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Sustainable Planning and Design of Ocean City Spatial Forms Based on Space Syntax

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Abstract: The form of an ocean city, as a physical space, has an important impact on the city's social economy, environment, etc. Whether the internal composition of an ocean city is well organized determines whether its form is sustainable and whether it can better carry out a variety of functions. Considering this context, in this study, we adopted the theory of space syntax (SS) to interpret the sustainability of the ocean city form. This was carried out from the perspective of the composition relationship of the internal organization of the ocean city (OC) physical space. We judged whether the composition relationship of internal space could effectively support the sustainable and healthy functioning of different features of ocean cities through the interpretation of SS-related theories. It is extremely hard to give an accurate definition of the form of a sustainable city. At the same time, it is impossible to make conclusions about which urban form is sustainable. However, combined with the concept of sustainable development, we argue that urban forms that continue to facilitate the virtuous cycle of the society, economy, and environment of a given city and also to be highly habitable for urban residents are sustainable. Thus, based on the above viewpoint, the research object and scope in this study only involved the ontology of the physical space form and whether urban physical space could effectively support the sound and sustainable development of three core elements: urban society, the economy, and the environment. This was comprehensively evaluated through our exploration of the form of urban physical space. Here, space syntax was taken as an analytical theoretical and practical tool to summarize the problems that existed in Shenzhen Bay through data analysis, and corresponding development proposals were put forward. The concept and method behind the strategy analysis of the ocean city (OC) design framework based on SS-related theories were presented and applied to practical cases to perform an objective and rational analysis, guide the design of actual projects, and promote ocean city (OC) design in the transition period in a judicious way. In addition, we discuss how design and planning can promote sustainable urban development.

Keywords: space syntax; ocean city; space form; sustainable planning and design

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1. Introduction

1.1. Research Background

The spatial layout of cities has always been a leading factor in human activities. Today, cities are characterized by gaps between people and automobiles, between people, and between buildings and public spaces. This seclusion and discrepancy was not the original intention of urban planners, going against their initial attempts to create a sound communication environment. However, when looking at several traditional cities, we find that they do not have such problems. On the contrary, there is little seclusion and instead harmonious social relations. The essence of urban learning is to investigate human beings and their living space. Over time, the relationships between people and their living spaces are becoming more complex. During the normal operation of a city, people readily attribute the driving force of urban development to social and economic factors and ignore its subjects and law. Theoretically, this simple judgment made by academic circles lays a foundation for the prerequisite of social and economic planning, reducing urban planning to a passive position in social development, economic construction, spatial layout, etc. Finally, the planning and design (PAD) of urban spaces fails to give full play to their due function and pay adequate attention to the rules of urban space, which leads to many misunderstandings in urban and rural construction. This argument must be explored in the context of the effect of economic and social forces on a city and how they come into being [1].

Cities are bound to face one particular challenge; that is, how to develop the population, resources, environment, and social economy in a coordinated way. Along with the development of the social economy and the acceleration of urbanization in China, cities—especially big cities and megacities—are faced with a grim situation [2]. For this reason, how to identify the nature, scale, and development direction of a city and create a pathway of sustainable development are currently issues of importance.

SS is a research method that combines space with society. Spatial ontology quantifies the complex spatial form, behaviors, and activities of humans, and discusses the internal relationship between the spatial organization, urban structures, and functional modes [3]. The OC form, which is a kind of physical space, is a significant carrier. Whether its internal structure is good or bad determines its sustainability and the variety of functions that it bears. In a nutshell, the OC design framework is a strategic and holistic OC design tool. The framework can be understood as the provision of a stable mechanical structure. This structure can be shared and replicated during operation and can be extended to satisfy the design requirements of different regions. When introducing the OC design framework, one should add the features of local elements, not only to ensure the integrity of the regional OC design but also to fully protect the local characteristics. The OC design framework should adapt to local and seasonal conditions and fulfill the requirement of diversity. In addition, the OC design framework is tantamount to supplying a framework or beginning for OC design, whose connotations and outcomes must vary from place to place [4].

To this end, by applying SS theory to the relationship between internal structure and composition in the OC physical space of marine cities, we determined their sustainability and judged whether their internal spatial structure can fully support the sustainable and healthy functioning of different features based on SS-related theories.

1.2. Research Purpose

The importance of oceans runs through the whole process of urban development, and the planning and design of marine cities are also crucial. Due to the "urban fringe" characteristic of coastal space, the planning and design methods used for marine cities are completely different from those of inland cities. However, most of the existing planning and design strategies for marine cities focus only on the location of the coast and fail to view the construction of marine cities from multiple levels. How to conform to and utilize the spatial relations of marine cities to create a better urban space is an important research question and was the focus of this study.

Since they are not incisive enough, the previous case studies on space syntax cannot offer guidance on construction problems in actual projects and cannot be satisfactorily used to develop design strategies for urban construction. Therefore, based on SS analysis, we merged spatial units as the marine space of "three bays and one estuary" via zoning and performed a quantitative evaluation and analysis of the marine ecological economy in each sea area by building an evaluation index system for the sustainable development of the marine ecological economy. We classified and divided sea areas according to their main features and the spatial autocorrelation analysis structure, as well as planned and designed a sustainable OC spatial form for marine cities to provide a reference to better guide the development of the marine economy and protect and utilize the marine resources and environment in each sea area. Here, backed by the SS research theory, we summarized strategies for the OC design framework to solve the problems existing in the construction of OCs and guide OC design during the transition period [5]. The main aim of this study was to obtain plans and proposals for sustainable spatial development based on a case study of Shenzhen Bay, under the common premise of SS analysis and a sustainable viewpoint, and to guide the spatial planning of other marine cities.

1.3. Research Significance

A city is both a complex and complicated internal system. The spatial structure of a city has a great impact on human activities. First, a reasonable spatial layout can boost the healthy development of a city, while a reasonable spatial structure can create a vibrant and safe environment and promote the development of society, the economy, and the environment. If a space is ill-planned, its urban function will fail and the whole society may even lose balance. The discussion of methods for urban function and form is becoming increasingly common. In this study, the analytical approach of SS provided a scientific explanation for the genesis and operation mode of urban space, delivered accurate information and rigorous data for future urban problems, and gave suggestions and optimal solutions to ensure normal operation and promote sustainable development of cities [6].

Based on SS theory, this study undertook a rational analysis of the characteristics of current OC spaces, guided the layout of various OC design elements, guaranteed the rationality of OC design, discussed the compatibility between OC design and OC planning systems, and ensured the enforceability of OC design. The significance of this research is that it summarized strategies for an OC design framework during the transition period through qualitative and quantitative analysis, which can help to shape a good OC living atmosphere; i.e., an environment where humans and nature can coexist in harmony in a vibrant OC space [7]. Most importantly, using the current spatial form of Shenzhen Bay, our study analyzed the prominent problems existing in the current spatial development of Shenzhen Bay and put forward targeted development proposals for these problems, to promote the economic development of Shenzhen Bay and provide experience to draw from for the development of other regions.

1.4. Research Methods

In this study, OC planning exhibition halls with different combinations of internal space were selected and analyzed, and research was conducted based on the acquired text resources, photos, etc. We adopted the following methods:

Literature review: Through the consultation of a large number of online and offline data sources, the literature was systematically sorted and analyzed. The classification of the internal spatial forms of OC planning exhibition halls was summarized and the relevant theories underpinning this article were clarified.

Field survey: The survey included surveying and mapping of the internal dimensions of the case investigated in this study using a laser measuring instrument.

Software analysis: To begin, according to the theory and technical platform of SS, the quantitative parameters of the internal space of the planning hall were calculated using the DepthMap software; then, the maps were read. The spatial differences in the different planar organizations were analyzed in accordance with the indicated colors and data, and the quantitative results of the abstract space were extracted.

Comparative analysis: After a quantitative and qualitative comparative evaluation of different spatial organizations, we provide reasonable advice on planning and design in this paper.

1.5. Domestic and Foreign Literature Review

SS was introduced in the 1970s. By Bill Hillier and Julienne Hanson is an integral part of SS theory. In the late 1990s, J. Hanson conducted a large empirical analysis on the relationship between spatial structure and social culture in the book. It systematically explains the relationship between different combinations of architectural space and social culture, and pointed out the relationship between social cognition, the mode of spatial organization, and space [8].

In the book, B. Hillier sets forth the central position of spatial structure in research on spatial relations. In addition, based on an empirical analysis [9], he gives an in-depth demonstration. During the 21st century, SS has been widely applied in urban planning, structural design, architectural space design, landscape design, etc. Using SS, A. H. Mahmou analyzed the influence of the tree planting mode in gardens on tourists' line of sight and found that its spatial layout had a certain guiding effect on pedestrians' walking propensity. In addition to the theoretical basis, analytical method, and modeling techniques of SS, K. Karimi stated that urban layout should be combined with the characteristics of "configuration" [10]. Y. Lerman et al. built a walking model based on pedestrianism and discussed the impact of walking paths on the siting of basic bus stops [11].

Jin Dongsheng published an article entitled "Space Syntax" in a journal called in 1985. This article first appeared in China, and its reach was gradually expanded with the development of SS theory [12]. In 2007, Duan Jin and B. Hillier jointly published and developed it in the application field in China [13]. Since then, research on SS by Chinese scholars has gradually increased and the theory has been widely applied across different disciplines. Tan Chengzhong investigated architectural space and put forward an evaluation criterion for spatial social stratification from the perspective of society. Wang Hongchao extracted and encapsulated different grid types from different cities and comprehensively evaluated the cohesion between social attributes in each stage using the SS method [14].

From the perspective of SS, Shen Peng examined the spatial form of Zhengdong New District in two historical stages; quantitatively evaluated the spatial structure regarding several aspects, such as integration, synergy, and intelligence; and determined development trends, including the expansion of the scope of the regional integration core, a reduction in spatial intelligence, and a decrease in the accessibility of external traffic [15]. By carrying out an analysis of the spatial form of Zhukou Ancient Village in Qimen County, Anhui Province, Chen Dandan compared it with the planned spatial form and verified the feasibility and effectiveness of the project in terms of the protection and renewal of the spatial form of Zhukou Ancient Village [16].

1.6. Research Review

In this work, research findings on SS published at home and abroad were collected; in terms of spatial ontology, it was found that the studies on SS were full-fledged and widely applied at several macro levels, such as for urban spatial structures, road networks, urban form evolution, the accessibility of urban parks, and the internal streamlining of buildings. The relationship between their internal spaces can be accurately reflected through an SS-related analysis and studied in conjunction with various perspectives, including sustainability planning. On this basis, a rational optimization strategy for a spatial layout is presented.

2. Overview of Related Theories

2.1. Ocean City (OC)

An OC (ocean city) generally refers to a coastal city with abundant marine resources and a large total marine economic output. OCs are usually cities with a long coastline and a developed marine economy. An OC has an "ocean" attribute, which is not only reflected in the urban location but is also embodied in distinctive "ocean" features and outstanding "ocean" advantages. From the denotation of these features and advantages, modern marine cities are comprehensive coastal cities with international influence, e.g., a famous international marine city and a gulf metropolis [17]. Such cities have prominent urban attributes, such as openness, security, connectivity, and flexibility, as well as high internationalization. They have an advanced modern industrial system, play a critical pivotal or nodal role in the global industrial and supply chains, and have very powerful innovation and service functions. Distinctive marine features are found in every aspect of these cities, which include marine science cities, port shipping hubs, seashore tourist cities, and maritime service centers.

2.2. Planning and Design (PAD)

Planning and design (PAD) refer to the specific planning or overall design of the project, taking into account the political, economic, historical, cultural, and folk customs, as well as geography, climate, transportation, and other factors, to further improve the design scheme and propose planning expectations, vision and development modes, development directions, control indicators, and other policies [18]. The content of PAD, as the outline for construction, is later used to guide architectural design, landscape design, and other design aspects (including building volume, form, architectural color, interface, structure, spatial layout, and landscape form).

In this study, the design included urban planning, landscape architecture, and architectural design. The PAD used in this study was concrete and data-specific.

2.3. Sustainable Planning

The concept of sustainable development was first raised by the International Union for Conservation of Nature (IUCN) in 1980 in the World Conservation Strategy. Sustainable planning is established based on sustainable development. Sustainable urban planning not only refers to sustainability at the technical level but, more importantly, sustainability of the environment, culture, and psychology. Sustainable planning is not limited to the mechanical layout and material construction of urban space but also includes the combination of urban development, natural ecology, and the principles of sustainable development in urban planning and their implementation at every level of planning; this not only satisfies the needs of contemporary people without jeopardizing the ability of future generations to meet their demands but also ensures their sound, sustainable, and coordinated development [19].

2.4. Evolution Mode of an Urban Form

Individual activities and space are interactive. The utilization of space by people entails a simple and clear straight line—that is, the space from one point to another—to reinforce ties with the outside world. At the same time, it is also necessary to examine the inner connectivity of cities; that is, the shortest distance between two points. The contradiction between these two factors leads to the realistic form of a city. The evolution law of urban spatial structure in China can be derived through an analysis of the evolution of global cities. In the beginning, most cities either develop linearly along the main street or form an irregular ring along a space with varying lengths and widths. With the maintenance of the linear space and the addition of extended and compact grids, the deformation of the city is generated; this reflects the basic morphological law of cities. In general, whether square or irregular, the network structure of a city is always dense in the center and sparse in the periphery. The spatial composition of a city proper is not important; instead, the key lies in the overall understanding of space and time.

3. The PAD of an OC Based on Space Syntax (SS)

3.1. Correlation Analysis of SS

3.1.1. Meaning of SS

Over the past forty years, SS research methods have been constantly improved and refined, and a well-established theoretical system has gradually been formed. Founded on spatial ontology, the basic idea of SS is to divide large-scale space and mathematically abstract and model it to explore the connection between spatial ontology and other non-spatial elements. The scope of SS research involves a large number of aspects, such as urban planning, urban design, architecture, and spatiography, gradually forming an integrated discipline with multiple ways of thinking [20].

SS is a theory and method that investigates physical space and the spatial composition of human cognition by quantitatively describing the spatial structure of a human settlement [21]. It highlights the research on the correlation between "space" as an independent element and architecture, society, and human cognition. According to SS, the OC space system consists of two parts: closed space and free space. Closed space generally refers to buildings, while free space is a place separated by objects where people can move around at will. In free space, any point can reach other points in space and demonstrate continuity; thus, it is also called open space. The space system created by people is produced in social development. Upon the completion of the space system, it has social attributes; these social attributes of OCs or architectural spaces are not determined artificially and subjectively by attaching functional labels.

The SS method is employed to understand and utilize the effect of a spatial configuration in urban systems or complex buildings. It can be seamlessly linked to GIS network analysis, superposition analysis, data connection, and other functions, and has great superiority regarding data modification, sorting, and mapping. ENVI focuses on image processing, such as correction, stitching, index calculation, and classification; in contrast, ArcGIS emphasizes the construction, analysis, and calculation of geographical information to provide statistical and regional analyses based on geographic space, and is more suited for the analysis and processing functions of spatial information.

According to the new space theory, which states that space is a part of social life, human settlements, such as the layout of OCs or architectural spaces, will influence society, the economy, and culture and innovatively show the social logic of spatial structure. SS is different from traditional research on space theory in that SS takes space as the starting point to dissect the relationship between the OC and social and cognitive areas (e.g., architectural space). The general research relations of SS are shown in Figure 1.

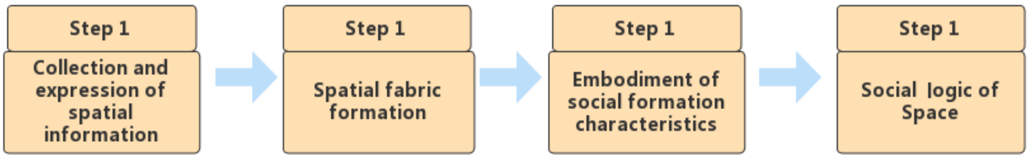


Figure 1. General research relations of SS.

The division of spatial scale and the segmentation of space is an important foundation of SS research.

Division of spatial scale: The division of spatial scale is the basis of SS and also the primary step in SS research. SS divides space into two space scales: large and small. The division criterion is whether individuals in a space can fully perceive the space. If so, then the space is a small-scale space; if not, or if they can only perceive a part of the space, then the space is a large-scale space [22].

Segmentation of space: SS assumes that it is difficult for individuals to feel the entirety of a large-scale space. In studies on large-scale spaces, such as cities, SS divides them into three types of small-scale space. Axial segmentation refers to the farthest distance that can be seen from a given point in space. Convex space segmentation refers to the ability of any point in space to see another point in space; that is, the space can be fully perceived. FOV (field of view) segmentation refers to the scope of horizontal space that can be perceived at a given point. At present, axial segmentation is most widely used in research utilizing SS theory.

3.1.2. Basic Principle of SS

The basic principle of SS is spatial segmentation; i.e., transforming the whole space system into a relational diagram made up of nodes and interconnections. The process in which the whole space system is divided into single components is called spatial segmentation. A walking route is usually considered a straight line, while interpersonal space can be regarded as a convex space. People generally move around in a visible range within which they can feel safe. Beyond this range, people usually lack a sense of security as a result of an unknown space. Thus, axial, convex space, and FOV segmentations come about through an investigation of people's mental activities.

3.1.3. Core Theory of SS

SS is a theory and method that quantitatively analyzes the form of a surrounding space and examines the relationship between spatial structure and human society. Founded on the internal structural characteristics of the architectural form itself, it draws support from the logic of internal structure; analyses with software according to certain quantitative criteria allow for the elucidation of the deep logical relations between spatial combinations and the optimization of the spatial structure of architecture. In popular terms, the effect of the method with which a space inside a building is established based on people's behaviors, such as walking tendency, staying, and gathering, is analyzed from a quantitative perspective [23].

3.2. Brief Analysis of SS Steps

SS theory aims to transform a perceptual space into a rational space by using SS methods and techniques and understanding spatial characteristics more objectively. The major steps are shown in Figure 2.

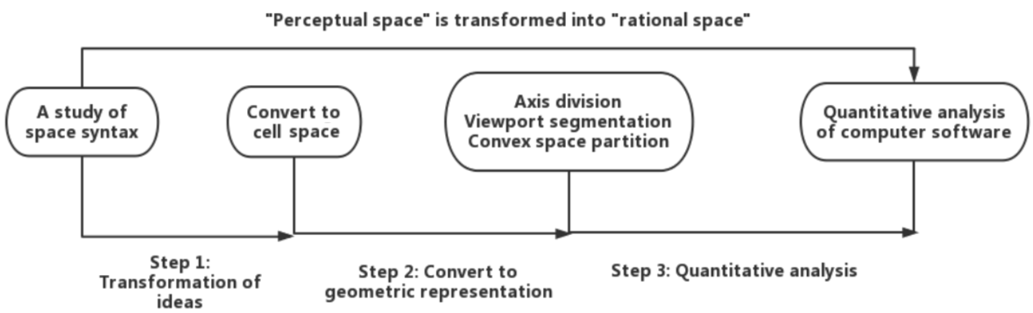


Figure 2. Brief analysis of SS steps.

First, based on SS theory, the space is reasonably converted; that is, the space system is divided into individual spatial units via internal logic. These spatial units are interconnected and mutually influenced. Each spatial unit has a different spatial form variable in the space system. Second, the most crucial step for SS to convert a perceptual space to a reasonable space is to resort to the three kinds of segmentation methods; i.e., axial, convex space, and FOV, to transform spatial configuration to understandable geometric representations and space activities that can barely be perceived in reality into rational geometric representations [24]. Finally, the geometric representations are imported into computer software and numerical calculations and analyses are performed. The value of the morphological variable is obtained, and the spatial characteristics can be understood more defensibly and completely. The details are as follows.

1. Analysis of the vector space

The analysis of the vector space mainly exploits the potential information of spatial targets via a conjoint analysis of spatial data and a spatial model. The basic information about these spatial targets includes their spatial position, distribution, morphology, distance, azimuth, and topological relations. Among them, the distance, azimuth, and topological relations constitute the spatial relations of spatial targets. This is a spatial characteristic between geographical entities and can be adopted as the ground of data organization, query, analysis, and inference. By dividing the geospatial targets into different types—that is, points, lines, and planes—we can acquire the morphological structure of these types of targets. The spatial calculation and analysis of many specific tasks can be carried out by combining the spatial data and attribute data of spatial targets [25].

- Primitive merging
- Primitive merging is the aggregation of the vector space, which merges or transforms data types according to spatial adjacency and categorical attribute fields to achieve the merging of spatial regions (data synthesis). Due to spatial aggregation, complex categories are often transformed into simpler ones; this analytical treatment is often needed during the graphical transformation from places and areas to large regions.
- Spatial query

A spatial query is meant to discriminate the spatial topology (the inclusion, separation, intersection, encompassment, and intersection of rectangles) of the elements of the input layer and query layer or the query scope of the interactive input and extract primitives that satisfy the topological discrimination conditions from the input layer.

- Superposition analysis

Overlay and superposition analysis is an operation that superimposes two or more layers of map elements and generates a new element layer. The result is that the original elements are segmented to generate new elements. The new elements synthesize the attributes of the original two or more layers of elements, where the overlay and superposition analysis not only produces new spatial relations but also associates the attributes of the input data layer to produce new attribute relations. Overlay and superposition analysis calculates and analyzes attributes of new elements based on a given mathematical model, thus producing the results required by users or answering the questions raised by users.

2. Grid space analysis

Grid-data-based spatial analysis is the foundation of GIS spatial analysis, which incorporates distance mapping, density mapping, surface analysis, statistical analysis, reclassification, grid calculation, visibility analysis, topographic factor analysis, hydrological analysis, etc.

- Distance mapping

Distance mapping analyzes and maps in accordance with the distance between each grid and its nearest element (also known as the "source") to reflect the interrelation between each grid and its nearest neighbor source. A large amount of relevant information can be obtained through distance mapping, which can be used to guide people to plan and utilize resources rationally [26].

- Density mapping

Density mapping mainly calculates the data distribution of the whole area in accordance with the value and distribution of known point elements, thereby producing a continuous surface. It is mainly generated based on point data and searches the ring area of each grid point taken as the center to calculate the density value of each grid point.

- Surface analysis

Surface analysis is mainly conducted by generating new datasets, such as isoline, slope, aspect, and hillside data; the process is used to acquire more information that reflects the spatial characteristics, spatial pattern, etc., implied in the original dataset.

3.3. Advantages of the Introduction of SS

By investigating its background, the problems with traditional OC design can be clearly defined. During the transition to urbanization, quantitative analysis can effectively avoid the subjective tendency of traditional design. Currently, all domestic quantitative analysis methods use geometry, such as the analysis of maritime city OCs or architectural drawings. Although such a quantitative analysis method is simple, it has limitations. That is, it cannot analyze the spatial structure based on people's characteristic behaviors, and thus, it is difficult to understand the essential characteristics of the OC space [27].

On the other hand, the spatial environment also influences people's activities, and people's activities, in turn, change the spatial structure. Through a quantitative analysis of the spatial environments and structures where people reside, play, and work, actual quantified data can be used to guide the functions in maritime city OCs, the establishment of the ecological environment and humanistic environment, etc. They play a significant guiding role in building an environmental space suitable for residing, playing, and working based on space research.

3.3.1. Necessity of Spatial Form Planning for OCs under SS

SS plays a considerable role in the analysis of the structural form of OCs; the most fundamental principle on which this is built is that an OC is formed through the interaction between self-organization and other organization and a complex spatial self-organization system formed by the interaction and interplay of multiple factors, such as social factors, economic factors, and environmental factors, over a long time. These elements will inevitably exert a coupling effect on long-term development, thus generating a series of complex internal connections and interactions between the physical space of the OC and its corresponding social and economic functions [28].

Just as the forms of OCs differ considerably, the spatial forms that they describe from the axis model are also dramatically different. However, by using topological logic to induce and deduce the relationship between these axes, we can see that the internal structures of these axes are highly unified, and it is this common structural relation that forms the internal development law of OC space.

3.3.2. Sustainability of OC Spatial Form Planning under SS

When exploring the form of sustainable OCs, SS theory considers form and function as inseparable, and the organizational structure of OC not only reflects form but also embodies function, which can explain the interaction between form and function [29]. For this reason, SS theory argues that the organization and composition form of space are crucial and essentially determine whether a space is sustainable. SS theory examines the OC spatial form in terms of three aspects: the natural law of space, the formation mechanism of the network, and the evolution of the OC [30]. For guidelines on the sustainable form of the OC, such as compactness, high density, diversification, mixed land, and green transportation, SS no longer evaluates in advance but examines the OC spatial structure or spatial “fabric” first to see how each local space is established and organized at various scales [31].

3.4. Sustainable PAD of Marine City Spatial Form

3.4.1. Compact Spatial Layout

A compact spatial layout can exert an important effect on the whole form of an OC, mainly based on shape, scale, distance, accessibility, centrality, and agglomeration. Taken together, the compact layout of all kinds of spaces in marine cities, such as production spaces, living spaces, and social interaction spaces, can help to provide more diversified OC functions and services for OC residents within different service radii so that residents in different regions of marine cities can be closer to the main functions and service centers, and the speed at which residents can access and be involved in the functional operation of the OC increases. A compact layout also delivers a major guarantee and support for more intensive development in marine urban areas than in suburban and rural areas [32].

3.4.2. Reasonably Built Density Distribution

Generally, high-density areas are those in the marine urban center or subdistrict center. These areas are typically the most concentrated places in terms of the variety of functions and services of marine cities. Whether these high-density areas can be rationally distributed in different regions of an OC has a direct bearing on whether residents in different regions of the OC can be closer to these functions and service centers. Meanwhile, if high-density areas in a built-up region are too concentrated in a given area, the overall development intensity in this area will be too high and traffic jams in the central area will become inevitable [33].

Many experts and scholars contend that a multi-center marine urban form is more sustainable than a single-center marine urban form; one of the important reasons for this is that the distribution of high-density areas in built-up regions is more well-founded. On this account, the rational density and distribution of built-up regions play an important role in the overall benign development of marine cities.

3.4.3. Mixed and Diversified Land Use

The mixed use of land is always an important principle that is followed by OC planning. The mixed use of the OC form has striking diversity and selectivity in functions and can deliver more OC functions and services to residents in the whole OC and region. While still offering residents higher diversity and selectivity, the mixed use of land can also bring residents closer to the function and service centers of the OC; it no longer separates marine urban functions mechanically but cuts the time and distance for residents to access these functional centers [34].

3.4.4. High-Density Marine Urban Road Network

As the most important framework for an OC, the network density of marine urban roads has always been an important indicator for measuring the effectiveness of the planning and implementation of marine cities. High-density marine urban roads offer more choices for the development of plots with different functions, thus providing space for the mixture of different functions and increasing the ability of residents to approach the function and service centers of marine cities [35]. Generally, the higher the density of the road network in marine cities, the easier it is for residents to quickly connect and access the various subdistrict centers of marine cities to become involved in the division of labor.

4. Case Analysis

4.1. Evaluation and Analysis of Regional Marine Eco-Economic Zoning in Shenzhen

4.1.1. Analysis of Spatial Heterogeneity

Considering the sub-indexes of the three subsystems in the Shenzhen marine eco-economic system—namely, marine ecology, marine economy, and marine society—an evaluation index system for marine eco-economic zoning was built and the marine ecological economy of Shenzhen was evaluated via zoning using comprehensive factor evaluation and analysis. Briefly, this process was divided into three steps: First, a zoning evaluation index system was built. Second, the weight of each index was calculated and determined by issuing questionnaires and scoring by experts. Third, rational values were assigned to concrete indexes for each region according to the evaluation criteria. Finally, the evaluation index was obtained via calculations and the zoning evaluation was made.

4.1.2. Data Source

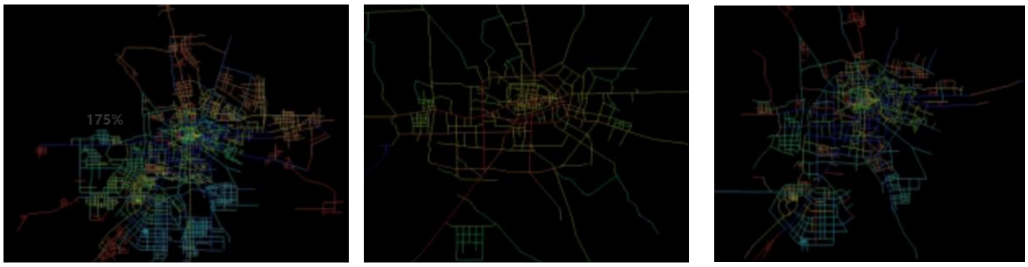
The research data used in this study primarily included Google satellite images, the previous urban master plans for Shenzhen, other specialized plans, and social and economic development plans. Amid studies on the urban form of Shenzhen City, our work mainly referred to the compilation year of the latest version of Shenzhen's urban master plan, and we processed data using three main reference pictures that depended on the data collection time of the Google satellite map; that is, the status quo map of construction land in 1994, the historical satellite image from 2004, and the status quo image from 2014 (Figures 3 and 4). The image from 2004 represented the year before the start of the "great construction" period. In 2004, Shenzhen entered a period of "great construction" and the changes in urban form were very dramatic. For this reason, in this study, we analyzed and investigated the basic evolution characteristics of Shenzhen's spatial form in the past and present by comparing the urban form structure data of Shenzhen City from three periods over the past 20 years to lay a foundation to determine the sustainability of the urban spatial form of Shenzhen City [35].

Figure 3. Shenzhen regional map.

Figure 4. Picture of present-day Shenzhen.

4.1.3. Data Preprocessing

According to the basic principle of the establishment of a central axis map in SS theory and based on the status quo map of construction land in 1994 and the satellite images of Shenzhen in 2004 and 2014, we created the urban spatial structure axis maps of Shenzhen for these three periods in history and at present in CAD, as shown in Figure 5 [36]. The definition of the central axis in SS theory involves taking the street as the convex space. If this space is penetrated by the least and longest ray, then this ray is defined as the axis of the space. In the whole city, the axis of each road is taken as a node in the topology and linked by referring to the interconnection between nodes; the resulting relationship diagram between nodes represents the axis diagram of the city. According to this basic principle, in our study, we took urban roads above the urban branch network as the basic reference elements to draw the axis map and adjusted some axis data based on social attributes, spatial transition, and the visibility relationship implied in the axis map to guarantee the comparability of the data. After the axis diagram was processed in CAD, it was imported into the DepthMap software and analyzed via the axis and line segment models; then, the relevant data were read into the SPSS software for comparative analysis.



(**a**) (**b**) (**c**)

Figure 5. Satellite images of Shenzhen in (**a**) 1994, (**b**) 2004, and (**c**) 2014.

5. Research Methods

A Shenzhen marine eco-economic database was built and the spatial unit map of marine zoning in Shenzhen was drawn. Each zone contained information at three levels: marine natural environment, marine industrial economy, and marine social culture. A standard scoring system was created for the marine eco-economic zoning evaluation and the factors, weights, and grading were determined. The marine eco-economic zoning evaluation system and digital maps were completed using the Shenzhen marine eco-economic database.

The criteria and principles for the selection of evaluation factors in the Shenzhen marine eco-economic zoning evaluation model were as follows. The evaluation factors had a certain hierarchy and were evaluated in terms of natural, humanistic, economic, social, and other dimensions. They could be divided into evaluation categories, classes, and levels, and had some inclusive relationships with one another. The selected evaluation factors represented the main characteristics of Shenzhen's marine ecological economy, offered guidance for the next evaluation, and generated corresponding data values to lay a foundation of quantitative analysis for evaluation. Relying on the above principles and the actual situation of marine eco-economic development in Shenzhen, the evaluation factors and hierarchical structure of zoning were determined.

5.1. Establishing Evaluation Units

In terms of natural and geographical conditions, Shenzhen coastal waters were divided into two parts: the Pearl River Estuary and Shenzhen Bay in the west by Nantou Peninsula, and Dapeng Bay and Daya Bay in the east by Dapeng Peninsula. In our study, combined with the management, development, and exploitation direction of Shenzhen, the marine ecological economy of the coastal waters was analyzed.

5.2. Determining Weights

In this study, the analytic hierarchy process (AHP) was adopted to rank several levels from high to low according to the subordination relationship among natural, economic, and social marine factors. Using the objective reality of the actual development of the marine ecological economy, the relative importance of each level was expressed quantitatively, and the weight of the relative importance order of all elements at each level was identified using a mathematical method.

5.2.1. Data Processing

Since the selected indicators had different units, the data were first standardized. In our study, a normalization method was applied to eliminate the differences between variables in magnitude and dimension so that they could be calculated uniformly and a longitudinal comparison and analysis could finally be carried out.

Profitability indicator:

$$z_i = \frac{x_i - \overline{x}}{\sqrt{\frac{(x_i - \overline{x})^2}{n}}} \tag{1}$$

Cost indicator:

$$z_i = -\frac{x_i - \overline{x}}{\sqrt{\frac{(x_i - \overline{x})^2}{n}}} \tag{2}$$

In the equations above, x_i represents the value of the indicator in year i and z_i denotes the value of the standardized indicator in year i. An increase in the profitability indicator signifies better performance, while an increase in the cost indicator signifies worse performance.

5.2.2. Indicator Weighting

When determining the weight of each level and factor, we generally used the consistent matrix method. According to the scale method shown in the following table, the (pairwise) importance of factors was scored via subjective evaluation to obtain a judgment matrix.

To guarantee the credibility of the hierarchical ranking, it was important to check the consistency of the judgment matrix; that is, to calculate the random consistency ratio. The formula is as follows:

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{RI \cdot (n-1)} \tag{3}$$

The result of a single hierarchical ranking was considered satisfactory only when CR < 0.1. Otherwise, the value of the judgment matrix element was adjusted. The hierarchical ranking and consistency check were performed on the index system using professional AHP software. The results are shown in Table 1.

Table 1. Results of the consistency check of the judgment matrix.

Judgment Matrix	CR	Result
Sustainable development index of marine economy	0.0000	Adopt
Natural resources	0.0362	Adopt
Economic development	0.0379	Adopt
Social resources	0.0000	Adopt

The test results showed that the marine economy sustainable development index, natural environment, industrial economy, and sociocultural judgment matrices all passed the hierarchical ranking and consistency check.

5.2.3. Determining the Index Weight

If the pairwise comparison matrix was a consistency matrix, then a normalized eigenvector W corresponding to eigenvalue n was taken as the weight vector of the factors C1, C2, . . . , Cn of the criterion layer C to the target layer. If the comparison matrix A was not a consistent matrix but within the allowable range of inconsistency, then the eigenvector (after normalization) corresponding to its maximum eigenvalue was adopted as the weight vector of the factors of criterion layer C to target layer O.

The indexes were derived through the following equations:

$$E_t = \sum_{i=} a_i z_i \tag{4}$$

where E_t is the marine ecological and economic sustainable development index; i = 1,..., 17; a_i represents the total weight of each index; and z_i denotes the treated observation value of the ith index.

$$S_i = \sum_{i=}^{k} \beta_i z_i \tag{5}$$

Here, S_i is the marine ecological and economic sustainable development index; i represents the sub-item weight of each index; z_i refers to the treated observation value of the ith index; β_i denotes the weight value of a single index; and k is the marine pollution coefficient.

6. Research on Sustainable PAD for the Spatial Form of OCs Based on SS

6.1. Eco-Economic Accounting of Ocean Cities

The marine eco-economic accounting value was calculated by correcting the marine economic accounting indexes based on marine economic accounting by considering the consumption of marine resources, the cost of marine environmental pollution, and the value of marine ecological adjustment in the process of the economic activities of the marine ecosystem. The marine eco-economic accounting framework is shown in Figure 6.

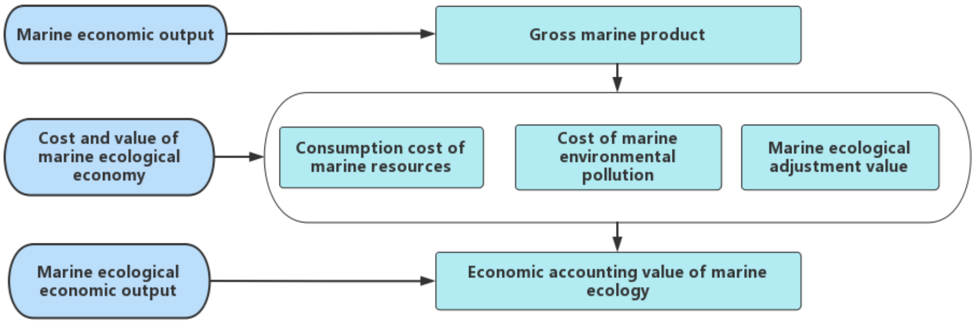


Figure 6. Marine eco-economic accounting framework.

The marine eco-economic accounting was performed by considering the consumption of marine resources, the cost of marine environmental pollution, and the value of marine ecological adjustment, thus furthering the current research on China's marine economic accounting system [37]. To enable the accounting work to be carried out smoothly, the scope of the cost accounting of the consumption of marine resources according to the actual situation of marine industrial development included marine fishery resources, marine oil and gas resources, and marine resources. In this study, based on the average land transfer price of each year from 2011 to 2015, the use cost of marine resources per unit area was derived by deducting the development cost and the added value of a sea area attribute change. The results are shown in Table 2 and Figure 7.

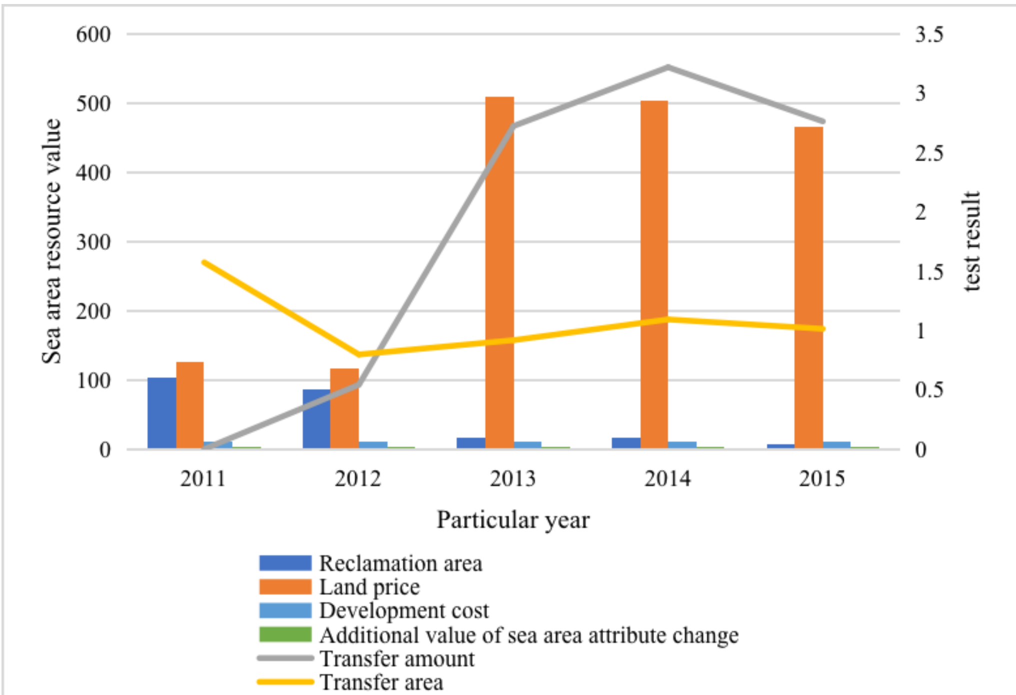


Figure 7. Analysis of the value of marine resources.

Table 2. Value of marine resources formed by reclamation in Shenzhen.

Year	Reclamation Area	Land Price	Transfer Amount	Transfer Area	Development Cost	Additional Value of Sea Area Attribute Change
2011	0.6	0.73	-	269.97	0.06	0.0015
2012	0.5	0.68	93.14	136.82	0.06	0.0015
2013	0.1	2.97	467	157.50	0.06	0.0015
2014	0.1	2.94	552	187.50	0.06	0.0015
2015	0.04	2.72	473.78	173.93	0.06	0.0015

The reclamation area of each part of Shenzhen's "three bays and one estuary" from 2011 to 2015 was divided by the sea area to obtain the proportion of reclamation per unit area of sea area and then multiplied by the sea area within each cell grid and the use cost of marine resources per unit area to calculate the environmental cost for the marine resources of each cell grid. The results are shown in Table 3 and Figure 8.

Table 3. Use cost of marine resources in the "three bays and one estuary".

Year	Pearl River Estuary	Shenzhen Bay	Dapeng Bay	Daya Bay	Total
2011	31.87	8.02	0.00	0.45	40.33
2012	24.46	6.16	0.00	0.34	30.96
2013	22.94	5.77	0.00	0.32	29.04
2014	22.77	5.73	0.00	0.32	28.83
2015	9.40	2.37	0.00	0.13	11.90

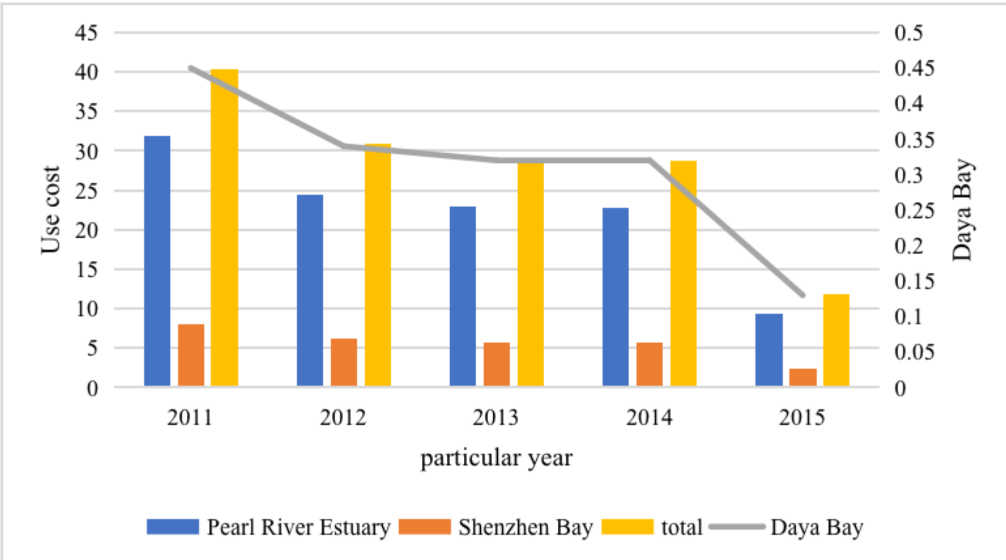


Figure 8. Data chart of use cost of marine resources.

Regarding the marine eco-economic center of Shenzhen, the overall situation basically remained unchanged from 2011 to 2014; however, in 2015, there was an obvious trend of individuals moving to the northeast. Since the offshore oil and gas industry, marine shipping industry, and other weighted industries were mainly concentrated in Nanshan, the two industries shrank substantially from 2014 to 2015, affected by the downturn in the international market, which led to a dramatic decline in their proportion in Shenzhen's marine economy and placed emphasis on the shift eastward.

6.2. Results and Analysis

From the chart analysis above, we can see that the development of the marine economy was the main basis for the sustainable development of the marine ecological economy. On the one hand, the development of the marine economy required marine resources and marine space and imposed tremendous pressure on the ecological environment of offshore areas. On the other hand, the ecological environment and resource-carrying capacity of the oceans imposed objective requirements for the development of the marine industry. At different stages of economic development, it was essential to match the industrial type and economic model with the ecological environmental resources. Accordingly, the sustainable development of the marine ecological economy should have an economic foundation and industrial activities, protect the ecological environment while developing the economy, and promote harmonious coexistence and coordinated development between humans and the oceans.

According to the evaluation results of this study, Shenzhen Bay, having the highest level of sustainable development of its marine ecological economy, mainly relied on two major urban areas, Nanshan and Futian. Shenzhen Bay was the area with the highest land value, while key development areas, such as the Shekou Free Trade Zone, Houhai Headquarters Cluster, and Super Headquarters Base of Shenzhen Bay, had the most intensive high-end service industry and economic activities in Shenzhen [38].

A planning proposal for the Shenzhen marine eco-economic zone was put forward based on the results above:

- Optimization and adjustment zone for the marine ecological economy in Shenzhen Bay

Shenzhen Bay has an important coastal landscape coastline for an OC. Shenzhen Bay and the Houhai Headquarters Base were built in the rear. It is a densely populated area with high-end OC functions. In the future, the area of the marine urban greenbelt and forest will be woefully incompatible with high marine urbanization and high population density in this region. Thus, it is necessary to reserve a public coastline [39]. Futian Mangrove Reserve can be built into a marine environmental protection education base to increase pro-sea-space support and restore the coastline to an ecological coastline and nature reserve.

- Coordinated development zone for the marine eco-economy in Dapeng Bay

This area is the main container port area and coastal tourist resort in east Shenzhen [40]. Dapeng New District is a national marine ecological civilization demonstration zone and a core bearing zone of marine strategies in Shenzhen. Future development should focus on improving the pilot innovation of integrated coastal zone management; facilitating the sustainable development of coastal zone resources; exploring a market-oriented pricing mechanism for the right to use the beach and sea resources; promoting the market-oriented allocation of sea and island resources; exploring the establishment of an early warning index system for the environmental carrying capacity of marine resources within the jurisdiction; making use of Shenzhen's financial advantages; increasing green financial input; exploring the establishment of public welfare funds for the construction of marine ecological civilization, investment, and financing mechanisms for the protection of the marine ecological environment; unleashing the vitality of the bay-style city; and building a demonstration village for coastal ecological civilizations.

- Countermeasures for developing the marine ecological economy in Shenzhen

Build a grid planning spatial unit system; actively explore the further refinement of spatial functional units based on the planning of the main marine functional zones; establish a marine eco-economic planning evaluation unit based on a kilometer grid in coastal areas; and set up a comprehensive evaluation system for marine economic development accounting, marine ecological value evaluation, and the quantitative evaluation of marine resources and environment based on the kilometer grid space unit.

- Develop a differentiated development and exploitation direction for the marine urban space

Set up a differentiated development pattern of "West City and East Park": Extend the axis structure in space, intensify the agglomeration of the modern service industry, and accelerate industrial transformation and functional upgrades in the western region. The eastern region is positioned as a regional ecological stabilizer and a world tourist destination that is connected to the natural terrain in space via the implementation of decentralized development.

Boost the functional transformation of the coastal area: Adapt to the transformation of marine cities and make overall plans for the use of land and sea space with the coastal zone as the core to promote connectivity between land and sea functions. Further increase the proportion and balanced layout of living shorelines, improve the inventory of ecological shorelines, and make shoreline utilization more scientific and rational. Optimize and upgrade the functions of the coastal OC in Shenzhen, combined with the functional positioning in eastern and western regions and the functional adjustment of marine cities in coastal areas [41].

7. Discussion

Based on field surveys, SS draws on graph theory to form spatial relation structure diagrams. SS can be used to transform the spatial form relationship of a city into a mathematical model, which can be used to quantitatively analyze the influential factors of urban spatial form and calculate and compare invisible elements in a quantitative way to more clearly and accurately describe the spatial form characteristics of the research area. SS theory has evolved to help architects and planners find potential space in cities and develop targeted designs for specific planning and construction projects. In addition to the results of the above analysis, the following problems existed in Shenzhen Bay.

- Lack of connection between subdistricts

The degree of synergy in Shenzhen Bay in Zhengzhou was low, and the connection between the parts and the whole of the park was poor. There was a shortage of connection between different areas, accessibility was poor, spatial vitality was low, and the ability to attract people was weak. Thus, the movement of people was reduced.

- Poor accessibility of the local area
- The global integration degree of Shenzhen Bay was found to be on the low side at 0.7495 on average, indicating that the connection between different areas of Shenzhen Bay was not close, and the ability to travel between areas was reduced; thus it was inconvenient for tourists to commute between areas.
- Differences between the east and west
- The development levels of the terrestrial and marine eco-economies in central China were much higher than those in the eastern and western regions. The development level of the marine eco-economy in the sea area was influenced by the residents' living and production activities. The development, exploitation, and environmental pollution in central and western waters were much higher than that in eastern waters, making the marine eco-economy in central and western waters lower than that in eastern waters.
- Differences between the north and south
- Ocean-related enterprises tended to aggregate in areas near the coastline. As they extended inland, the aggregation of ocean-related enterprises fell sharply and the development level of the marine ecological economy also dropped rapidly.

8. Conclusions

SS is a theory and method that investigates physical space and the spatial composition of human cognition by quantitatively describing the spatial structure of human settlements. It highlights the study of space as an independent factor and the correlation between space and architecture, space and society, and space and human cognition. In this study, based on the SS theory, we measured the sustainability of Shenzhen's urban spatial form, analyzed and compared Shenzhen's spatial forms, and drew the following conclusions. Relying on its regional advantage, Shenzhen gathered some high-quality marine enterprises in the early stage of development. It had some scale merits in traditional industries, such as marine transportation, marine oil and gas, and coastal tourism, and strong innovation ability in emerging industries, such as marine electronic information, marine engineering equipment, and marine biology. However, Shenzhen also had distinct "short slabs" in terms of its marine resources and environment. From the perspective of resource conditions, Shenzhen had scarce marine resources, coastal resources, and island resources. The development space of its marine industry was limited to a large extent. It was difficult for the emerging marine industry to form agglomeration strength. Furthermore, in terms of the conditions of the marine environment, there were marked differences in environmental quality between the eastern and western waters of Shenzhen. Reinforcing the guidance on spatial planning; optimizing the spatial layout of the marine economy; and vigorously promoting the concentrated, agglomerative, and intensive development of the marine economy are important approaches for heightening the quality and efficiency of marine economic development in Shenzhen and improving Shenzhen's economy through sustainable spatial planning.

Regarding the coordination degree between the marine economy and the development of resources and environment, there were remarkable differences between the sea areas. The ecological environment of the Pearl River Estuary was under great pressure and short-term recovery was challenging. The socioeconomic intensity of offshore land is expected to continue to grow. In the years to come, it is imperative to control the scale of reclamation, change traditional shoreline use, avoid non-intensive land use and ecological destruction, and promote the sustainable growth of the city.

Shenzhen Bay is a densely populated area with high-end urban functions while also being an area experiencing great pressure in terms of ecological protection and sea environment management. In the future, it is necessary to optimize the marine economy and ecological environment concurrently, avoid non-intensive land use and ecological destruction, and promote the process of sustainable and smart urban growth. The marine ecological and environmental conditions in Dapeng Bay and Daya Bay are superior. For this reason, it is appropriate to adhere to the principle of ecological protection first and limit development; prudently plan and leverage coastal land resources; and develop coastal tourism and emerging marine industries with low pollution, low energy consumption, and high added value in a targeted way, to push forward the development of the marine ecological economy. According to the spatial development characteristics of Shenzhen Bay, development can proceed in terms of the following aspects. First, integrate the landscape resources of Shenzhen Bay, plan plants, build local habitats, connect and repair water systems, shape an open marine space, refine the landscape resistance zone, and build an open space system with sustainable planning in the park. Second, to relieve the development pressure in the downtown region, intensify the development of the public transport system and increase the connections between old and new urban road networks to form a smooth and sustainable road network. Regarding the active public space in the region, we should promote the construction of infrastructure, enliven the regional atmosphere, and promote the coordinated and sustainable development of the region.

According to SS theory, the space system of OCs consists of two parts: closed space and free space. The social attributes of OCs and architectural spaces are not determined artificially and subjectively by attaching functional labels. The space system created by people often acts on people's behavior after its completion, thus producing different social effects. Our study generated a sustainable PAD strategy for the spatial form of the OC based on SS. This is beneficial to the sustainable development of Shenzhen in all aspects. Through a general survey of findings published at home and abroad, we found that the research on the sustainable planning and design of ocean cities has aroused wide concern in theoretical and practical circles, and its theory and methods are constantly being improved. However, as a new research frontier and vibrant subject, the sustainable planning and design of ocean cities warrant further study in many regards. Therefore, the contribution of the results presented in this paper to the sustainability of spatial planning in Shenzhen will also be evident in future practice.

9. Research Limitations and Further Research Directions

Based on SS theory, we carried out a quantitative analysis of the spatial structure of Shenzhen Bay, summarized the existing problems in the spatial structure of two areas, and put forward concrete optimization suggestions. However, the following aspects can be improved in future research. When performing data analysis, we used the satellite map as the main reference. However, due to the large study area and limited personal competence, there were still some phenomena for which the relevant data were not complete enough. Although this had little effect on the analysis results, it should be avoided in future research as much as possible.

Further potential research directions are as follows.

- How to develop a compact strategy and sustainable development

Shenzhen has built a fully functional business and cultural area and its industry and logistics have also made considerable progress. However, part of the periphery of Shenzhen has developed in a scattered fashion along both sides of the transportation lines. Thus, on a larger regional scale, based on the existing urban structure and the research undertaken in this study, considering how to develop a compact strategy and sustainable development may be a further research direction.

- How to develop sustainable town traffic and spatial strategies

In our study, the traffic road system was investigated in an attempt to build a continuous and unified traffic relationship and improve the accessibility and visibility of the space. How to extend and modify the rail system and associate it with spatial design to expand the traffic system to the edge zone, break through natural limitations, and form an overall pattern of north–south extension and sustainable development along the main roads in the town are also important research directions.

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