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# Aligning UNESCO HUL Approach with Digital Transformation: A Spatiotemporal Inventory Framework for Urban Landscape Heritage

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**Abstract**

This study investigates the integration of the Historic Urban Landscape (HUL) approach with sustainable digitization frameworks to address gaps in heritage informatics infrastructure for urban landscape conservation. Employing mixed-methods research (document analysis, case study, and spatiotemporal modeling), this project analyzed the historical accumulation and dynamic evolution of heritage values in World Heritage sites, with a focus on the Lushan Kuling historic town. Results demonstrate that a multidimensional spatiotemporal inventory system, grounded in human-environment interaction theory, effectively captures heritage significance through three operational layers: theoretical frameworks, technical workflows, and digital deliverables. Building on critical heritage studies, the findings reconceptualize inventory-building as a cyclical process of data generation, interpretation, and application rather than static documentation. The proposed digital management framework was empirically validated through geospatial visualization of temporal layering patterns in Lushan Kuling historic town. This research provides policymakers with a model for aligning UNESCO's HUL recommendations with digital twin technologies, particularly in addressing the fragmentation of heritage attributes in rapidly urbanizing contexts.

## 1. Introduction

The UNESCO-endorsed Historic Urban Landscape (HUL) approach redefines historic urban areas as "*dynamic spatial configurations where cultural and natural values accumulate over time*" (UNESCO, 2011). By integrating natural features, human-environment interactions, and intangible heritage into heritage cognition, HUL offers a holistic approach to reconciling urban heritage conservation with developmental pressures (Bandarin & Oers, 2017). Despite its theoretical prominence, HUL implementation faces critical barriers in practice: fragmented information resources and lack of standardized protocols for inventory management. Existing inventories predominantly focus on static attributes, failing to systematically capture spatiotemporal dynamics, human-environment interdependencies, or value evolution—limitations that hinder cross-scale planning and adaptive governance.

Concurrently, digital technologies present transformative opportunities for synthesizing natural-cultural data and enhancing heritage documentation (Wang et al., 2018; Yang & Han, 2020). However, current research on digital inventories for HUL remains fragmented, with unresolved challenges in interoperable data standards and digital sustainability. Rapid iteration of digital formats (e.g., GIS databases, 3D models) exacerbates issues of archival instability and high maintenance costs (Malssen, 2022), underscoring the urgent need for a dynamic, future-proof information management framework.

This study bridges the HUL approach with digital sustainability principles to address three core challenges:

1) Theoretical: Constructing a spatiotemporal value cognition model that formalizes human-environment interaction processes, enabling multidimensional representation of heritage attributes.

2) Methodological: Designing a dynamic inventory framework compatible with evolving heritage values, supported by designed workflows for cross-platform data integration.

3) Practical: Leveraging digital twin technology and sustainable archiving strategies to strengthen decision-support capabilities in adaptive heritage management.

Through a case study of Lushan Mountain Cultural Landscape (a UNESCO World Heritage Site), the research proposes a tripartite system – theoretical framework → technical workflow → digital toolkit – to resolve information silos and static management paradigms in urban landscape conservation.

## 2. A Theoretical Framework of Digital Inventory for HUL

### 2.1 The Value and Documentation Needs of Historic Urban Landscape Heritage

The HUL approach conceptualizes urban heritage through spatiotemporal duality – a dialectic between gradual evolutionary processes and intentional spatial planning (UNESCO, 2011). The formation of most historic urban landscapes originated from a clear plan and has undergone a long evolution process, such as the Lushan Kuling historic town, which was firstly planned around 1896 (Figure 1). This duality manifests as relationality, emphasizing systemic interdependencies between material heritage, socio-cultural practices, and environmental contexts (Zhang, 2014), and stratification, which traces layered historical drivers (e.g., governance shifts, economic transitions) that imprint on urban morphologies (Xiao et al., 2018). Documentation frameworks must address these dimensions holistically: relationality requires distinguishing "heritage value models" (original socio-

spatial logic) from “current condition models” (adaptive reuse patterns) to decode human-environment feedback loops (Bandarin & Oers, 2015; Yang, 2019), while stratification demands multi-temporal analyses spanning geomorphological constraints, urban development phases, and historical intervention catalogues, as outlined in the *Valletta Principles*. Yet conventional inventories, fixated on static attributes, inadequately capture the co-evolution of heritage values with dynamic urban pressures or intangible living practices. To bridge this gap, inventory systems must prioritize temporal granularity (tracking value shifts across epochs) and systemic connectivity (mapping interdependencies between tangible-intangible elements), thereby aligning HUL documentation with adaptive governance frameworks that respond to both heritage dynamism and digital sustainability imperatives.


Figure 1. Plan of Kuling Estate in 1896

Kuling Town is a typical mountain town historical landscape. As an important carrier of the cultural landscape value of the Lushan World Heritage, it contains rich natural and cultural features. At the same time, its rapid changes and development also reflect the need for digital inventory of historic urban landscapes. Kuling is a valley located in the central and northern part of Lushan Mountain, with an altitude of 1,165 meters. The bottom of the valley has a flat valley of about 5 square kilometers. Due to its special geographical conditions and natural environment, the temperature in the Kuling Valley is 6-7℃ lower than that at the foot of the mountain in midsummer, making it an ideal summer resort. After the British businessman and missionary Litte Edward Selby (LI Deli) rented Kuling in 1895, he gradually formed a mountaintop summer resort through systematic town planning and construction.

According to the brief description of the cultural landscape of Mount Lushan and the Outstanding Universal Value Statement by the World Heritage Center, the characteristics and value of the modern villa complex in Mount Lushan represented by Kuling are: it was a popular holiday resort from the late 19th century to the 20th century, with about 600 villas built and arranged in the landscape environment according to the Modern planning concepts at the time, and became the summer capital of the Republic of China in the 1930s and 1940s. It reflects a variety of architectural styles and is a historical witness to the penetration of Western culture into the hinterland of China from the late 19th century to the mid-20th century (UNESCO, 1996). The heritage value of Kuling lies mainly in the historical information it carries as a witness to social change and cultural exchange, as well as the combination of human activities and natural environment reflected in its site selection, planning and construction process.


Figure 2. Kuling historic town including both natural and cultural features

Kuling's contribution to the value of the World Heritage is reflected in the Outstanding Universal Value criterion iv, which is an outstanding example of a certain type of architecture (group), landscape or technology at an important stage in history. In the World Heritage assessment of ICOMOS, the value of Lushan Cultural Landscape is positioned as spiritual value closely related to natural beauty, and the main heritage is a group of buildings. How to systematically record the natural and cultural elements of Kuling's historical town and their interactions and relationships in the process of evolution is the key to the contemporary digital archive system.

### 2.2 Objects of the Historic Urban Landscape Heritage Inventory

Conventional heritage inventories, often confined to static archival records of isolated monuments or zones, inadequately address the systemic interdependencies inherent in urban landscapes. The HUL approach redefines inventory objects through a stratified ontology that integrates tangible-intangible dimensions and multi-scalar spatial hierarchies (element-plot-city-environment). Analysis of international documents over four decades reveals an evolution toward systematic classification: early instruments like the *Nairobi Recommendations* (1976) and *Washington Charter* (1987) prioritized urban fabric and intangible elements, while the *Vienna Memorandum* (2005) expanded this by emphasizing perceptual attributes (e.g., visual corridors, urban identity cognition) as critical components of heritage value. Contemporary classifications coalesce into two typological axes: tangible elements (urban morphology, architectural ensembles, natural/visual settings) and intangible elements (historical functional evolution, socio-economic structures, cross-scale relational networks). Crucially, this stratified framework demands dynamic documentation tools capable of capturing both tangible-intangible synergies and temporal legibility. Such an approach transcends static lists, instead positioning inventories as adaptive systems that mirror the HUL’s inherent complexity and align with digital sustainability goals through machine-readable, interoperable data structures.

### 2.3 The core content of Historic Urban Landscape heritage archive

The inventory construction of HUL heritage necessitates transcending static monument-centric paradigms to embrace temporal stratification and human-environment feedback loops. Contemporary conservation frameworks, informed by instruments like the *Valletta Principles* and *Nara Document*, now mandate multi-layered documentation that interweaves material transformations with socio-cultural agency. This evolution reflects both epistemological shifts in heritage ontology – from fixed artifacts to dynamic processes – and technological capacities to model complex urban systems.

1) Temporal Stratification: Capturing Urban Palimpsests

Unlike conventional cultural relics inventories fixated on singular historical states, HUL inventory requires diachronic granularity – tracking urban morphogenesis through iterative renewal cycles. Key challenges include: mapping stratigraphic interfaces where governance regimes overlay indigenous spatial logic; establishing update protocols for “living archives” that synchronize with urban development rhythms. Such temporal legibility demands machine-actionable metadata schemas to timestamp morphological changes and adaptive reuse patterns, ensuring archival responsiveness to gentrification pressures or climate resilience retrofits.

2) Human-Environment Synergies: From Elemental Lists to Relational Networks

HUL inventories must operationalize the ritual-utilitarian duality of urban landscapes – where quotidian practices (e.g., pilgrimage routes, artisanal markets) continuously reshape heritage significances. This entails documenting not just physical elements but their performative contexts: how vernacular building techniques respond to microclimates, or how memoryscapes anchor community identity amidst demographic flux. Crucially, archival structures should encode multi-scalar relationality, using graph databases to model interdependencies between architectural features, intangible practices, and environmental thresholds.

3) Digital Platforms as Mediators of Systemic Complexity

The implementation gap between HUL theory and inventory praxis can be bridged through semantic interoperability frameworks. Next-generation digital platforms enable: temporal layering via 4D GIS that superimposes historical maps, planning permits, and crowd-sourced oral histories; stakeholder co-curation through blockchain-versioned archives that reconcile expert assessments with local knowledge. By transforming inventories from passive repositories to reflexive decision-support systems, such tools actualize the HUL mandate for adaptive governance—turning archival completeness from an academic ideal into an operational safeguard against heritage entropy. In the case of Lushan Kuling historic town, the team identified and interpreted the existing features and elements of the historic landscape by overlaying historical images onto the digital twin database (Figure 2).

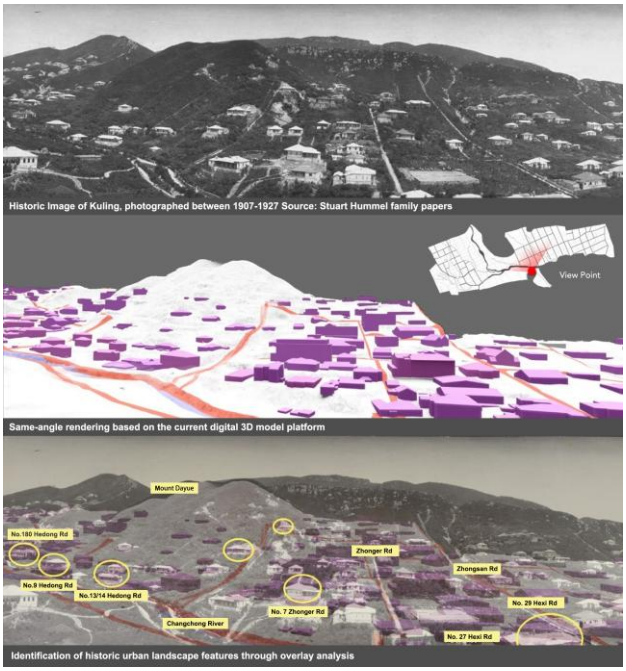


Figure 3. Historic feature identification of Kuling landscape

### 2.4 Technical pathways for HUL Digital Inventory

The proposed digital inventory framework operationalizes HUL theory through a four-phase cyclical workflow, each phase reinforced by specific technical protocols. **Phase 1 (Baseline Intelligence)** employs machine learning-aided archival audits and crowdsourced urban memory mapping to diagnose heritage integrity gaps, generating prioritized digitization approaches. **Phase 2 (Multispectral Recording)** integrates LiDAR, hyperspectral imaging, and oral history geotagging to capture stratified urban palimpsests - from subsurface archaeological strata to ephemeral socio-spatial practices. **Phase 3 (Knowledge Graph Curation)** utilizes semantic ontologies to interlink HBIM models, GIS-temporal layers, and intangible heritage lexicons, enabling federated queries across architectural typologies, craft techniques, and environmental stressors. **Phase 4 (Decision-Ready Simulation)** deploys digital twin interfaces with scenario modeling capacities, allowing planners to stress-test conservation strategies against climate projections or demographic shifts. Crucially, this workflow embeds reflexivity loops: blockchain-notarized field updates trigger automated metadata revisions, while citizen science apps feed real-time usage patterns back into archival ontologies.

The framework’s efficacy hinges on three interoperable toolkits calibrated to local resource contexts. **Toolkit 1 (Data Capture)** combines cost-effective photogrammetry for vernacular structures with AI-assisted archival crosswalks to reconstruct erased urban narratives. **Toolkit 2 (Relational Analytics)** employs graph neural networks to decode hidden correlations—for instance, how colonial-era zoning laws continue to constrain informal settlement morphologies. **Toolkit 3 (Co-Governance Interfaces)** features augmented reality overlays for participatory heritage zoning and NFT-based stewardship contracts to incentivize community archiving. Rather than prescriptive technology stacks, the system advocates modular scalability: a resource-constrained historic quarter might prioritize Toolkit 1’s mobile-based 3D photomapping, while a World Heritage site could implement Toolkit 3’s blockchain-

BIM integration for cross-border accountability. This tiered approach transforms archives from passive repositories into proactive urban acupuncture tools – targeting heritage vulnerabilities through precisely calibrated digital interventions.

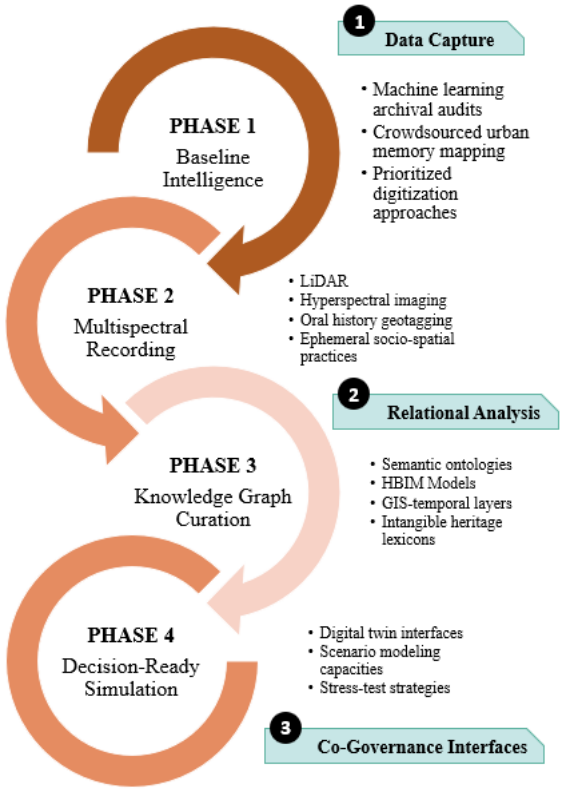


Figure 4. The technical pathway for HUL digital inventory

### 2.5 2.5 Evaluation criteria for digital inventory of Historic Urban Landscapes

Based on the Recommendation Concerning the Preservation of, and Access to, Documentary Heritage including in Digital Form (UNESCO, 2015), including in Digital Form, the Principles of Seville – International Principles of Virtual (ICOMOS, 2017), and other documents, and combined with the Self-Assessment Tool for Evaluating Digital Sustainability (ICCROM, 2022), this study proposes four principles: authenticity, historical rigor, cost feasibility and process transparency.

1) Authenticity means that digital models and data need to truly reflect heritage reality and have sufficient historical evidence to support them; 2) Historical rigor means that digital inventory should cover all historical stages of the heritage, attach importance to the recording and expression of the relationship between the heritage and the surrounding environment, and have characteristics that fully reflect heritage features; 3) Cost feasibility require that the construction of heritage inventory be carried out on the basis of economic investment, technical maintenance capabilities and the evaluation of previous achievements; 4) Process transparency means that the process of digital inventory construction needs to be recorded, and data should be made public, transparent and standardized. Based on the above four standards, this study further designed an evaluation framework for HUL digital inventory (Appendix 1).

## 3. Building A Digital Inventory for Lushan Kuling Histoirc Urban Landscape

Based on the urban historical landscape framework and technical path analyzed in the previous sections, this study systematically identifies the relationship between the value expression of each feature of the historical landscape of Kuling historic town and other elements. Spatial features such as buildings, plots of land, and infrastructure are the core value-bearing elements, connecting the environmental base with non-material elements such as social structure and cultural activities, and forming the nodes of value expression; while historical time, traditional technology, cultural activities and other elements give meaning to the spatial structure and form the cultural background content. Natural elements such as topography, hydrology, and climate provide the basic conditions for the evolution of town form and function; viewpoints carry the spatial cognition and landscape experience of different historical periods. The interrelationship of Kuling heritage elements needs to be centered on 3D spatial objects, and reflected in archives through the connection and co-present of element attributes, supporting the overall expression of heritage value and landscape characteristics.

### 3.1 Urban Pattern: Physical Relationship between Built Environment Formation and Natural Context

Kuling town landscape reflects the integration of Western planning logic and mountain natural environment. Its archive organization needs to be developed around the construction logic of "natural environment-historical background-built environment". The spatial object is based on the natural environment of topography, geology and hydrology, and the built environment elements such as road system, plots, buildings, etc. are used as the spatial framework to express the relationship and spatial adaptation approach of the town in the natural environment of East valley. At the same time, a historical version model database should be established for each element, and historical events, planning ideas and social foundations that affect planning in different periods should be integrated to analyze and visualize the pattern and planning evolution of each period.

### 3.2 Functional Spatial Organization: The Functional Relationship between the Built Environment, Historical Events and Cultural Activities

The functional spatial pattern of Kuling has gradually evolved from an early summer resort to a multifunctional social space. Its archival expression should take plots and buildings as core entities, focusing on its functional evolution process, user groups, and social life characteristics. Among them, public spaces such as churches and hotels should be the focus. In its attribute table, the fields of "functional type", "related groups", and "usage mode" can be set up to record its dynamic changes through time attributes, with historical photos and other related information.

### 3.3 Visual Landscape: the Visual Connection between the Natural and Built Environment in the Landscape

The visual landscape features of Kuling are composed of natural terrain, coniferous forests and Western-style buildings. Its archive organization should be centered around the 3D objects and viewpoints that make up the landscape, such as terrain, buildings, and vegetation. The 3D model can provide digital support beyond the two-dimensional archives for the expression

of visual landscape features. It is necessary to identify the core viewpoints and set up spatial anchor points, record their location, visual direction, visual element set, cultural relevance and other information, and store typical observation angles through 3D views.

### 3.4 Resource Utilization Patterns: Material Relationships in the Utilization of Natural Resources in Urban Construction

Kuling emphasizes local materials and technical adaptation, and its resource utilization model should be organized around the chain of "resources-technical process-utilization examples". With non-renewable resources as the core entity, record their natural attributes such as type, origin, and reserve status, and establish associations with utilization examples such as buildings, ancillary facilities, and cultural relics. Relevant examples should rely on 3D models to record fields such as material type, processing technology, morphological characteristics, and preservation status in details, and link to non-material content such as traditional technologies and skills, historical events, etc., to track the material selection logic and technical wisdom formed by Kuling under natural constraints.

### 3.5 Internal and External Connections: Associations of Spatial Environments in Social and Historical Contexts

The development mechanism of Kuling has put forward unique requirements for its layered expression. The development of Kuling is influenced by the global trend of summer resort construction and the changes in modern Chinese society. This process is not directly manifested as a specific spatial entity, but needs to be expressed through the coordinated expression of multiple factors. In the archives, time labels can be designed with history as the main line, and by screening the 3D entities under specific time labels, historical events such as Li Deli's land acquisition dispute, religious dissemination, architectural style input, management changes, and political turmoil can be visualized to achieve a retrospective presentation of Kuling's evolution process and driving force.

## 4. Discussion and Conclusion

Based on the discussion and proposals in this project, the digital transformation of urban historical landscape inventory still needs to be explored in depth in the following aspects:

### 4.1 Reconfiguring Heritage Epistemology through Digital Reflexivity

The construction of HUL digital inventory necessitates a paradigm shift from heritage-as-artifact to heritage-as-negotiation – a continuous dialectic between material persistence and mnemonic fluidity. This study demonstrates that digital inventory, when reconceptualized through the lens of critical heritage informatics, can transcend its documentary function to become an apparatus for spatial justice. By implementing cyclical workflows with embedded reflexivity loops (blockchain-authenticated updates, citizen-sourced data streams), inventories evolve into living contracts that mediate between preservation orthodoxies and urban metamorphosis. The proposed framework’s integration of graph-based relational analytics and digital twin simulations operationalizes Massey’s concept of “thrown togetherness” in heritage landscapes, revealing how power geometries – from colonial planning legacies to neoliberal placemaking – are literally inscribed into archival ontologies.

### 4.2 Triple Bind of Techno-Political Implementation

Despite theoretical advancements, three structural tensions constrain HUL digital inventory praxis. First, the standardization-particularism paradox: while 3D metadata schemas enable cross-border data interoperability, they risk erasing vernacular knowledge taxonomies. Second, the temporal dissonance between real-time sensor data streams and generational stewardship cycles, which complicates the alignment of archival update protocols with community-based monitoring rhythms. Third, the extractive ethics latent in AI-driven archival systems, where training datasets from marginalized neighborhoods risk becoming intellectual property assets of platform corporations. Mitigating these requires reorienting digital tools through computing principles – prioritizing learning architectures over centralized data lakes, and blockchain-mediated benefit-sharing agreements over extractive crowdsourcing.

### 4.3 Toward Situated Cyber-Inventory Praxis

Future implementations must embrace technological bricolage - strategically hybridizing high-resolution LiDAR mapping with guerrilla archiving tactics like TikTok-based oral history harvesting. Such counter-archival practices leverage digital tools’ subversive potential while avoiding techno-solutionist traps. Crucially, investment in heritage cyberliteracy programs becomes paramount to equip local stewards with skills to audit algorithmic bias in archival systems or negotiate NFT-based cultural IP contracts. Ultimately, HUL digital inventory thrive not through technological supremacy, but by becoming tactical media— spaces where the right to remember coalesces with the right to imagine alternative urban futures.

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## Appendix

| Evaluation Criteria | Quality Level | Spatial Feature Files |
|---|---|---|
| Information Completeness | A | The 3D digital mapping data completely covers the conservation area, without obvious gaps or data errors, and covers the surrounding environment associated with the heritage value |
| | B | The coverage rate of 3D digital mapping data is ≥90%, a small amount of data missing is allowed, and the surrounding environment record can be simplified |
| | C | The 3D digital mapping data covers the key heritage areas, and the town as a whole and the surrounding environment are expressed by 3D blocks |
| | D | The 3D digital mapping data covers key individual buildings or plots, and the town as a whole and the surrounding environment are only recorded by 2D data |
| | E | There are no 3D digital mapping results. The town and its surrounding environment are expressed by 2D data or very limited 3D blocks |
| Information Authenticity | A | Completely establish the spatial data hierarchy system, and the spatial and attribute information of the LoD model meets the standards; the modeling of important objects reaches LoD3-4, and general objects use appropriate simplified expressions; all modeling processes are recorded in details |
| | B | A basic LoD system is established, and the models at all levels basically meet the technical specifications; the modeling depth generally meets the purpose of the archive; the process records and basic parameters are relatively complete |
| | C | The LoD system is incomplete or uncoordinated, but can express basic spatial hierarchical features; the modeling process is not systematically recorded |
| | D | The archive only contains a single-level model of LoD1 or LoD2, which is not capable of expressing spatial hierarchy; it lacks systematic process records and parameter descriptions |
| | E | No clear LoD system, no recorded process and parameters |
| Information Availability | A | The database structure is clear, and the files are in a universal open format, with good retrieval, browsing and exchange capabilities; it supports multi-platform use, facilitating long-term preservation and cross-system integration |
| | B | The organization of archives is relatively standardized, using a common open format, and supporting basic retrieval and consultation |
| | C | There are mixed file formats, some content relies on professional software to access, and the exchange efficiency is low |
| | D | The archive directory and naming are confusing, the format is closed or highly dependent, and the threshold for use is high |
| | E | The file content is messy, the format is unclear or the file is unreadable |
| Information Cost | A | The cost of archive construction is highly matched with the heritage value, and sustainable technology is adopted with low maintenance cost |
| | B | The cost investment is relatively reasonable, mature and stable technical solutions are adopted, and the long-term maintenance pressure is controllable |
| | C | Some links are not coordinated or inefficiently utilized, which makes maintenance difficult |
| | D | Investment does not match demand, there is over-construction, and long-term maintenance is difficult |
| | E | Lack of cost planning and long-term maintenance plan |