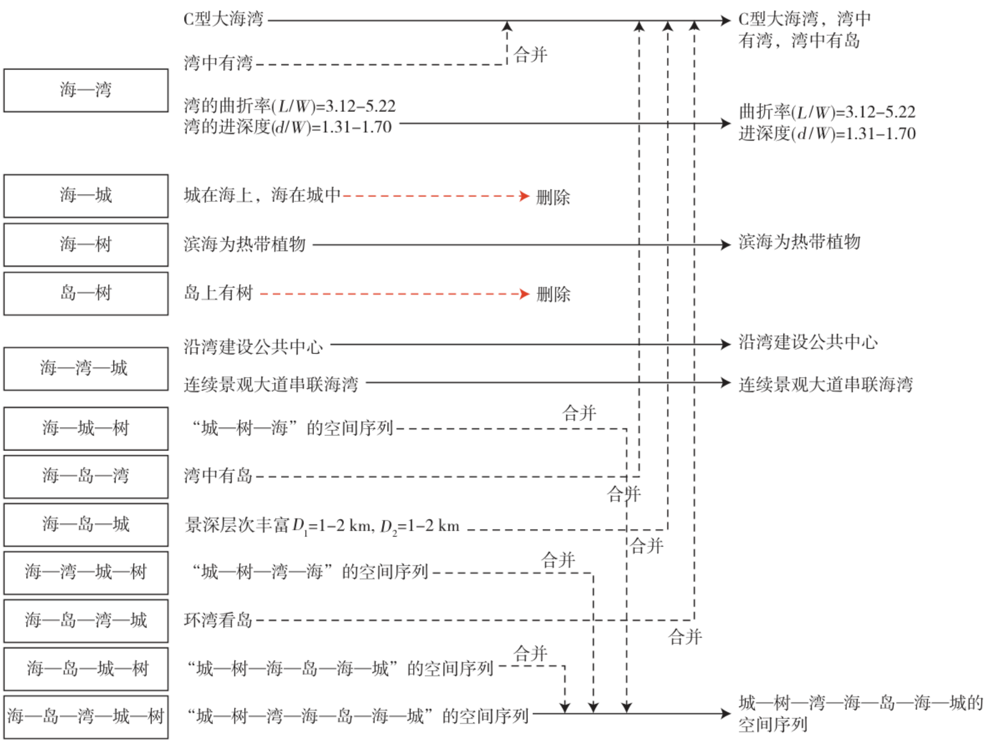


Fig.3 Combining a set of spatial organization rules of space genes

4 Conclusion

After more than two decades of rapid development, China's social, economic, and cultural development has entered a new stage. The question of shaping the distinctiveness of Chinese cities has again attracted broad national and social attention from the renewed perspective of cultural confidence. As relatively distinctive patterns of spatial organization, space genes and their specific rules for arranging spatial elements can provide a scientific basis for planning and design aimed at sustaining and expressing urban character. More importantly, the role of space genes is not confined to visual or stylistic character. As patterns of interaction among space, nature, and culture selected by urban systems, they carry locally grounded information for sustainable development and can provide a basis for deciphering place-specific pathways to sustainability.

On the basis of the conceptual meaning and operating mechanism of space genes, this article has proposed an approach to their identification and extraction and explained it through a practical case. The pathway can provide a foundation for planning technologies that use space-gene analysis to guide and control the city as a whole, central districts, or local areas, and it is an important component of place-specific planning and design for sustainable development. A standardized pathway will also promote the construction and development of space-gene databases and extend space-gene research into deeper, broader, and more innovative fields. This is of particular contemporary significance in China, where urban character and cultural confidence have become major concerns.

Notes

① Since the 2014 Beautiful Xiamen Strategic Plan established the city's development direction, subsequent plans have taken "Beautiful Xiamen" as strategic guidance. At the 2017 BRICS Summit, General Secretary Xi Jinping explicitly praised Xiamen as "a high-quality ecological garden city." Word-cloud analyses of public online questionnaires and tourist-attraction reviews likewise describe Xiamen as a beautiful, romantic, livable garden city.

② During the Tang and Song dynasties, demand for the mooring of merchant and fishing vessels led to the emergence of settlements combining commerce and fishing around Wutong Wharf, near today's Wuyuan Bay, and Dongdu Wharf, near today's Yundang Lake. In the late Yuan and early Ming dynasties, a number of fortified settlements were established at coastal strongpoints on Xiamen Island to defend against Japanese pirates. Later, Quanzhou Port and Zhangzhou's Yuegang Port were successively abandoned because of channel siltation, allowing Xiamen Port - originally an auxiliary port of Quanzhou and an outer port of Yuegang - to rise because of its exceptional geographical advantages. By the first year of the Jiaqing reign of the Qing dynasty (1796), Xiamen had become a major transport hub and trade port in southern Fujian. Numerous wharves were concentrated between today's First Wharf and Shuixian Temple, and extensive commercial and residential districts formed spontaneously. From the Opium War in 1840 until the Japanese occupation of Xiamen in 1941, development was concentrated in the southwestern part of Xiamen Island. In the early years of the People's Republic of China, Xiamen was a military front line and remained in a prolonged state of confrontation; it could expand only slowly eastward along the southern shore of Yundang Harbor, now Yundang Lake. In 1980, the State Council formally approved the establishment of the Xiamen Special Economic Zone, initiating rapid development and the transformation from an island city into a bay-oriented city.

③ Xiamen is located in southern Fujian on the western side of the Taiwan Strait, at Kinmen Bay and the mouth of the Jiulong River. Offshore chains of islands, including Greater and Lesser Kinmen, Dadan, Qingyu, and Wuyu, shelter Xiamen Port, which has long been a renowned natural deep-water harbor on China's southeast coast; Xiamen itself developed as a port city. The earliest city site on Xiamen

Island faced mountains to the east, had sheltered bays to the west and north, and opened southward onto the necessary route to the sea - a typical location for a port-trade city. Meteorologically and hydrologically, Xiamen Port has relatively weak winds, an annual mean wind speed of 3.4 m/s, and an average of 25.8 days of strong winds per year. Deep inner bays formed through long-term geological, geomorphological, and climatic processes, together with offshore island chains, prevent ocean swells from penetrating far inland and keep waves relatively small. These conditions provide exceptional harbor-building advantages and convenient, safe spaces for waterfront production and everyday life. In addition to industry, Xiamen consequently attracts service industries and concentrations of people and has developed numerous public activity centers closely associated with its bays.

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Revised: November 2024