Evaluating Spatial Efficiency and Behavioral Coupling Mechanisms through Climate-Adaptive Perception in Coastal Service Hubs: A Case Study of Haikou's "Sky Mountain"

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ABSTRACT Understanding the interaction between environmental conditions and human behavioral responses is essential for developing adaptive and intelligent public-service infrastructures in complex coastal environments. This study proposes an integrated evaluation–coupling framework for climate-adaptive perception and behavior-aware optimization based on a coastal service hub in Haikou, China. A multi-source environmental sensing and assessment system is first established by integrating spatial attributes, microclimate characteristics, environmental perception indicators, and user behavioral observations. The relative importance of environmental variables is quantified using the Analytic Hierarchy Process (AHP), while Structural Equation Modeling (SEM) is employed to investigate the coupling mechanisms between environmental stimuli, perceptual responses, and behavioral outcomes. Experimental analysis demonstrates that viewscape coverage, waterfront openness, and microclimate regulation are the dominant factors influencing spatial performance and user engagement. The results further reveal significant perception-mediated pathways in which climate-adaptive environmental conditions enhance user comfort and prolong stay duration, while cultural expressiveness improves revisit intention through strengthened place identity. Based on the identified coupling relationships, a climate-adaptive and behavior-guided optimization framework is developed to support intelligent environmental regulation and adaptive spatial decision-making. The proposed methodology provides an effective approach for environmental signal representation, multi-source information fusion, behavioral response modeling, and adaptive optimization in smart coastal infrastructures, with potential applications in intelligent sensing, human-centric environmental systems, and next-generation adaptive service environments.

INDEX TERMS environmental sensing, multi-source information fusion, behavior-aware modeling, adaptive optimization

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

In recent years, accelerated urbanization has increasingly placed coastal areas at the forefront of urban planning. As critical nodes connecting urban spaces and coastal resources, coastal service hubs must not only meet users' basic service needs but also incorporate high-performance fiber-reinforced architectural membranes to optimize users' microclimate comfort under dynamic marine weather conditions and reflect regional cultural characteristics [1,2]. From an optimization design perspective, current service hub construction faces three major challenges: first, how to better integrate local characteristics and environmental features, incorporating regional culture and climate adaptability for user comfort into the design; second, how to establish a scientific environmental quality evaluation system to quantify design merits and drawbacks; third, how to systematically analyze the interaction between the spatial environment and user behavior, and use these insights to inform and optimize design strategies. Addressing these issues is crucial for enhancing the practical value and environmental quality of coastal service hubs, while also contributing significantly to the advancement of public space theory and design methodology [3,4].

Although certain advancements have been made in the design of public spaces and coastal service hubs both in China and internationally, several notable limitations persist. In terms of design practice, cases such as the "Wutong Yu" urban service hub in Nanjing's Yuanmei Plaza, the under-bridge service hub on Shanghai's Wuning Road, and the service hubs around Suzhou's Jinji Lake have demonstrated commendable efforts in expressing regional culture and implementing climate-adaptive design. However, exploration into the coupling relationship between environment and behavior remains limited [5]. In the field of environmental evaluation research, methods such as the AHP-Fuzzy Comprehensive Evaluation have been widely applied in assessing urban environmental quality [6]. Nevertheless, their integration with behavioral data analysis in small-scale spaces remains insufficient, as seen in examples like the Chengdu Tianfu Jincheng Greenway service hubs, new public reading spaces in Xiamen, and the Lin'an Qingshan Lake Greenway. Furthermore, existing public space studies often focus on a single dimension, either environmental factors or behavioral analysis, lacking in-depth investigation into the coupling mechanisms between the two [7]. This isolated perspective limits a systematic understanding of the complex interactions between environment and behavior, particularly regarding the comprehensive analysis of dynamic behavioral paths and environmental evaluation [8]. Against this backdrop, this study selects coastal service hubs as its research focus, specifically concentrating on tropical coastal regions. It aims to address existing research gaps through an integrated "evaluation-coupling" framework. On one hand, a scientific environmental evaluation system will be constructed to quantify the environmental quality of coastal service hubs. On the other hand, behavioral path modeling will be employed to elucidate the specific influences of the service hub's spatial environment on user behavior and its underlying regulatory mechanisms. Based on this, an optimized design methodology grounded in "environment-behavior coupling" will be proposed. By integrating these two research strands—evaluation systems and behavioral paths—a novel framework for guiding the spatial optimization of coastal service hubs will be established. Figure 1 summarizes the overall research framework, linking environmental stimuli, user perceptions, and behavioral responses (SOR) to the evaluation–coupling workflow adopted in this study.

II. METHODS

A. DATA COLLECTION METHODS AND RESEARCH OBJECT

The research object selected for this study is the "Sky Mountain" Service Hub located in Haikou, Hainan Province. This case integrates community connectivity and tourism service functions, situated in a tropical coastal area, making its spatial design highly representative. The research fully combines field and expert-based approaches, synthesizing multi-dimensional data sources:

1. Field Investigation and Behavioral Observation: Systematically recorded the service hub's spatial distribution, facility conditions, and user behaviors during different time periods (e.g., staying locations, activity types, path flows).

2. Questionnaire Survey: Questionnaires were designed for different tourists and local residents. A total of 320 questionnaires were distributed, with 298 valid responses collected. The interviewees covered diverse age, gender, and occupational groups. This study was approved by the Ethics Committee of Hainan University, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

3. Expert Consultation: The Fuzzy Delphi Method was employed to conduct multiple rounds of scoring and feedback with six experts in the fields of planning, architecture, and environmental psychology, ultimately determining the classification structure and evaluation indicators for the environmental factors. The SD questionnaire items and anchors employed in data collection are listed in Table 2, while the literature-derived factor pool that informed the instrument design is summarized in Table 1.

B. DUAL-TRACK RESEARCH METHODOLOGY SYSTEM

The integrated methodology—screening and weighting by AHP followed by mechanism testing via SEM—is visualized in Figure 2.

III. ESTABLISHMENT OF THE SPATIAL ENVIRONMENT EVALUATION SYSTEM FOR THE SERVICE HUB

A. EXTRACTION OF OVERALL SPATIAL EVALUATION FACTORS

Drawing upon environmental psychology and related theories, and integrating research on urban service hubs both in China and internationally, the overall user experience of the coastal urban service hub space was evaluated comprehensively across five dimensions: Spatial Layout and Functional Attributes, Environmental Integration, User Behavior and Experience, Facilities and Services, and Social Benefits. Through subsequent extraction and consolidation, an initial sample of indicators was obtained and organized for screening and evaluation by experts. The selected rate for all indicators exceeded 0.5, and no experts suggested adding or modifying these indicators, indicating a consensus among the expert panel. Therefore, the questionnaire survey regarding these indicators was concluded. Table 1 reports the statistics of candidate evaluation factors collated from the literature. Based on this distillation, the finalized evaluation index system for Haikou's urban service hubs is organized in Table 3. The final results are as follows:

B. EXTRACTION OF PERCEPTION EVALUATION FACTORS FOR NODE SPACES

Perception evaluation factors consist of multiple pairs of adjective opposites, each expressing two contrasting meanings. This method first involves collecting adjective pairs related to the spatial qualities of urban service hubs in Haikou City, adhering to the following principles:

(1) Respondents should be mentally mature and capable of accurately expressing their psychological perceptions of the waterfront space.

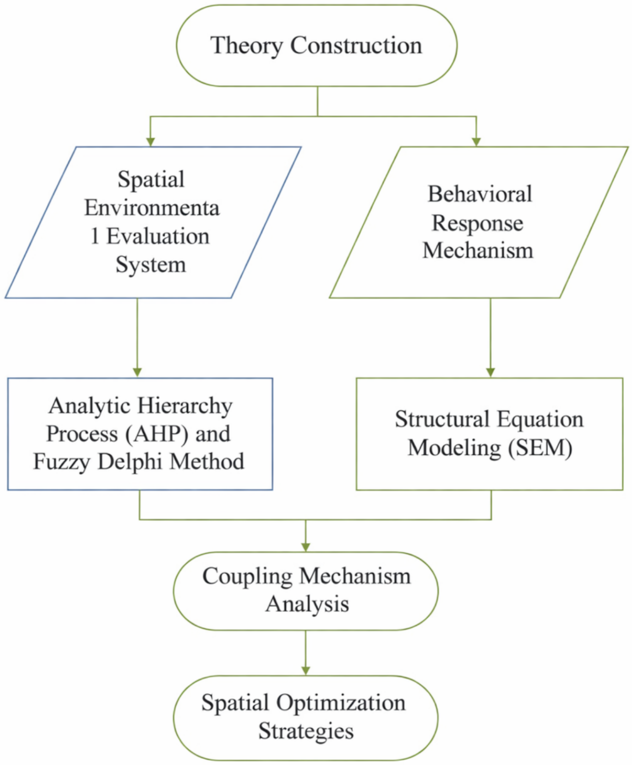

FIGURE 1. Research Framework

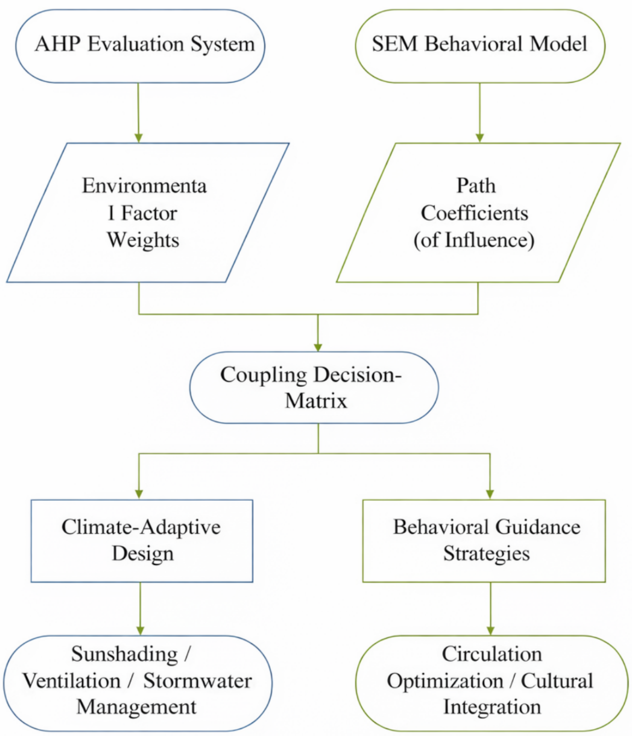

FIGURE 2. Dual-Track Research Methodology System

(2) The selected adjective pairs should primarily relate to the spatial character of the service hub and align with the local features of the waterfront area.

(3) Adjective pairs familiar to respondents should be pri-

TABLE 1. Statistical Table of Evaluation Factors from Literature on Urban Service Hubs

Evaluation Factor	Evaluation Code	Evaluation Indicator
Spatial Layout & Functional Attributes (B1)	C1	Accessibility
	C2	Spatial Hierarchy Richness
	C3	Functional Complexity
	C4	Scenic View Coverage Rate
	C5	Openness of Waterfront Interface
	C6	Service Radius Coverage Rate
	C7	Utilization Rate of Eco-friendly Materials
Environmental Integration (B2)	C8	Proportion of Native Plant Species
	C9	Water Body Interaction Design
	C10	Microclimate Regulation Effectiveness
	C11	Nightscape Integration Degree
	C12	Biodiversity-Friendly Measures
User Behavior & Experience (B3)	C13	Peak Hour Occupancy Rate
	C14	Incidence Rate of Social Behaviors
	C15	Support Level for Waterfront Activities
	C16	Spatial Belongingness Index
	C17	Multi-sensory Experience Richness
	C18	Safety Perception Score
Facilities & Services (B4)	C19	Completeness of Waterfront-specific Facilities
	C20	Smart Service Penetration Rate
	C21	Barrier-free Facility Coverage Rate
	C22	Maintenance and Update Timeliness
	C23	Relevance of Cultural Display Content
	C24	Emergency Service Response Efficiency
Social Benefits (B5)	C25	Waterfront Economic Catalytic Effect
	C26	Community Activity Capacity
	C27	Ecological Education Effectiveness
	C28	Spatial Inclusivity Index
	C29	Social Media Engagement

TABLE 2. SD Perception Evaluation Factors for Urban Service Hubs

No.	Neutral Term	Adjective Pair
1	Vitality	Lively – Deserted
2	Functionality	Multi-functional – Single-purpose
3	Waterfront Affinity	Water-accessible – Isolated
4	Shade Degree	Shaded – Exposed (to sun)
5	Ventilation	Ventilated and Comfortable – Stuffy and Uncomfortable
6	Cultural Distinctiveness	Culturally Distinct – Culturally Lacking
7	Aesthetic Appeal	Modern Design – Dated and Monotonous
8	Safety	Well-protected – Hazard-Prone
9	Lighting	Soft Lighting – Harsh or Dim Lighting
10	Material Quality	High-quality Texture – Coarse and Cheap
11	Sociability	Conducive to Socializing – Isolated and Enclosed
12	Natural Integration	Harmonious with Nature – Heavily Artificial
13	Accessibility	Easily Accessible – Inconvenient to Reach
14	Maintenance Level	New and Well-maintained – Dilapidated and Worn-out

oritized, avoiding obscure or difficult-to-understand terms.

To further assess the applicability of the adjective pairs for evaluating the perception of nodal service hub spaces, a small number of preliminary questionnaires were distributed at various service hub sites across districts. Through communication and inquiry, adjective pairs that respondents found difficult to understand or uncommon were recorded and noted. Ultimately, 14 suitable pairs were selected as the perception evaluation factors for nodal service hub spaces in Haikou City.

Perception-oriented factors and SD adjective pairs for node spaces are detailed in Table 2.

C. ESTABLISHMENT OF THE EVALUATION INDEX SYSTEM FOR SERVICE HUB SPATIAL PERCEPTION

This evaluation index system is structured into three levels: Target Layer (A), Criterion Layer (B), and Indicator Layer (C).

TABLE 3. Evaluation Index System for Urban Service hubs in Haikou City

Target Layer (A)	Criterion Layer (B)	Indicator Layer (C)
Evaluation Indicators for Overall Urban Service Hub Space	Spatial Layout & Functional Attributes (B1)	Accessibility
		Spatial Hierarchy Richness
		Functional Complexity
		Scenic View Coverage Rate
		Openness of Waterfront Interface
		Service Radius Coverage Rate
		Utilization Rate of Eco-friendly Materials
	Environmental Integration (B2)	Proportion of Native Plant Species
		Water Body Interaction Design
		Microclimate Regulation Effectiveness
		Nightscape Integration Degree
		Biodiversity-Friendly Measures
	User Behavior & Experience (B3)	Peak Hour Occupancy Rate
		Incidence Rate of Social Behaviors
		Support Level for Waterfront Activities
		Spatial Belongingness Index
		Multi-sensory Experience Richness
		Safety Perception Score
	Facilities & Services (B4)	Completeness of Waterfront-specific Facilities
		Smart Service Penetration Rate
		Barrier-free Facility Coverage Rate
		Maintenance and Update Timeliness
		Relevance of Cultural Display Content
		Emergency Service Response Efficiency
	Social Benefits (B5)	Waterfront Economic Catalytic Effect
		Community Activity Capacity
		Ecological Education Effectiveness
		Spatial Inclusivity Index
		Social Media Engagement
Evaluation Indicators for Nodal Service Hub Space	Spatial Perception (B6)	Vitality
		Functionality
		Waterfront Affinity
		Shade Degree
		Ventilation
		Cultural Distinctiveness
		Aesthetic Appeal
		Safety
		Lighting
		Material Quality
		Sociability
		Natural Integration
		Accessibility
		Maintenance Level

First Layer: Target Layer (A). The evaluation of the holistic spatial vitality of the Haikou “Sky Mountain” urban service hub and the evaluation of the spatial vitality of its nodal points.

Second Layer: Criterion Layer (B). This layer categorizes the vitality factor indicators of the urban service hub space from five dimensions (Spatial Layout, Environmental Integration, User Behavior, Facilities & Services, Social Benefits). It also incorporates the evaluation of perceptual factors from the spatial perception dimension.

Third Layer: Indicator Layer (C). This layer details and refines the directions set by the Criterion Layer, providing specific, measurable indicators based on each dimension.

The resulting perception-oriented evaluation system and its hierarchical structure are presented in Table 3.

D. SPATIAL ENVIRONMENTAL FACTOR WEIGHTING SYSTEM

Conduct AHP analysis using expert ratings and YAAHP software to evaluate the waterfront service center. The AHP derived weights for each evaluation dimension and specific indicator are shown in Table 4. At the standard layer (B) level, analysis shows that among the six evaluation dimensions, the ranking of the top three dimensions is as follows: spatial layout and functional attributes (0.5499)>user behavior and experience (0.2402)>spatial perception (0.2098). The distribution of comprehensive weights indicates that the dimensions of “spatial layout and functional attributes” have the highest overall importance in the evaluation system,

TABLE 4. Weights of Evaluation Indicators for Urban Service Hubs in Haikou City

Criterion Layer (B)	Relative Weight	Indicator Layer (C)	Relative Weight	Absolute Weight	Rank
Spatial Layout & Functional Attributes (B1)	0.5499	Accessibility	0.4190	0.1066	3
		Spatial Hierarchy Richness	–	0.0196	12
		Functional Complexity	–	0.0245	11
		Scenic View Coverage Rate	0.4916	0.2703	1
		Openness of Waterfront Interface	0.2196	0.1208	2
		Service Radius Coverage Rate	–	0.0540	8
User Behavior & Experience (B3)	0.2402	Peak Hour Occupancy Rate	–	0.0371	10
		Incidence Rate of Social Behaviors	0.1629	0.0896	4
		Support Level for Waterfront Activities	–	0.0637	6
		Spatial Belongingness Index	–	0.0565	7
		Multi-sensory Experience Richness	–	0.0810	5
		Safety Perception Score	–	0.0447	9

followed by "user behavior and experience" and "spatial perception".

In order to clearly distinguish the overall dimension weights, further analysis of the absolute weights within the dominant standard layer ("spatial layout and functional attributes") shows that "landscape coverage" is the strongest individual indicator overall (0.2703). The subsequent ranking within this dimension is: waterfront interface openness (0.1208)>accessibility (0.1066)>service radius coverage (0.0896)>functional complexity (0.0810)>spatial hierarchy richness (0.0637).

Similarly, by analyzing the absolute weights within the "User Behavior and Experience" standard layer, the following rankings were obtained: Social Behavior Incidence (0.0565)>Multi sensory Experience Richness (0.0540)>Waterfront Activity Support Level (0.0447)>Spatial Belonging Index (0.0371)>Security Perception Score (0.0245)>Peak Time Occupancy Rate (0.0196).

This highlights that social interaction and scenic viewing are the primary needs of visitors for the service hub and should be given priority.

IV. QUANTITATIVE EVALUATION OF THE SERVICE HUB'S SPATIAL ENVIRONMENT

A. QUANTIFICATION OF OVERALL SPATIAL VITALITY FACTOR INDICATORS

Regarding the established evaluation index system for the Haikou urban service hubs, 29 targeted evaluation indicators were previously selected. The author now provides a positive description for these 29 indicators. The positive description primarily utilizes a five-level scale— "Strongly Agree", "Agree", "Neutral", "Disagree", and "Strongly Disagree"— to evaluate each indicator. This method was applied at the "Sky Mountain" urban service hub, and visitor evaluation data was simultaneously collected through questionnaire surveys. Finally, the collected data underwent fuzzy comprehensive calculation to derive the comprehensive evaluation results. Comprehensive evaluation outputs for the study area—covering overall vitality scores and rank ordering—are summarized in Table 5.

TABLE 5. Comprehensive Evaluation Results

Criterion Layer	Score	Evaluation Result	Evaluation Factor	Score	Evaluation Result
Spatial Layout & Functional Attributes (B1)	43.02	Moderate	Accessibility	45.50	Moderate
			Spatial Hierarchy Richness	38.20	Poor
			Functional Complexity	41.00	Moderate
			Scenic View Coverage Rate	48.60	Moderate
			Openness of Waterfront Interface	46.30	Moderate
			Service Radius Coverage Rate	39.50	Poor
			Utilization Rate of Eco-friendly Materials	42.04	Moderate
Environmental Integration (B2)	58.85	Good	Proportion of Native Plant Species	61.20	Good
			Water Body Interaction Design	55.40	Moderate
			Microclimate Regulation Effectiveness	59.75	Moderate
			Nightscape Integration Degree	62.10	Good
			Biodiversity-Friendly Measures	55.80	Moderate
User Behavior & Experience (B3)	45.36	Moderate	Peak Hour Occupancy Rate	42.50	Moderate
			Incidence Rate of Social Behaviors	48.20	Moderate
			Support Level for Waterfront Activities	46.10	Moderate
			Spatial Belongingness Index	44.80	Moderate
			Multi-sensory Experience Richness	47.30	Moderate
			Safety Perception Score	43.26	Moderate
Facilities & Services (B4)	60.85	Good	Completeness of Waterfront-specific Facilities	62.40	Good
			Smart Service Penetration Rate	58.30	Moderate
			Barrier-free Facility Coverage Rate	61.50	Good
			Maintenance and Update Timeliness	59.20	Moderate
			Relevance of Cultural Display Content	63.10	Good
			Emergency Service Response Efficiency	60.60	Good
Social Benefits (B5)	59.12	Good	Waterfront Economic Catalytic Effect	57.40	Moderate
			Community Activity Capacity	61.20	Good
			Ecological Education Effectiveness	58.50	Moderate
			Spatial Inclusivity Index	60.10	Good
			Social Media Engagement	58.40	Moderate

B. QUANTIFICATION OF SPATIAL VITALITY PERCEPTION FACTOR INDICATORS

The SD (Semantic Differential) method questionnaire was employed using a 7-point evaluation scale to prevent respondents from confusing the degrees of adjectives. The scale consisted of: Very Poor, Poor, Slightly Poor, Neutral, Slightly Good, Good, and Very Good, corresponding to scores of -3, -2, -1, 0, 1, 2, and 3, respectively.

This forms a symmetric scale with 0 as the central axis, as shown in Table 6. As shown in Table 7, a higher score indicates that the evaluation content is closer to the positive adjective of the neutral factor, representing a greater advantage; conversely, a lower score indicates that the evaluation content is closer to the negative adjective of the neutral factor, representing a lesser advantage.

TABLE 6. Evaluation Scale

Very Poor	Poor	Slightly Poor	Neutral	Slightly Good	Good	Very Good
-3	-2	-1	0	1	2	3

TABLE 7. SD Evaluation Scores for the Sky Mountain Urban Service Hub

No.	Neutral Factor	Score
1	Vitality	0.55
2	Functionality	0.80
3	Waterfront Affinity	1.50
4	Shade Degree	2.20
5	Ventilation	0.70
6	Cultural Distinctiveness	2.10
7	Aesthetic Appeal	1.85
8	Safety	2.00
9	Lighting	1.55
10	Material Quality	2.35
11	Sociability	0.70
12	Natural Integration	1.25
13	Accessibility	0.30
14	Maintenance Level	-0.15

C. CORRELATION ANALYSIS BETWEEN WATERFRONT NODE SPATIAL VITALITY AND INFLUENCING FACTORS

Pearson correlation analysis was used to examine whether a statistically significant relationship exists between two variables. As shown in table 8, significance is determined based on the p-value: if $p < 0.05$, the correlation between the two variables is considered statistically significant. Only after confirming significance can the direction and strength of the correlation be reasonably interpreted. In other words, passing the p-value test is a prerequisite for discussing the degree of correlation. Furthermore, the absolute value of the correlation coefficient r reflects the strength of the relationship. Generally: $0 < |r| \leq 0.1$ indicates a very weak correlation, nearly negligible; $0.1 < |r| \leq 0.3$ suggests a weak correlation; $0.3 < |r| \leq 0.5$ denotes a moderate correlation; $0.5 < |r| \leq 0.8$ represents a strong correlation; $0.8 < |r| \leq 1$ implies a very strong correlation.

The results show that viewscape coverage rate ($r = 0.72$, $p < 0.01$) is the most strongly correlated dominant factor with spatial vitality and has the highest weight (0.2703). Open and expansive views significantly enhance users' willingness to stay and promote activity diversity. Social behavior occurrence rate ($r = 0.68$, $p < 0.01$), as a core indicator (weight = 0.0896), further confirms the role of the service hub as a social hub. Meanwhile, waterfront interface openness ($r = 0.61$, $p < 0.01$) underscores the distinctive requirement of coastal service hubs—open waterfront designs notably enhance spatial vitality. Among the secondary factors, multisensory experience richness ($r = 0.53$) improves site attraction through elements such as sound, light, and tactile quality, while accessibility ($r = 0.48$) indicates that convenient transportation is essential for promoting space use. However, factors such as functional complexity and service radius coverage show a certain misalignment between design intentions and practical needs,

TABLE 8. Pearson Correlation Matrix

Indicator	Correlation Coefficient with Spatial Vitality (r)	p-value	Significance	Remarks
Viewscape Coverage Rate	0.72**	0.002	Highly Significant	** denotes p < 0.01 (highly significant), * denotes p < 0.05 (significant)
Social Behavior Occurrence Rate	0.68**	0.005	Highly Significant	
Waterfront Interface Openness	0.61**	0.008	Highly Significant	
Multisensory Experience Richness	0.53*	0.021	Significant	
Accessibility	0.48*	0.032	Significant	
Functional Complexity	0.41	0.062	Not Significant	
Service Radius Coverage	0.38	0.075	Not Significant	
Waterfront Activity Support Level	0.36	0.089	Not Significant	

with no significant impact on vitality. For instance, excessive pursuit of multifunctionality in service hub design may overlook core experiential requirements.

V. ENVIRONMENT-BEHAVIOR COUPLING MECHANISM

A. VALIDATION OF SEM PATH RELATIONSHIPS

Based on the previous AHP analysis, key environmental factors influencing the spatial performance of the service hub and their relative importance (weights) have been identified. This provides a solid quantitative foundation for the selection and focus of core exogenous latent variables in the SEM model (e.g., prioritizing high-weight factors such as viewscape, social behavior support, and waterfront accessibility). Although

Pearson correlation establishes a symmetrical strength between environmental factors and vitality, it cannot determine directional effects. To bridge this gap, this study constructed a structural equation model based on the classic stimulus biological response (SOR) framework of environmental psychology. The SOR theory assumes that environmental stimuli (S) are not only related to internal psychological states, but also actively trigger internal psychological states (O), which in turn drive behavioral responses (R). Then deploy SEM to rigorously test these theoretically predefined directional paths, quantify their specific path effects (beta coefficients), and validate the overall structural fit [9,10].

B. MEASUREMENT MODEL VALIDATION

All observed variables of the latent variables had factor loadings greater than 0.6 (Table 3). In the table 9, the composite reliability (CR) ranged from 0.78 to 0.91, and the average variance extracted (AVE) was above 0.5, indicating that the measurement model exhibits good reliability and validity.

C. PATH RELATIONSHIPS OF THE STRUCTURAL MODEL

After passing the measurement model test, the directional path analysis of the structural model demonstrated a high goodness of fit. This indicates that the theoretically hypothesized pathways align well with the actual

empirical data, providing robust support for the proposed environment-behavior coupling mechanisms [11]. Path analysis revealed key pathways and significant effects through

TABLE 9. Measurement Model Indicators of Key Latent Variables

Latent Variable	Example Observed Variables	Standardized Factor Loading (Range/Mean)	CR	AVE
Microclimate Factor	Shade degree score, ventilation score, microclimate regulation efficacy evaluation	> 0.65 (e.g., 0.68-0.82)	0.85	0.59
Cultural Expressiveness	Cultural distinctiveness score, cultural display relevance evaluation	> 0.70 (e.g., 0.72-0.86)	0.89	0.62
Functional Complexity	Functionality score, functional complexity evaluation	> 0.60 (e.g., 0.63-0.78)	0.78	0.54
Comfort Perception (O)	SD comfort-related adjective pair ratings, questionnaire comfort perception items	> 0.65 (e.g., 0.67-0.80)	0.83	0.55
Cultural Identity (O)	Spatial belongingness index, cultural identity questionnaire items	> 0.75 (e.g., 0.76-0.88)	0.91	0.67
Stay Duration (R)	Observed duration records, self-reported duration in questionnaire	> 0.70 (e.g., 0.71, 0.85*)	0.82	0.60
Revisit Intention (R)	Revisit intention questionnaire items	> 0.80 (e.g., 0.82, 0.89*)	0.86	0.68
Activity Diversity (R)	Number of observed activity types, questionnaire activity participation items	> 0.65 (e.g., 0.66-0.77)	0.80	0.52
Satisfaction (R)	Overall satisfaction questionnaire item	> 0.85 (e.g., 0.86, 0.90*)	0.88	0.71

which environmental factors at the "Sky Mountain" hub influence behavioral responses via psychological perception [12,13]. The microclimate factor (e.g., shading, ventilation) was confirmed to have a significant direct positive impact on stay duration (β = 0.32, $p < 0.01$), and also produced a significant indirect effect by enhancing comfort perception, forming the core pathway: microclimate $\rightarrow$ comfort $\rightarrow$ stay duration (total effect 0.62). This identifies the microclimate factor as the strongest environmental influencer of staying behavior. Cultural imagery serves as a driver, indirectly enhancing revisit intention (β = 0.31, $p < 0.01$) by strengthening cultural identity (β = 0.61, $p < 0.001$). The indirect path effect outweighs the direct effect, highlighting the importance of cultural expressiveness in attracting revisits (total effect 0.41). Furthermore, functional complexity showed significant direct positive effects on both activity diversity (β = 0.26, $p < 0.05$) and frequency of space use (β = 0.26, $p < 0.05$), indicating that diversified functional spaces can effectively promote usage [14]. Notably, the analysis found that age moderates the relationship between ventilation efficiency and satisfaction, with ventilation having a more significant impact on improving satisfaction among older adult groups (β = 0.51, $p < 0.01$), providing an important reference for age-friendly microclimate design [15]. Estimated structural paths and their significance levels are summarized in Table 10.

However, it is worth noting that although these pathways are statistically significant and have theoretical basis, SEM in cross-sectional observational studies captures directional structural relationships rather than absolute causal relationships. The potential impact of unmeasured confounding variables will be further discussed in future research.

VI. SPATIAL OPTIMIZATION STRATEGIES: CLIMATE-ADAPTIVE AND BEHAVIOR-GUIDED MODEL

Based on the empirical results of the "evaluation-coupling" integrated framework, this study proposes a climate-adaptive and behavior-guided spatial optimization framework to enhance the performance of coastal service hubs from three dimensions:

TABLE 10. SEM Path Analysis Results

Path Relationship	Standardized Path Coefficient (β)	p-value	95% Confidence Interval	Type of Effect
Direct Effects				
Microclimate Factor $\rightarrow$ Stay Duration	0.32	< 0.01**	(0.12, 0.47)	Direct
Functional Complexity $\rightarrow$ Activity Diversity	0.26	< 0.05*	(0.10, 0.39)	Direct
Functional Complexity $\rightarrow$ Frequency of Space Use	0.26	< 0.05*	(0.10, 0.39)	Direct
Cultural Expressiveness $\rightarrow$ Revisit Intention	0.18	< 0.05*	(0.07, 0.32)	Direct
Indirect Effect Pathways				
Microclimate Factor $\rightarrow$ Comfort $\rightarrow$ Stay Duration	0.56 $\rightarrow$ 0.44	<0.001***	See sub-path CI	Indirect (via Comfort)
Cultural Expressiveness $\rightarrow$ Cultural Identity $\rightarrow$ Revisit Intention	0.61 $\rightarrow$ 0.31	<0.001***	See sub-path CI	Indirect (via Cultural Identity)
Key Mediation Paths				
Microclimate Factor $\rightarrow$ Comfort	0.56	<0.001***	(0.41, 0.68)	–
Comfort $\rightarrow$ Stay Duration	0.44	<0.001***	(0.30, 0.58)	–
Cultural Expressiveness $\rightarrow$ Cultural Identity	0.61	<0.001***	(0.49, 0.74)	–
Cultural Identity $\rightarrow$ Revisit Intention	0.31	<0.01**	(0.20, 0.45)	–
Total Effects (Top)				
Microclimate Factor $\rightarrow$ Stay Duration	0.62	–	–	Direct + Indirect (Comfort-mediation)
Cultural Expressiveness $\rightarrow$ Revisit Intention	0.41	–	–	Indirect-Dominant
Moderation Effect (Example)				
Ventilation Efficiency $\rightarrow$ Satisfaction (Older Group)	0.51	<0.01**	(0.35, 0.66)	Direct (Age-moderated)

A. MICROCLIMATE-ADAPTIVE OPTIMIZATION STRATEGIES

Shading and Ventilation Design: In line with the core pathway analysis of environmental factors, improving shading and ventilation performance has a significant impact on stay duration (total effect β = 0.62). Service hub design should expand shaded areas, optimize vegetation distribution, and incorporate natural or active ventilation systems to shape a comfortable microclimate. Special attention should be paid to the ventilation preferences of older adults, as improving ventilation efficiency significantly enhances their satisfaction [16].

Enhanced Waterside Design for Comfort: Through open waterfront interfaces (weight 0.1208, correlation r = 0.61), optimize trails, interactive facilities, and water treatment in waterside areas to strengthen spatial integration with coastal features and improve staying willingness and spatial vitality.

B. CULTURE-DRIVEN SPATIAL OPTIMIZATION STRATEGIES

Strengthening Cultural Symbols and Displays: According to path analysis (total effect β = 0.41), cultural expressiveness significantly influences revisit intention. Service hub design should incorporate local cultural characteristics through cultural symbols, display content, and creative art installations to enhance cultural identity. Cultural elements should align with tourism experiences and community activity needs, promoting deep integration of function and cultural expression [17].

Fostering Belonging and Landmark Spaces: Focus should be paced on improving the spatial belongingness index (correlation r = 0.56) to create iconic and aesthetically unique coastal service hubs that attract return visits and extended stays through distinctive cultural imagery.

C. FUNCTIONAL HYBRIDIZATION AND ACTIVITY DIVERSIFICATION STRATEGIES

Rational Allocation of Functional Spaces: Although functional complexity has a relatively low weight (0.0810), it exerts significant direct positive effects on both activity diversity and frequency of space use (β = 0.26, $p < 0.05$). Service hubs should increase multifunctional zones—such as children's play areas, fitness trails, and multipurpose plazas—to meet the needs of various age groups and enhance user participation.

Improving Facility Services and Accessibility: It is recommended to enhance dedicated waterfront facilities, increase the coverage of barrier-free design, and integrate smart service technologies (e.g., online navigation and real-time information push) to optimize transportation accessibility (weight 0.1066). Additionally, service reliability and convenience can be ensured through regular maintenance and emergency response systems [18].

D. INCLUSIVE DESIGN STRATEGIES FOR DIFFERENT AGE GROUPS

Our preliminary moderate analysis emphasizes the necessity of incorporating the concept of inclusiveness into the optimization of service centers. Special attention should be paid to the specific microclimate sensitivity of elderly people, as data shows that improving ventilation can significantly enhance their spatial satisfaction. In addition, by strengthening security protection in a targeted manner and gradually improving spatial inclusiveness (weight 0.0637), a more inclusive and comfortable environment can be created for users of different age groups.

VII. CONCLUSION AND OUTLOOK

This study, based on the case of the 'Sky Mountain' service hub in Haikou, proposes an 'evaluation-coupling' integrated framework that integrates spatial assessments and behavioral path analysis to investigate the interaction between high-performance fabric environmental factors and user behavior, along with their significant path effects. Through an integrated approach employing the AHP and SEM, key environmental factors influencing service hub spatial performance were identified, including their weights and correlations. The direct and indirect effects of microclimate conditions, cultural expressiveness, and functional complexity on behavioral responses were also analyzed.

Although this study provides valuable insights, some limitations must be acknowledged to make the research results instructive. Although the sample size of 298 valid questionnaires is sufficient to establish a baseline SEM, it may limit the statistical power of age adjusted findings, particularly in terms of specific microclimate preferences in the elderly subgroup. Future research should use larger, geographically diverse, and age stratified samples to strongly validate these inclusive design dynamics. Secondly, a fuzzy Delphi group consisting of six experts is used to weight the environmental assessment system; Future method iterations will benefit from a wider range of interdisciplinary expert groups to mitigate potential subjective biases. Finally, although SEM successfully elucidated the structural behavior pathway, the analysis did not consider certain unmeasured confounding variables. Subsequent research should incorporate these variables into a more comprehensive causal model to improve the theoretical framework of environmental behavior interactions in tropical coastal environments.

Key findings include:

1. In terms of spatial environment evaluation, the comprehensive weight of the dimension of "spatial layout and functional attributes" is the highest (0.5499), and "landscape coverage" is the most important single indicator (absolute weight 0.2703). In addition, behavior path modeling identified microclimate environment (shading, ventilation) as the strongest behavioral influencing factor (total effect β=0.62), significantly prolonging dwell time and forming a key indirect path through comfort perception.

2. Cultural expressiveness effectively drives revisit intention by enhancing cultural identity (total effect β = 0.41), highlighting the importance of cultural distinctiveness in enhancing the service hub's attractiveness.

3. Functional complexity has a significant direct effect on both activity diversity and frequency of space use (β = 0.26, $p < 0.05$), though its relatively lower weight ranking suggests that design should strike a balance between functional hybridity and core experiential quality.

In response to these findings, this study proposes a series of targeted spatial optimization strategies, particularly utilizing microclimate adaptive design of cultural driven spatial enhancement, and promoting functional mixing. Ultimately, these strategies aim to provide a scientific basis for the inclusive design of coastal service centers tailored to different user groups.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Ethics Committee of Hainan University, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

AUTHOR CONTRIBUTIONS

Conceptualization –Quan Yuan and Huali Zhang; methodology – Quan Yuan and Huali Zhang; investigation – Quan Yuan and Huali Zhang; writing-original draft preparation – Quan Yuan and Huali Zhang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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