Spatio-temporal Full-cycle Integrated Framework for Old Residential Community Renovation: Theoretical Construction, Mechanism Analysis, and Case Study

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Abstract: The renovation of old residential quarters often faces challenges such as lack of spatio-temporal coordination and fragmented governance. Integrating theories of whole-cycle management, spatial production, and sustainable development, this study develops a spatio-temporal whole-cycle integrated framework comprising temporal, spatial, and governance dimensions, and delves into its underlying mechanisms and empirical validity. The analysis reveals that the spatio-temporal interaction mechanism maintains a dynamic balance between tasks at different stages and the allocation of spatial resources; the governance empowerment mechanism is underpinned by multi-stakeholder collaboration, institutional support, and digital enablement, while the feedback and optimization mechanism ensures closed-loop control and continuous improvement throughout the renovation process. Finally, a preliminary validation was conducted using the Jinniu Flower Garden project in Shanghai, with the aim of providing theoretical foundations and implementation pathways for the renewal of old residential quarters, thereby promoting a more sustainable governance model for urban regeneration.

1. Introduction

As China's urban renewal enters a new phase focused on stock enhancement and quality improvement, the renovation of old urban residential communities has become a national strategic project vital to both public well-being and developmental transformation. Statistics from the Ministry of Housing and Urban-Rural Development indicate that between 2019 and 2024, renovation works commenced on 280,000 old residential communities nationwide, benefiting over 48 million households [1]. However, behind the considerable scale and speed of renovation, a series of systemic dilemmas are emerging: significant fragmentation exists in the temporal process, with many projects prioritizing construction over long-term management, leading to some relapsing quickly due to unclear responsibilities and funding gaps after renovation[2]; spatially, manifestations are fragmented[3], as renovation content is often confined within the community boundaries, failing to be coordinated with external urban spaces, vertical potential spaces, and eco-low-carbon spaces, resulting in low resource utilization efficiency; in terms of governance, mechanisms for multi-stakeholder collaboration are lacking, with ambiguous demarcation of rights and responsibilities, insufficient participation of social capital [4], and public participation often becoming a mere formality [5], raising concerns about sustainability. These dilemmas essentially stem from a insufficient grasp of the systemic complexity inherent in the current renovation model. Fundamentally, the current challenges arise from an inadequate understanding of this complexity, urgently necessitating a shift away from partial, short-term engineering thinking towards the construction of a holistic, whole-cycle governance framework.

Academic research has explored these dilemmas from multiple perspectives, roughly forming three focal points: the temporal dimension emphasizes phase analysis, such as pre-renovation demand assessment and prioritization [6-7], mid-phase financing models [8], and post-renovation property management[9] and satisfaction evaluation[10]; the spatial dimension focuses on renewal techniques, such as spatial redesign for aging-friendly environments [11-12], urban agriculture integration [13], resilience enhancement [14], and green transformation[15-17]; the governance dimension concentrates on institutional adaptations, such as civil law responses during renewal[18] and community governance models [19]. While these studies provide a valuable foundation, three shortcomings persist: temporal and spatial issues are often treated in isolation, lacking in-depth interpretation of their interaction mechanisms; theoretical integration is insufficient, failing to form a systematic operational framework; and empirical support is limited, with many propositions not yet fully validated through case studies. Precisely because of this, constructing a sustainable governance mechanism that integrates spatial resources and orchestrates the entire life cycle becomes particularly imperative.

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2. Theoretical foundation

2.1. Whole-cycle management theory and its application expansion

Whole-cycle management theory emphasizes three key principles: first, systemicity, meaning it focuses on the interconnections and integrity of all links within the system rather than local optima; second, process orientation, meaning management covers the entire process from birth to demise, including feedforward, process control, and feedback mechanisms; third, sustainability, meaning it pursues long-term benefits and the unification of economic, social, and environmental values[20].

In the field of urban renewal, the concept of whole-cycle management has been introduced, but its application has mostly been confined to the linear management of temporal processes, such as emphasizing the phases of project initiation, design, construction, operation, and maintenance. This study provides a crucial expansion: integrating space as an active dimension into whole-cycle management, positing that the production, distribution, consumption, and renewal of space is equally an object requiring whole-cycle management. Consequently, the core concept of"spatio-temporal whole-cycle"is proposed, aiming to achieve a more precise understanding and more effective governance of the complex system of old residential community renovation through the dual-dimensional integration of time and space.

2.2. Spatial production and sustainable development theories

Henri Lefebvre's theory of spatial production posits that space is not merely a container but is also a product and carrier of social relations [21]. The decline of space in old residential communities reflects an imbalance in specific social relations, and their renovation constitutes a process of reproducing new social relations in space. This necessitates that renovation practices must transcend physical form updates and delve into the redistribution of spatial rights and the restructuring of community governance.

Simultaneously, renovation must respond to the contemporary imperatives of sustainable development. The concept of sustainable development as defined by the Brundtland Report provides the value orientation for renovation. This implies that renovation activities must possess long-term effectiveness temporally, avoiding short-term actions; must possess synergistic qualities spatially, achieving harmonious development between internal and external, above-ground and underground, and built and ecological spaces; and must pursue inclusivity in objectives, promoting social equity and resident well-being. Sustainable development theory provides the ultimate standard for evaluating the comprehensive benefits of renovation activities.

2.3. Spatio-temporal characteristics and practical dilemmas of old residential community renovation

Based on the aforementioned theories, old residential community renovation exhibits distinct spatio-temporal complexity.

2.3.1 The Multi-dimensionality of temporal characteristics

This includes firstly, historicity, as the built environment carries the imprints of past policies, technologies, and standards; secondly, long-cyclicity, as renovation is not an endpoint but the beginning of an operation and maintenance cycle lasting decades; and thirdly, non-linearity and iterativity, as feedback during use triggers new assessments and micro-regenerations, forming a recurrent, closed-loop process.

2.3.2 The interwoven nature of spatial structure

Its spatial problems constitute a nested system. Internal spatial issues are explicit; however, their causes and solutions are often tightly interwoven with the potential of external and vertical spaces, as well as the constraints of ecological spaces, necessitating integrated consideration.

These characteristics mean that traditional fragmented renovation approaches, which lack a systemic perspective integrating time and space and often merely address superficial symptoms (like treating a headache only when it hurts), struggle to cope with this multi-dimensional, interwoven complexity, consequently leading to governance failure.

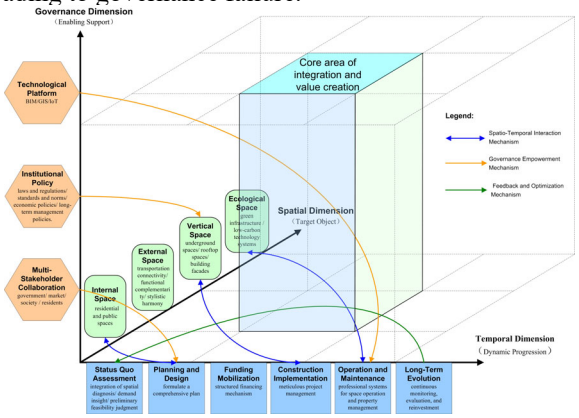

Fig. 1. Spatio-Temporal Whole-Cycle Integrated Framework for Old Residential Community Renovation.

3. Theoretical construction of the spatio-temporal whole-cycle integrated framework

Building upon the aforementioned theoretical foundation, a spatio-temporal whole-cycle integrated framework (as shown in Figure 1) is constructed, aiming to systematically address the complexities inherent in old residential community renovation. This framework

consists of three inter-coupled and organically unified subsystems: the temporal dimension, the spatial dimension, and the governance dimension. It transcends traditional linear or planar research paradigms.

3.1. Temporal dimension: a six-stage closed-loop process chain

The temporal dimension serves as the vertical backbone of the framework, dictating the sequential logic and dynamic progression of the entire renovation process. It is conceptualized as a closed-loop process chain comprising six core stages (see Figure 2).

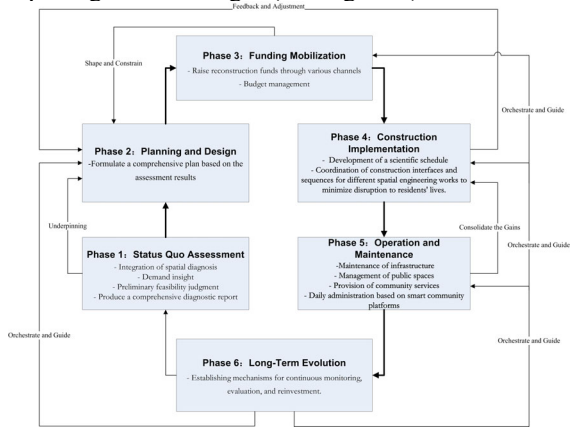

Fig. 2. Schematic Diagram of the Six-Stage Closed-Loop Process Chain.

These six stages are interconnected end-to-end. The outputs from the Long-Term Evolution stage become inputs for a new round of Status Quo Assessment, forming a spiral-escalating closed-loop management system that drives the continuous iterative upgrading of the quality of old residential communities.

3.2. Spatial dimension: four spheres for synergistic optimization

The spatial dimension constitutes the horizontal axis of the framework, defining the physical carriers of renovation activities and their systemic interconnections. It is structured into four spatial spheres requiring synergistic optimization (as shown in Figure 3).

These four spatial spheres are not isolated during renovation but are intricately intertwined and mutually supportive. For instance, a rooftop (vertical) photovoltaic system can power public lighting within the community (internal), and the green benefits it generates (ecological) can potentially be channeled into carbon trading markets to contribute to operational funding (temporal).

3.3. Governance dimension: a three-element enabling support system

The governance dimension serves as the vertical support axis of the framework, providing the institutional, actor-oriented, and technological enablers that ensure the integration of the temporal and spatial dimensions (as shown in Figure 1).

Multi-Stakeholder Collaboration: This element clarifies the role positioning and demarcates the rights and responsibilities of the four core actors: government, market, society, and residents. It aims to construct a new synergistic governance pattern characterized by "government guidance, market operation, social coordination, and resident participation" [22].

Institutional Policy: This element involves designing the rule systems that guarantee the framework's operation. This includes laws and regulations, standards and norms, economic policies, and long-term management policies.

Technological Platform: This element provides the digital tools that underpin the framework's functioning. It emphasizes the application of Building Information Modeling (BIM) for whole-cycle digital twin management, the use of Geographic Information Systems (GIS) for spatial analysis and decision support, and reliance on Internet of Things (IoT) technology to build smart community platforms enabling intelligent facility maintenance and precise community services [23].

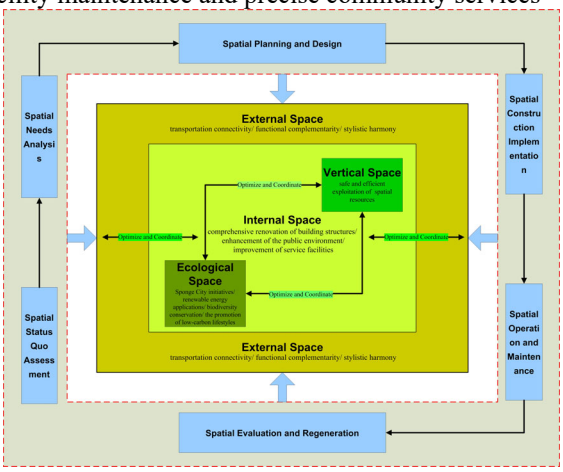

Fig. 3. Schematic Diagram of the Synergistic Optimization of the Four Spatial Spheres.

3.4. Theoretical implications and innovativeness of the integrated framework

The integrated framework conceptualizes old residential community renovation as a complex socio-technical process involving the continuous intervention in and optimization of the spatial system across the temporal process, all enabled by a specific governance environment. Its innovativeness is manifested in three aspects:

- Systemicity: It places the three core dimensions (time, space, and governance) within a single analytical framework, providing a holistic cognitive model.
- Integrativeness: It emphasizes the cross-dimensional interactions between these three dimensions, meaning any renovation decision must simultaneously consider its temporal stage, spatial location, and governance feasibility.
- Dynamism: Through the closed-loop design of the temporal dimension and the feedback mechanisms of the governance dimension, the framework possesses self-renewing and continuously optimizing capabilities.

The proposal of this integrated framework provides a novel theoretical tool for systematicall analyzing the internal logic of old residential community renovation and for guiding renovation practice.

4. Intrinsic mechanisms of the framework

The spatio-temporal whole-cycle integrated framework constructed in this study is not a mere superposition of the temporal, spatial, and governance dimensions. Rather, it constitutes a system characterized by organic linkage and synergistic symbiosis through a series of complex mechanisms. These mechanisms determine its efficacy in transforming from a static theoretical model into dynamic practical effectiveness. This study distills three core intrinsic mechanisms: spatio-temporal interaction, governance empowerment, and feedback optimization.

4.1. Spatio-temporal interaction mechanism

This mechanism serves as the foundational mechanism of the framework, revealing the bidirectional driving and constraining relationships between the temporal and spatial dimensions. Its mode of action can be deconstructed into two aspects.

4.1.1 Temporal dimension drives the spatial dimension

Each stage of the temporal process sets goals, tasks, and constraints for spatial renovation, guiding the direction and manner of spatial resource allocation.

Positive Driving: During the planning and design stage, conclusions from the status quo assessment necessitate the formulation of a comprehensive plan encompassing all four spatial spheres.

Constraining Driving: The construction period, techniques, and sequencing of construction activities during the implementation stage strictly constrain the physical realization process of spatial renovation.

4.1.2 Spatial dimension reacts upon the temporal dimension

Space is not a passive object of renovation; its inherent physical attributes, property rights status, ecological sensitivity, and development potential actively react upon the temporal process.

Constraining Effect: Complex coordination involving external spaces may significantly prolong the planning, design, and implementation phases. Rigid constraints related to vertical or ecological spaces may force a reversion of the temporal process to the planning and design stage, or even to the status quo assessment stage, for plan adjustments.

Facilitating Effect: High-value spatial potential can accelerate the temporal process. For instance, if an assessment reveals significant potential for photovoltaic revenue from rooftop (vertical) spaces, it can attract social capital investment, thereby accelerating the funding mobilization and construction implementation processes, and providing a revenue stream for long-term evolution.

The essence of the spatio-temporal interaction mechanism is the dynamic matching and balancing of renovation goals, resources, and constraints within the spatio-temporal matrix. Successful renovation practice inevitably relies on the accurate anticipation and synergistic management of these two directional influences.

4.2. Governance empowerment mechanism

This mechanism serves as the supporting mechanism of the framework, elucidating how the governance dimension functions as an “empowerment system” to provide the impetus, rules, and tools for the efficient and equitable integration of the temporal and spatial dimensions. Its empowerment pathways manifest at three levels.

4.2.1 Stakeholder synergy pathway: providing organizational impetus

The governance dimension addresses the “who does what” question by constructing platforms for multi-stakeholder collaboration, clarifying the roles and responsibilities of various actors at specific spatio-temporal nodes (e.g., resident participation during the planning and design stage, property company involvement during the operation stage).

4.2.2 Institutional policy pathway: providing regulatory safeguards

The governance dimension clears obstacles and provides incentives for spatio-temporal integration through the formulation of innovative institutional policies. For example, enacting a “Rooftop Space Utilization Management Measure” that clarifies property rights, profit distribution, and safety standards provides the legal basis and economic incentives for the sustained use of vertical spaces across the temporal dimension. Policies such as floor area ratio incentives and green approval channels provide economic motivation for implementing ecological spatial measures during planning and design.

4.2.3 Technological platform pathway: providing decision-making and operational tools

The governance dimension offers precise and intelligent means for spatio-temporal integration through the introduction of digital technology platforms. Utilizing BIM technology enables clash detection across multiple spaces and disciplines during the planning and design stage, avoiding rework later. Employing IoT platforms allows for real-time monitoring and intelligent maintenance of energy consumption in ecological spaces and the structural safety of vertical spaces during the

operation and maintenance stage, significantly enhancing management efficiency.

The core of the governance empowerment mechanism lies in its reform of the relations of production (actors and institutions) and its innovation of the instruments of production (technology) to liberate and develop the productive forces (the renovation activities) represented by the temporal and spatial dimensions.

4.3. Feedback and optimization mechanism

This mechanism serves as the safeguarding mechanism of the framework, ensuring the system's capacity for learning, adaptation, and evolution, thereby realizing genuine “whole-cycle” management. It constitutes a closed-loop system of information and decision flows that permeates the entire temporal chain.

4.3.1 Information monitoring and collection

During the operation, maintenance, and long-term evolution stages, massive datasets concerning the operational status of various spatial facilities, environmental quality, and social benefits are continuously gathered through methods such as resident satisfaction surveys, property management complaint systems, sensor networks, and regular physical inspections.

4.3.2 Information processing and evaluation

The collected data are compared and analyzed against the baseline data from the status quo assessment stage and the anticipated targets from the planning and design stage to evaluate the effectiveness of the renovation and identify emerging issues and needs. For instance, data analysis might reveal that the utilization rate of a rooftop garden is significantly lower than projected, or that the maintenance costs for a specific ecological facility have exceeded budgets.

4.3.3 Decision optimization and re-input

Evaluation conclusions are translated into optimization decisions and fed back to upstream stages of the temporal chain, triggering micro-updates or a new cycle of intervention.

Minor Feedback: Issues like equipment failures discovered during operation are directly reported to the property maintenance team for resolution within the operation and maintenance stage.

Major Feedback: If spatial functions are found to be incapable of meeting new demands or significant structural safety hazards emerge, the feedback will trigger a new round of status quo assessment, subsequently initiating renewed planning, design, and implementation, forming a spiral-escalating “major cycle”.

The feedback and optimization mechanism transforms the framework from a static "predict-and-execute" model into a dynamic adaptive system characterized by "monitor-learn-adapt." This ensures the old residential community can continuously respond to internal demand shifts and external environmental challenges, achieving long-term, sustainable development.

In summary, the three mechanisms interact synergistically to form the dynamic core of the spatio-temporal whole-cycle integrated framework . The spatio-temporal interaction mechanism propels the system, determining its direction and pace. The governance empowerment mechanism acts as the fuel and lubricant, providing the energy for operation and reducing friction. The feedback and optimization mechanism serves as the steering wheel and navigation system, ensuring the system continuously optimizes its path forward on the correct trajectory. All three are indispensable, collectively endowing the framework with robust theoretical vitality and practical guidance.

5. Case validation: the renovation practice of Jinniu Flower Garden in Shanghai

To examine the scientific soundness and practical efficacy of the proposed “spatio-temporal whole-cycle integrated framework”, this study selects the renovation project of the Jinniu Flower Garden old residential community in Xuhui District, Shanghai, as a typical case for in-depth validation. This project was recognized as a “Ministry of Housing and Urban-Rural Development Urban Renewal Best Practice Case”. It has become a national benchmark due to its systematic renovation model characterized by “comprehensive element rehabilitation, full-coverage elevator installation, and area-based governance” [24]. This approach is highly aligned with the spatio-temporal-governance integration essence of our framework, making it a highly representative case for validation.

5.1. Case background and profile

Constructed in 1996, Jinniu Flower Garden is located in Caohejing Subdistrict, Xuhui District, Shanghai. It comprises 25 multi-story residential buildings with 40 stairwell units and 1,056 households. Prior to renovation, the community faced typical dilemmas of old residential areas:

- Deterioration of Physical Space: Building water leakage, damaged roads, outdated infrastructure, and a lack of accessible facilities.
- Aging Demographic Structure: Residents aged 60 and above accounted for over 50% of the population, making the issue of "homebound elderly" struggling with stairs particularly acute.
- Lagging Community Functions: A severe shortage of public activity spaces, a critical lack of parking spaces (only 170 available), and weak connectivity with surrounding urban functions.

Initiated in 2021, the project achieved, through 22 months of efforts, the installation of elevators in all 40

stairwells, comprehensive element rehabilitation, and simultaneously enhanced the level of community governance.

5.2. Validation of the framework application process

5.2.1 Application of the temporal dimension: full implementation of the six-stage closed loop

The renovation process of Jinniu Flower Garden clearly demonstrates the closed-loop management across the six temporal stages.

Status Quo Assessment: This phase involved not only detailed building safety inspections and infrastructure surveys but also in-depth research on resident needs through questionnaires and advisory meetings, providing precise data support for the renovation.

Planning and Design: A systematic “1+5” plan was formulated. While enhancing the quality of the building structures themselves, it simultaneously advanced the rectification of illegal structures, scaled elevator installation, pipeline and wiring upgrades, environmental improvements, and the creation of a 15-minute life circle [25]. The plan embodied spatio-temporal synchronous design, for instance, integrating elevator design with underground pipeline relocation, ground-level greening restoration, and facade renovation.

Funding Mobilization: A structured financing mechanism was adopted. Elevator funds were raised through a “government subsidy and resident cost-sharing by floor and proportion” model. Funds for comprehensive renovation were actively secured from municipal special funds, and social capital was innovatively introduced via a PPP model to participate in subsequent operations, validating the framework's concept of matching diverse funding sources to spatio-temporal needs.

Construction Implementation: This stage demonstrated meticulous spatio-temporal coordination. The contractor adopted an area-based approach characterized by “unified planning, unified approval, and unified construction” to minimize repeated excavation and disruption to residents. Particular emphasis was placed on coordinating work across underground, ground-level, and above-ground spaces. Underground pipeline relocation was completed first to lay the foundation for elevator installation; this was followed by simultaneous advancement of ground-level greening, parking space renovation, above-ground facade updates, and elevator installation.

Operation and Maintenance: A long-term management mechanism was established. A professional property management company was introduced, and the unified maintenance of all 40 elevators was incorporated into its scope. “Elevator steward groups” were created for transparent maintenance information and rapid response. Furthermore, funding for sustained operation was secured by raising property management fees (with owner consent) and revitalizing public space revenue .

Long-Term Evolution: Green and smart elements were incorporated. The renovation introduced photovoltaic power generation facilities, smart waste disposal rooms, and non-motorized vehicle charging piles. The planning and construction of a smart community platform created an interface for future low-carbon and smart development, demonstrating future-oriented adaptability.

5.2.2 Application of the spatial dimension: comprehensive optimization through four-sphere synergy

The renovation systematically optimized all four spatial spheres.

Internal Space: Comprehensive building renovation was completed, including roof waterproofing, facade refurbishment, and stairwell beautification. Internal functions were optimized, adding 193 parking spaces (total 363), and introducing children's playgrounds and fitness facilities.

External Space: Regional linkages were strengthened. By demolishing walls and integrating surrounding standalone buildings and courtyards, spatial integration and resource sharing were achieved. Creating a 15-minute life circle involved coordinating the renovation of a nearby market and constructing new neighborhood hubs , extending community renewal to the block level.

Vertical Space:

-Underground Space: A comprehensive survey was conducted, and intricate underground pipelines were relocated, reserving space for elevator shafts and solving the most significant technical challenge.

-Rooftop Space: Roof waterproofing and insulation were repaired, and photovoltaic power generation facilities were installed to develop and utilize green energy.

-Facade Space: 40 elevators were installed, achieving full coverage and thoroughly resolving the “vertical transportation” pain point.

Ecological Space: Green technologies were introduced, such as photovoltaics, rainwater collection and utilization, and smart waste disposal rooms. Ecological greening was implemented by re-planning green layouts, “using waste materials to supplement greenery”, increasing green space area and biodiversity, and creating a “home within a park” environment.

5.2.3 Application of the governance dimension: strong support through three-element empowerment

The success of Jinniu Flower Garden was rooted in exceptional governance efficacy.

Multi-Stakeholder Collaboration: Party-building leadership was emphasized. A temporary Party branch for elevator work was established, with the residential area Party branch acting as a “strong fortress”. Party members took the lead in tackling challenges.The “three carts”(the neighborhood committee, homeowners' association, and property management) collaborated

effectively, each fulfilling its role. Residents participated deeply. “Three-person elevator teams” (often including lower-floor residents) and resident supervision self-governance groups were formed. Dozens of coordination meetings, door-to-door communication, and visits to buildings with elevators helped resolve conflicts and build consensus.Government-enterprise-society linkages to solve problems like power capacity expansion and pipeline relocation.

Institutional Policy Innovation: A three-level linkage mechanism (district, subdistrict, community) and joint meeting system were formed for efficient problem-solving. Innovative “graduated fund contribution” schemes and elevator subsidy policies balanced interests among residents on different floors. Regulatory documents like the “Jinniu Flower Garden Community Full-Process Supervision Plan for Elevator Installation” were formulated to ensure project quality and safety.

Technological Platform Empowerment: The area-based model of unified design, approval, and construction enhanced efficiency and reduced costs. The contractor set up an open construction technique exhibition area to transparently display materials and techniques, accepting resident supervision and building trust. In subsequent operations, digital groups were utilized for efficient communication and rapid response.

5.3. Validation of mechanism effectiveness

5.3.1 Validation of the spatio-temporal interaction mechanism

Temporal Dimension Drives the Spatial Dimension: The explicit “1+5” planning and design scheme dictated the specific renovation content for the four spatial spheres. For instance, the decision to install elevators mandated the simultaneous implementation of underground pipeline relocation and facade updates.

Spatial Dimension Reacts Upon the Temporal Dimension: The complexity of the underground pipelines posed the most significant technical challenge affecting the elevator installation schedule, which was resolved through preliminary in-depth surveys and coordinated construction, albeit placing higher demands on project timeline management. Conversely, the installation of rooftop photovoltaics became a highlight for green and low-carbon development in the project's long-term evolution.

5.3.2 Validation of the governance empowerment Mechanism

The effective operation of the governance system was crucial for overcoming spatio-temporal challenges. Confronted with opposition to elevator installation from lower-floor residents, reliance on the “three-person teams” for patient communication, Party members taking the lead, and interest-balancing schemes successfully resolved the issue. Facing the challenge of power capacity expansion, it was only through multi-departmental coordinationthat the problem was solved, ensuring the normal operation of all 40 elevators .

5.3.3 Validation of the feedback and optimization mechanism

The project demonstrated a preliminary feedback loop. During the construction stage, opinions were collected and construction details were optimized through resident supervision and the open exhibition of construction techniques. During the operation stage, channels like the “elevator steward groups” enabled rapid response to and resolution of malfunctions, leading to the continuous improvement of service quality. This mechanism ensures the long-term sustainability of the renovation outcomes.

5.4. Validation conclusion: feasibility and effectiveness of the framework

Through an in-depth analysis of the Jinniu Flower Garden case, the “spatio-temporal whole-cycle integrated framework” constructed in this study is effectively validated.

The comprehensiveness and systematicity of the framework are demonstrated. The successful practice of Jinniu Flower Garden is by no means an isolated achievement; rather, it is the result of systematic efforts and synergistic advancement across the temporal, spatial, and governance dimensions, fully aligning with the theoretical model of this framework.

The explanatory and guiding power of the framework are confirmed. The framework's “six-stage” temporal chain, “four-sphere” spatial structure, “three-element” governance system, and their interaction mechanisms provide a clear interpretation of the underlying logic behind Jinniu Flower Garden's success, moving beyond mere description of superficial phenomena. The systematic thinking and actionable roadmap it offers possess strong guiding significance for complex renovation practices.

The practical effectiveness of the framework is supported by both quantitative and qualitative evidence.

Quantitative Benefits: The number of parking spaces increased from 170 to 363 (a 114% increase); 40 elevators achieved full coverage, benefiting over 50% of elderly residents; initiatives like burying power lines and installing photovoltaic systems enhanced green and low-carbon performance.

Qualitative Benefits: Resident satisfaction is extremely high, with significant improvements in their sense of fulfillment, happiness, and security; community cohesion strengthened, and neighborly relations became more harmonious; the value of the entire area was enhanced.

The renovation project of Shanghai's Jinniu Flower Garden old residential community serves as a successful and vivid practical annotation of the spatio-temporal whole-cycle integrated framework. It proves that only by using systematic thinking to orchestrate the temporal process and spatial resources, and empowering them with effective governance, can the complex dilemmas of

old residential community renovation be overcome. This enables the transition from merely having adequate housing to enjoying enhanced living, ultimately achieving the multifaceted integration of economic, social, and environmental benefits. This case not only validates the scientific nature and practicality of the proposed framework but also provides valuable, replicable experience for old residential community renovation in other regions across the country.

6. Conclusion and outlook

6.1. Research conclusions

This study addresses the core challenges of spatio-temporal fragmentation and governance decentralization prevalent in current old residential community renovation. It systematically constructs a spatio-temporal whole-cycle integrated framework and validates its scientific soundness and practical efficacy through an in-depth case study of Shanghai's Jinniu Flower Garden. The main conclusions of this research are as follows:

Regarding theoretical construction, this study has developed an integrated theoretical framework comprising temporal, spatial, and governance dimensions. This framework systematically deconstructs the entire renovation process into six temporal stages, comprehensively covers the renovation object across four spatial spheres, and innovatively positions the governance system as the supporting axis empowering spatio-temporal integration. This framework transcends traditional linear or planar research paradigms, providing a holistic and systematic analytical tool for understanding and guiding old residential community renovation.

Regarding mechanism analysis, this study delves into the three core intrinsic mechanisms driving the framework's operation. The spatio-temporal interaction mechanism elucidates the bidirectional driving and constraining relationships between temporal tasks and spatial resource allocation. The governance empowerment mechanism reveals how multiple stakeholders, institutional policies, and technological platforms provide impetus, rules, and tools for spatio-temporal integration. The feedback and optimization mechanism ensures the system's capacity for dynamic monitoring, learning, and adaptation, forming a spiral-escalating closed loop. The analysis of these mechanisms profoundly reveals the internal logic behind the success of complex renovation projects at the operational level, constituting the theoretical depth of this research.

Regarding case validation, the renovation of Shanghai's Jinniu Flower Garden, a benchmark case, serves as empirical evidence comprehensively validating the feasibility and effectiveness of the constructed framework and its mechanisms. The case demonstrates that this framework can effectively guide practice, enabling everything from precise needs assessment and integrated planning and design to structured financing, meticulous construction organization, long-term operational management, and even future-oriented development planning. The quantitative and qualitative benefits it delivered powerfully attest to the significant superiority of this systematic renovation model based on the framework over traditional approaches.

In conclusion, this study confirms that integrating the temporal, spatial, and governance dimensions through systematic thinking is the fundamental path to addressing the complex dilemmas of old residential community renovation and maximizing its long-term economic, social, and environmental value.

6.2. Research limitations and future prospects

6.2.1 Research limitations

Regarding the generalizability of the case, this study's validation primarily relies on a benchmark case from Shanghai, a megacity. The success of this case benefited from relatively strong government fiscal capacity, high resident consensus, and robust grassroots governance capabilities. The framework's applicability and adaptability to old residential communities in cities of different tiers, with varying socio-economic conditions, and different levels of property rights complexity, require testing with a larger number of samples.

Regarding the refined measurement of mechanisms, while this study analyzes the three core mechanisms, the construction of quantitative models to measure their interaction intensity and relationships remains underdeveloped. For instance, determining which governance model is most effective for resolving specific types of spatio-temporal contradictions requires more precise measurement and validation through large-sample data.

Regarding the deep application of technological platforms, although the study acknowledges the supporting role of technological platforms, the exploration of how they can deeply empower whole-cycle management could be further intensified.

6.2.2 Future prospects

Building upon this research, in-depth exploration could be conducted in the following directions: comparative case studies, quantification and modeling validation, smart technology empowerment, and policy and institutional innovation.

This study represents a initial step towards constructing a systematic analytical framework for old residential community renovation. It is anticipated that future research will continue to deepen and refine this foundation, collectively advancing China's urban renewal endeavors towards a more scientific, efficient, and people-oriented development path.

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