

# The Life Cycle in the Sustainable Development of Urban Agglomerations as Socio-Economic Systems

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**Keywords:** life cycle; sustainable development; urban agglomerations; socio-economic systems; transport and logistics services; life cycle cost; innovative technologies.

**Abstract:** This article examines the role of the life cycle within the sustainable development framework of urban agglomerations conceptualized as socio-economic systems. It analyzes developmental patterns of socio-economic systems, pivotal stages in the evolution of life cycle theory, and methodological approaches to life cycle cost assessment tailored to urban agglomerations. Special emphasis is placed on transport and logistics services within the suburban passenger railway system, which serves as the foundational infrastructure for the spatial functionality of agglomerations. Research findings demonstrate that the application of life cycle theory effectively promotes sustainable development in urban agglomerations and enhances residents' quality of life.

## 1 INTRODUCTION

Contemporary urban agglomerations constitute complex socio-economic systems whose effective development necessitates novel management approaches. "Urban agglomerations, as rapidly evolving socio-economic systems, serve as leaders in technological advancement, engines of economic growth, zones for implementing innovative solutions and technologies, and drivers of efficient regional potential utilization" (Goloskokov, 2008). Within the context of sustainable development, the life cycle concept has acquired particular significance, enabling the evaluation of long-term consequences of management decisions and the optimization of resource utilization.

This study aims to analyze the role of life cycle theory within the sustainable development mechanism of urban agglomerations conceptualized as socio-economic systems. To achieve this objective, the following tasks are addressed: (1) examining developmental patterns of socio-economic systems and mechanisms underpinning their sustainable development; (2) analyzing the genesis and

institutionalization of life cycle theory; and (3) exploring the practical application of life cycle theory exemplified by the evolution of transport and logistics services within the suburban passenger railway system.

**Relevance of the Study.** The relevance of this research stems from the imperative to identify effective governance instruments for complex socio-economic systems under intensifying external and internal pressures. Life cycle theory enables the consideration of long-term consequences of management decisions while maintaining equilibrium among the economic, social, and ecological dimensions of development. This is of particular significance for urban agglomerations, which house the majority of the population and serve as hubs concentrating substantial capital investments and innovative activities.

## 2 MATERIALS AND METHODS

The study employed the following methodological approaches: systems analysis, structural-logical

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analysis, comparative analysis, econometric modeling, index method, and discounted cash flow analysis.

The systems approach facilitated the examination of urban agglomerations as complex socio-economic systems characterized by multi-tiered structures and dynamic evolution. Structural-logical analysis was utilized to identify pivotal developmental stages in life cycle theory and to determine systemic progression patterns of socio-economic formations. Econometric modeling enabled the development of a life cycle cost assessment methodology specifically adapted to the unique characteristics of urban agglomerations. Discounted cash flow analysis incorporated the time value of money principle in evaluating long-term agglomeration development projects. The index method provided quantitative evaluation of transport and logistics service quality.

The research object comprises urban agglomerations conceptualized as socio-economic systems. The research subject constitutes the methodological toolkit of life cycle theory applied within the sustainable development mechanism of urban agglomerations.

The empirical foundation derived from data on the Moscow Transport Hub, encompassing: passenger flow distribution; rolling stock specifications; and temporal trends in fare structures and transportation costs.

### 3 RESULTS AND DISCUSSION

#### 3.1 Urban Agglomerations as Socio-Economic Systems for Sustainable Development

Urban agglomerations constitute complex socio-economic systems that play a pivotal role in the development of contemporary territories. It is well-documented that municipal legal boundaries rarely align with functional urban boundaries. Mega-regions such as Greater Moscow, Greater Paris, the New York Metropolitan Area, and the Guangzhou – Shenzhen – Hong Kong corridor represent territorial spaces governed by multiple municipalities and even distinct jurisdictions, yet operating as integrated urban entities where human capital concentrates. These agglomerations propel the global economy and embody humanity's developmental potential. Urban areas have long transcended administrative boundaries, and attempts to constrain this organic

process through bureaucratic mechanisms consistently prove ineffective.

An urban agglomeration comprises interconnected settlements unified by economic, social, and infrastructural linkages. Core characteristics include high population density, concentrated economic activity, and advanced transport, digital, and social infrastructure networks. Agglomerations both shape societal development and dynamically respond to socioeconomic transformations. As primary nodes concentrating population, capital, and innovation, they represent critical research subjects in sociology, economics, and urban studies.

Russia's largest urban agglomerations are the Moscow and Saint Petersburg metropolitan areas, "whose combined share in gross regional product (GRP) increased from 50.2% in 2016 to 53.2% in 2022" (Government, 2019). Other significant agglomerations include the Samara-Tolyatti, Yekaterinburg, and Kazan metropolitan regions.

Agglomeration development generates multiplicative resource synergies. Urban agglomerations drive economic advancement through three interconnected mechanisms:

1. Resource concentration (labor, capital, and technological assets);
2. Innovation ecosystems (anchored by universities and research centers);
3. Economies of scale (cost reductions through expanded production capacity).

Socio-economic development in agglomerations manifests through migration patterns, socioeconomic stratification, and cultural heterogeneity. Post-industrial and so-called "creative" economies emerge predominantly in major agglomerations, where dynamic environments continuously generate stable demand for novel services. However, this development trajectory concurrently exacerbates systemic challenges, including environmental degradation, transportation congestion, and inflationary pressures on housing and essential goods.

China's eastern coastal regions exemplify the zenith of agglomeration-related environmental crises, where persistent smog obscures solar radiation and ambient noise levels exceeding WHO thresholds ( $\geq 65$  dB) induce severe psychological distress among residents. Resolution necessitates comprehensive spatial development strategies, encompassing expansive green infrastructure networks, industrial relocation beyond urban cores, reduced private vehicle dependency, and systematic traffic calming measures on urban thoroughfares.

Recent years have witnessed sustained inflationary trends across major urban agglomerations, affecting all facets of daily life – from housing and food costs to transport services and recreational expenditures. This multifactorial phenomenon stems from:

1. Demographic pressure: continuous population growth intensifies housing demand amid constrained land availability and elevated construction costs;
2. Logistics inflation: rising fuel and freight costs propagate through supply chains, disproportionately impacting agglomerations with high logistics expenditure burdens;
3. Cost-push dynamics: escalating utility and resource costs increase operational pressures on businesses, triggering price adjustments;
4. Demand-pull effects: higher disposable incomes in core urban zones stimulate consumption, amplifying demand-driven inflation.

A viable mitigation strategy involves strategic expansion of transport-logistics infrastructure. Targeted development of road networks, intermodal bridges, and integrated mobility systems can reduce logistics expenditures by 12–18% (Government, 2019), thereby moderating consumer price indices for delivered goods.

Transportation represents one of the most complex urban challenges lacking definitive solutions. Currently, only two approaches demonstrate efficacy: (1) establishing a hierarchical public transit network – spanning ultra-high-speed trunk corridors to extensive local bus routes; and (2) enhancing residential mobility through rental market incentives that facilitate housing relocation during employment transitions. These measures must be complemented by polycentric spatial development, systematically decentralizing urban functions from core zones.

A critical governance priority for agglomerations is ensuring rapid transit connectivity alongside livable urban environments. Moscow exemplifies successful agglomeration management, having expanded through territorial integration to become Europe's largest and the world's tenth-largest metropolitan region. Home to approximately 20 million residents (14% of Russia's population), it contributes 26% to the nation's GDP. Recent strategic infrastructure initiatives include:

- Construction of over 900 km of roadways;
- Development of 271 engineered structures (bridges, viaducts, tunnels);
- Commissioning of the Moscow Central Circle (MCC);

- Launch of initial Moscow Central Diameters (MCD) routes.

These interventions enhance territorial connectivity, enabling high population mobility and fostering sustainable agglomeration development. As socio-economic systems oriented toward sustainability, urban agglomerations demand integrated governance frameworks encompassing transport accessibility, environmental security, equitable distribution of economic functions, and human-centered urban environments. Sustainable agglomeration development remains unattainable without continuous optimization of the economic-social-ecological balance inherent in urbanization processes.

### 3.2 Life Cycle Cost Assessment in Urban Agglomeration Development Mechanisms

Life Cycle Theory (LCT) delineates the developmental phases of systems, organizations, and products—from inception to decommissioning—alongside their governing laws, patterns, and principles. The evolution of LCT is characterized by five pivotal stages: (1) conceptual germination (pre-1920); (2) formal theoretical articulation (1920–1950); (3) conceptual consolidation (1950–1980s); (4) expansion to socio-economic systems (1980–2000s); and (5) contemporary advancements (2000s–present).

The authors propose a classification of academic traditions that have advanced LCT:

- Biological school: Applies organismic life cycle models to socio-technical systems
- Marketing school: Focuses on product lifecycles and consumer behavior patterns
- Organizational school: Examines institutional evolution and decline dynamics
- Economic school: Quantifies resource allocation across temporal phases
- Sociological school: Analyzes community lifecycle trajectories in urban contexts
- Innovation school: Integrates diffusion theory with technological adoption curves
- Contemporary Russian research tradition: Adapts LCT to post-Soviet spatial governance

- Russian transport research tradition: Specializes in infrastructure lifecycle optimization.

A critical dimension of LCT is its institutionalization – the formal integration of life cycle principles into the regulatory frameworks governing socio-economic systems (Zhou, 2018). This embeds lifecycle considerations into policy design, budgetary planning, and sustainability certification protocols.

Life Cycle Cost (LCC) serves as a critical criterion for evaluating and selecting alternative projects within socio-economic system development frameworks (Schumpeter, 1939). LCC applications include:

- Justifying procurement decisions for technical systems and technology replacement;
- Assessing project investment attractiveness;
- Determining optimal compromise solutions in resource allocation;
- Analyzing resource intensity of maintenance operations;
- Formalizing warranty obligation parameters.

LCC holds particular significance in transport systems, where it enables efficient financial resource utilization while mitigating technical and economic risks in developing transport-logistics infrastructure for megacities and urban agglomerations. Rail transport – a cornerstone of agglomeration development – has implemented a comprehensive LCC management system for rolling stock. This approach encompasses:

1. Granular cost accounting across all lifecycle phases (from locomotive procurement to decommissioning);
2. Integration of RAM analysis (Reliability, Availability, Maintainability);
3. Transition to manufacturer life cycle contracts;
4. Development of an integrated equipment condition database.

Implementation yielded a 25% reduction in technical downtime and 15–20% cost savings in maintenance and repair operations (Dyakov, 2014).

### 3.3 Development of Transport-Logistics Services for Suburban

## Passenger Rail Systems Based on Life Cycle Theory

Research findings indicate that implementing transport-logistics services (TLS) in suburban passenger rail operations constitutes a critical condition for enhancing urban agglomeration resilience. TLS is defined as an integrated set of transport-logistics parameters delivering differentiated service quality tiers, characterized by synergistic gains from deploying innovative technologies, high-efficiency technical systems, and elevated service standards (Chuverina, 2025).

TLS typology is stratified by service maturity levels:

- Transport Service (TS): Basic mobility provision
- Transport-Logistics Service (TLS): Integrated mobility with auxiliary logistics
- Innovative Transport-Logistics Service (ITLS): Technology-enhanced service delivery
- Digitally-Enhanced Innovative Transport-Logistics Service: ITLSd (with embedded digital ecosystem functionality) (Podsorin, 2023).

These service tiers exhibit distinct life cycle durations and life cycle cost (LCC) profiles (Chuverina, 2025). Survey data reveal that "only 20% of passengers prioritize basic transportation exclusively" (Chuverina, 2025), while the remainder demand elevated service quality. Notably, approximately 30% of respondents expressed willingness to adopt ITLS – premium mobility services mandating continuous high-speed internet access and a unified mobile application for journey planning and execution (Chuverina, 2022).

To evaluate the efficacy of innovative transport-logistics services (TLS), a methodology was developed integrating both cost parameters and a transport-logistics service quality index. Calculations conducted for the Moscow–Mytishchi corridor (Moscow–Pushkino route) revealed that "the minimal life cycle cost adjusted by the transport-logistics service quality index indicates the optimal solution for developing suburban passenger rail systems" (Bubnova, 2024). Comparative analysis of TLS variants – Transport Service (TS), Transport-Logistics Service (TLS), Innovative TLS (ITLS), and Digitally-Enhanced ITLS – demonstrated ITLS as the most efficient configuration. LCC values adjusted by the TLS quality index are as follows:

- TS: 12,905.26 million RUB
- TLS: 9,266.52 million RUB
- ITLS: 10,114.31 million RUB

- ITLS: 9,235.20 million RUB (Chuverina, 2025).

Thus, applying life cycle theory to alternative project selection in suburban passenger rail infrastructure actively contributes to urban agglomeration development as a socio-economic system. It establishes foundational frameworks for other socio-economic system domains dependent on transport functionality, thereby enabling holistic sustainable development.

### 3.4 Efficiency of Life Cycle Theory Application for Sustainable Urban Agglomeration Development

Life Cycle Theory demonstrates significant applicability across economic sectors, particularly in transport systems (Sztangret, 2020). It enables organizations to optimize cost management, enhance systemic resilience, and accelerate innovation adoption (Üç, 2016). Amid escalating demands for environmental accountability and sustainable development, LCT implementation transcends operational preference to become a strategic imperative.

Effective life cycle management of suburban passenger rail systems facilitates achievement of three core sustainable development objectives for urban agglomerations:

1. Environmental sustainability: emission reduction and resource efficiency through strategic life cycle governance;
2. Social sustainability: creation of accessible mobility ecosystems, enhanced passenger safety protocols, and improved quality-of-life metrics;
3. Economic sustainability: long-term capital investment efficiency, stimulation of adjacent territorial development, and mitigation of societal costs associated with transport externalities.

Efficiency of Life Cycle Theory Application for Sustainable Urban Agglomeration Development  
Evaluating supplementary agglomeration effects – such as resource-sharing synergies and dynamic transport-logistics infrastructure development – necessitates advancing Life Cycle Theory methodological frameworks. Seminal contributions in this domain include (Brulhart, 2008, Ciccone 2002, Duo 2020).

Implementing LCT instruments, particularly the TLS quality index proposed herein, to justify transport-logistics complex development within urban agglomerations catalyzes:

- Phased modernization of infrastructure components;
- Enhancement of service-oriented functionality;
- Advancement of passenger-centric service paradigms;
- Systemic competitiveness through service differentiation.

This approach transforms infrastructure planning from cost-centric metrics toward holistic value creation, directly reinforcing the tripartite sustainability framework.

## 4 CONCLUSION

This study yields the following conclusions:

1. Urban agglomerations constitute complex socio-economic systems requiring interdisciplinary governance frameworks that integrate economic theory, sociology, systems analysis, and systems control theory. Effective management of these systems fosters sustainable development, enhances residents' quality of life, and ensures macroeconomic stability.

2. Life Cycle Theory serves as an effective governance instrument for urban agglomerations, enabling assessment of long-term decision impacts and optimization of resource allocation. Its application advances balanced economic, social, and ecological development – operationalizing the tripartite sustainability framework central to agglomeration resilience.

3. Life Cycle Cost assessment of transport services incorporating the transport-logistics service quality index facilitates comprehensive evaluation of both economic efficiency and socio-spatial consequences in large urban systems. This methodology holds particular significance for transport-logistics infrastructure, which functions as the backbone of urban functionality and spatial cohesion.

4. The most promising trajectory for modernizing suburban railway systems amid urbanization lies in implementing innovations within transport-logistics services, specifically through digital process transformation in passenger service delivery. This is empirically validated by life cycle cost calculations incorporating the transport-logistics service quality index.

5. Applying Life Cycle Theory to urban agglomeration governance directly advances United Nations Sustainable Development Goals (SDGs), particularly:

- SDG 8: Decent Work and Economic Growth;
- SDG 9: Industry, Innovation, and Infrastructure;
- SDG 12: Responsible Consumption and Production.

Collectively, Life Cycle Theory constitutes a robust governance framework for ensuring sustainable development of urban agglomerations as socio-economic systems. Its implementation enables systematic optimization of investment flows, enhances residents' quality of life, and maintains dynamic equilibrium across economic, social, and ecological development dimensions.

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