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Assessment of the Sustainability of Urban Transport System Management Based on Structural-Synergetic Modeling

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ABSTRACT

The transport complex, which ensures the vital functioning of territories and settlements across the country, requires new analytical tools capable of supporting managerial decision-making under conditions of decentralized governance and the influence of demographic, institutional, and natural–climatic constraints. The relevance of this study is determined by the importance of sustainable development in Arctic cities and urban agglomerations as strategic territories that ensure national security and socio-economic resilience. The **purpose** of this research is to model the dynamic structure of economic subprocesses within the public transport subsystem of an urban or metropolitan transport system in order to assess its performance and identify deviations from the trajectory of sustainable development. The study employs a structural–synergetic modeling method, which allows for both quantitative and qualitative evaluation of interdependencies in complex urban transport systems. Using the example of Murmansk over the period 2013–2022, models were developed to reflect the annual changes in the structure of the city's public transport functioning. This structure includes four types of subprocesses: core, auxiliary, life-supporting, and development-constraining. The study **resulted** in an assessment of the impact of decentralized decisions made by key stakeholders on the sustainability of Murmansk's public transport system, as well as the identification of the nature and direction of synergetic effects. Directions for further modernization of the methodology and techniques of structural modeling are proposed, focusing on the improvement of statistical accounting for relevant indicators. The developed approaches can serve as diagnostic and monitoring tools for assessing the sustainability of transport systems in Arctic regions. The results obtained are of practical interest to federal, regional, and municipal authorities, analytical centers, and infrastructure companies involved in the implementation of sustainable transport and urban mobility policies.

Keywords: sustainable development; Arctic urban systems; transport system; public transport; structural-synergetic modeling; sustainability; system dynamics; stakeholder coordination; urban mobility; regional governance

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INTRODUCTION

In the socio-economic life of cities and urban agglomerations in the Russian Federation, public transport performs one of the most important public functions by ensuring citizens' freedom of movement. At the same time, the volume and quality of transport services provided to the population depend on a wide range of external and internal factors influencing the efficiency of passenger transportation. The governance and regulation of public transport are organized in different ways across cities and urban agglomerations. In recent years, the involvement of private operators has become a widespread practice. Municipal administrations have established single-customer services responsible for organizing transport services for the population, and dedicated funds have been created to finance such service provision. Approaches to the operational control of public transport also vary significantly. On the one hand, many functions are carried out by enterprises subordinate to city administrations; on the other hand, rolling stock operators are granted a high degree of autonomy in carrying out commercial activities. The financing of urban passenger transport is differentiated and takes into account a number of factors, including the historically formed topology of the street and road network; the intermodal configuration of rolling stock used for passenger services; demographic and migration processes; natural and climatic operating conditions, as well as the income levels and lifestyles of urban residents.

The formation of an integrated public transport management system in each city or urban agglomeration constitutes a significant challenge. Addressing this challenge requires robust information and analytical tools capable of producing reliable assessments of the effectiveness of both intentional and unintended actions undertaken by participants within the public transport subsystem of a city or urban agglomeration.

Methods and tools for the optimal planning of transport system operations have been extensively studied and are widely applied in practice. System-based modeling of transport systems is tailored to addressing different classes of problems. For example, various modifications of the gravity model are used to identify optimal transport links in passenger transport planning. At the same time, optimization methods and calculations applied to complex systems do not always adequately account for the specific features of interaction among elements that differ in functions and organizational structures. Factors such as randomness and nonlinearity can significantly reduce the effectiveness of optimization methods, even in highly deterministic systems. Errors associated with the application of queuing theory methods to forecasting the required level of transport infrastructure development may reach 30–50% [1]. The application of life-cycle methodologies and simulation modeling techniques can substantially improve the quality of design and analytical work; however, their effectiveness is constrained by the spatial and temporal characteristics of the objects to which they are applied [2–4].

Program-based and project-oriented management is also not without shortcomings, as it requires coordination and synchronization of actions among stakeholders whose composition, capacities, and strategic objectives may deviate significantly from the sustainable development trajectory of a complex system. For example, improving the transport complex of territories and settlements in the Arctic Zone of the Russian Federation (AZRF) necessitates the alignment of decisions taken at the municipal, regional, and national levels, taking into account ongoing geopolitical and geoeconomic processes. Ensuring solvent demand for transport services in the AZRF cannot be achieved solely through the managerial competencies of local authorities or through the actions of institutional and individual operators of transport infrastructure and rolling stock. The introduction of a balanced scorecard system through the establishment of key performance indicators for stakeholders involved in the formation of transport complexes in this territory cannot fully capture the specific features of the development stages of its constituent entities [5]. At the same time, management theory indicates that maintaining proportionality among system components during transitions from periods of quantitative growth to stages of qualitative development constitutes a critical management task. Moreover, in decentralized systems, developmental imbalances tend to be significantly greater than in centralized ones, as a result of the higher degree of freedom granted to participants. In addition to the inherent levels of self-organization and governance within the transport system itself [6], it becomes necessary to take into account information flows from all other participants interested in receiving transport services. Consequently, in the absence of synchronization of their decisions and actions, organizational links among participants undergo qualitative and quantitative transformation, primarily driven by the most inert elements — those characterized by particularly long adaptation periods. In urban transport systems, such elements include the public transport subsystem serving urban and suburban populations. A gradual decline in service quality is compensated by an increasing share of private passenger vehicles, which in turn leads to a progressive deterioration in the utilization of the urban street and road network and a decline in the overall quality of the urban environment [7,8].

The advancement of methods for assessing the performance of public transport operations in cities of the Russian Federation has increasingly relied on the application of sociometric approaches. For instance, since 2021, experts from the Association of Transport Engineers and the company SIMETRA have compiled a ranking of Russian cities[1] based on the quality of public transport services provided to the population. This ranking is derived from indicator groups such as physical and fare accessibility, transport system functionality, comfort and convenience, safety, and sustainable development.[2] At the Institute for Transport Economics and Transport Policy of the National Research University Higher School of Economics, a methodology for auditing the condition of public transport transport systems has been developed and tested in 50 cities across the country. This methodology is based on an assessment of a set of indicators [5] reflecting the structure of rolling stock, including capacity classes, the share of electric transport and dedicated lanes for MPT, route duplication, and rolling stock capacity across different times of day and transport modes.

It should be noted that, despite their considerable value, existing research studies do not fully account for the full range of factors influencing the operation of transport systems in cities and urban agglomerations. These include, for example, the level of budgetary funding allocated to public transport operators; trends in real household incomes and population dinamics; the presence and scale of competition from private automobiles (including motorization rates, fuel prices, parking policies, and the prioritization of public transport in urban traffic); the renewal of street and road network infrastructure within cities or urban agglomerations; and the systematic planning of route network development. The interests of urban residents can be adequately addressed by municipal authorities and both private and public transport operators only through a comprehensive analysis of the effects generated by the functioning of the transport system.

Within the framework of the intellectual economy — understood as an economic model based on the primacy of knowledge, innovation, and the advancement of methodologies for studying complex systems — the aggregate economic processes occurring in the public transport subsystem of a city or urban agglomeration should be examined through the lens of an ecosystem-based organization of transport production. Accordingly, the use of the term “intellectual economy”

[1] The 2023 ranking of Russian cities in terms of public transport quality URL: https://publictransport.simetragroup.ru/rating.

[2] URL: http:// publictransport.simetragroup.ru/rating

implies the need to consider not only traditional aspects of economic activity and stakeholder decision-making related to the development of the subsystem in question, but also the synergistic effects arising from interactions among participants within the urban transport ecosystem. According to G.B. Kleiner, intelligence in socio-economic systems is understood as "the ability to form, analyze, and present an adequate systemic picture of the world that reflects the structure of functioning and the dynamics of systems that are substantially interconnected with a given system" [9]. Consequently, the analytical toolkit used to study the behavior of the public transport subsystem of a city or urban agglomeration-which plays a significant role in achieving United Nations Sustainable Development Goal No. 11, "Make cities and human settlements inclusive, safe, resilient and sustainable[3]" — must account for the properties of complex spatially distributed systems and the requirements imposed on them.

The considerations outlined above determined the choice of the public transport subsystem within the transport system of Murmansk as the object of this study. This subsystem is examined as a set of interrelated processes arising from the activities of key operators — JSC Elektrotransport and JSC Murmanskavtotrans — as well as users and owners of private motor vehicles and regulatory authorities, through indicators influencing the key parameters of its internal and external environment. The subject of the study comprises the dynamic aspects of organizational relationships that determine the nature of the functioning and development of the public transport subsystem.

METHODOLOGY AND RESEARCH METHODS

According to contemporary views on interactions within living, non-living, and organizational environments, functional and linear relationships are regarded as the fundamental forms of organizational linkages. Functional relationships specify goals, objectives, decisions, and the allocation of responsibility within processes and systems, both in relation to objective reality and to subjective activity, while linear relationships ensure their consolidation and integration.

The structural configuration of these relationships may be formed in time and space either sequentially or in parallel. This inevitably leads to duplication, the creation of reserves, and, consequently, the consolidation of specific quantitative proportions within organizational relationships among the parts of a whole. These proportions determine the level of organization of processes and systems and reflect their underlying essence. Thus, through the distribution of functions, it becomes possible both to identify the system as a whole and to assess the resulting synergistic effect.

A whole that has goals, objectives, functions, decisions, and responsibilities embedded (or assigned) acts as an element — or one of the elements — of an organizational unit and occupies a specific position and role within its structure. An increase in the number of elements and organizational units leads to greater structural complexity, while stability and resilience are ensured through feedback mechanisms.

Although feedback mechanisms shape the dynamics of relationships within the processes and systems of objective reality and subjective activity, for a long time their role was largely limited to restoring organizations to a state of equilibrium. This was due to the fact that equilibrium in the natural, humanitarian, and socio-economic sciences was traditionally regarded as the desired final state of functioning and development. In socio-economic organizations, however, equilibrium — understood as homeostasis or self-sufficiency — meant the attainment of a state at which all tasks had been completed and productive capacity had been expended on reducing uncertainty (entropy). As a result, further change was considered meaningless.

Thus, self-sufficiency treated as a goal rather than as a necessary condition gave rise to ideas

[3] URL: https://www.un.org/sustainabledevelopment/ru/cities/

about the inevitability of decline, the "end of history," societal disintegration, and the closure of systems. Any form of present stagnation was therefore perceived as preferable to a guaranteed deterioration in the future.

The emergence of concepts of dynamic equilibrium in open systems made it possible to reconsider earlier pessimistic assessments of the development prospects of complex systems [10]. The proposition that "matter, energy, information, and the dynamic properties of a system, as well as its structure, are so interrelated that any change in one of these components entails corresponding functional-structural quantitative and qualitative changes in the state of the others" [11] has come to be regarded as the law of internal dynamic equilibrium.

Thus, the role and significance of the dynamic aspects of organization have come to be recognized: the potential of organizational functioning is determined by the totality of static factors discussed above, which, in their unity and interaction, ensure the responsiveness and flexibility of processes and systems. Stability, uniformity, and optimal development of the latter within socio-economic organizations are achieved through continuity and rhythmicity, which together form the necessary level of internal self-organization. The maintenance of continuity and rhythmicity is ensured through the division and cooperation in form of joint, goal-oriented activity, which serves as a mechanism for generating diverse organizational forms [12–14].

Open systems actively exchange resources and the outputs of their activities. Since any interaction presupposes certain relationships among the participants in a process, its effectiveness depends on the current state of the system itself. An organization endowed with an adequate self-regulation mechanism is capable of compensating for emerging counteractions by neutralizing them or by generating new elements required for adaptation to changing conditions. Accordingly, the urban public transport subsystem, as an open system, interacts not only with passengers and transport operators but also with road infrastructure under prevailing financial-economic conditions and regulatory constraints. Therefore, an adequate assessment of the synchronicity of processes occurring both within this subsystem (e.g., the volume of transport work, the development of the route network, and fleet renewal) and in the city's external environment (growth in motorization, changes in budgetary funding, demographic shifts, etc.) is key to understanding its sustainability and efficiency.

Interaction with the external environment may take not only a linear but also nonlinear forms. In the latter case, even minor changes in the parameters of a single element may lead to significant fluctuations or deviations in other elements and affect the entire chain of processes. Consequently, the principal challenge is not the pursuit of absolute stability or flawless operational reliability, but rather the maintenance of a dynamic equilibrium that reflects the desired state of the system — in this case, movement toward Sustainable Development Goal No. 11.

Addressing this challenge appears feasible through an analysis of the structure of the aggregate economic process of providing public transport services in a city or urban agglomeration. According to O.A. Biyakov, such a process constitutes a complex system of interrelated subprocesses (production, consumption, infrastructure-related, and others) operating within a unified economic space and determining the overall dynamics and development outcomes of a territory [15]. In other words, the aggregate economic process encompasses all stages of resource formation and utilization, taking into account factors that facilitate or hinder development. Structural modeling, through the decomposition of this process, makes it possible to identify the degree of collinearity among the target development vectors of key stakeholders in urban and agglomeration transport systems, as well as the direction of the resulting synergistic effect. This method was tested by the author in a previous study [16] and is therefore not described in detail in the present paper.

In the course of the study, the decomposition of the aggregate economic process of the public transport subsystem within Murmansk's transport system was decomposed into four types of subprocesses, each evaluated on the basis of three indicators. The integral values of these indicators were constructed using weighting coefficients and their position within the hierarchy of subprocesses. A significant constraint on the selection of indicators was imposed by the requirements of the structural process modeling method, specifically the availability of statistical observations over an extended time period. Accordingly, the study employed data covering the period from 2013 to 2022.

To analyze the core subprocesses, three indicators were selected: the number of passengers carried (M1), passenger turnover (M2), and the total length of public transport routes (M3). These indicators reflect the achieved performance outcomes of the main public transport operators in Murmansk. Supporting subprocesses were examined using indicators such as the average age of the vehicle fleet operating on routes (S 1), employment in public transport (S 2), and the level of budgetary financial support allocated to the public transport development (S 3), which together characterize the capacity of the city's public transport subsystem to provide transport services to the population. When analyzing life-supporting subprocesses, consideration was given to the city's population size (LS 1), the regional real wage level (LS 2), and the cost of the consumer basket (LS 3). These indicators define the operating conditions of the urban public transport subsystem. Finally, to characterize subprocesses that hinder development, the following indicators were selected: the number of privately owned passenger cars per 1,000 residents (P1), the regional inflation rate (P2), and the price of electricity for industrial consumers (P3). The selection of these indicators is justified by their substantial influence on the capacity of the urban road network and on the feasibility of transitioning to new energy sources, given the natural, climatic and topographical characteristics of the city's transport system.

MODELING THE DYNAMIC STRUCTURE OF ECONOMIC SUBPROCESSES IN THE TRANSPORT SYSTEM OF THE HERO CITY OF MURMANSK

Table 1 presents the normalized values of the indicators characterizing the aggregate economic development process of the public transport subsystem within Murmansk's transport system. These values were obtained by applying a median smoothing procedure to the time series, as this approach reduces statistical noise when calculating the accelerations of indicator dynamics used to describe the structure of the subprocesses of the aggregate economic process.

Table 2 presents the calculated values of accelerations (and decelerations) of the components of the aggregate economic process underlying the development of Murmansk's transport system. These values are used to assess the effectiveness of potential utilization and to model the dynamic structure of its economic subprocesses.

This method makes it possible to compare subprocesses that differ in nature and in the speed of their dynamics.

For example, since 2021, Murmansk has demonstrated a sharp acceleration in passenger transport dynamics, which has led to a convergence between the observed indicator dynamics of public transport subprocesses and the target vector.

This is evident from the data presented in *Table 3*, which shows the actual and target ranking of the subprocesses of the aggregate economic process underlying the development of this subsystem. At the same time, in the 2021 and 2022 models, the effects of the administrative decision to establish the Murmansk agglomeration[4] has not yet evident. This effect is expected to manifest in the alignment of the M2 and M3 with the target

[4] The Murmansk agglomeration includes the city of Murmansk, the closed administrative — territorial formation (CATF) of Severomorsk, as well as the Kola District. Its population amounts to 352 thousand people as of 1st January 2023.

Table 1

Normalized Values of Indicators of the Aggregate Economic Development Process in the Public Transport Subsystem of the Hero City Murmansk

Structure of the Aggregate Economic Process		2015	2016	2017	2018	2019	2020	2021	2022
Core Subprocesses	M1	-1.4	-13.4	17.1	5.8	-25.7	-66.6	56.7	125.4
	M2	10.6	-28.2	8.6	38.3	-35.5	-74.1	97.0	-12.3
	M3	-1.5	11.6	3.6	-23.4	-17.1	-6.4	16.2	-5.7
Supporting Subprocesses	S1	-0.4	3.1	-4.0	0.4	5.5	-11.8	-64.9	17.6
	S2	7.0	-4.6	1.4	-4.9	-3.2	10.6	5.4	-1.3
	S3	110.2	-100.2	-28.7	-7.1	33.8	0.0	3.7	44.4
Life-Supporting Subprocesses	LS1	22.8	-23.0	-0.2	1.2	-1.0	-5.8	-46.6	34.5
	LS2	-3.8	5.5	-7.7	6.2	-2.3	-1.4	2.3	3.4
	LS3	13.1	1.8	-2.7	-12.1	-4.9	8.0	2.5	2.9
Subprocesses Hindering Development	P1	-19.7	3.3	-0.1	7.5	-15.1	-0.7	10.0	10.5
	P2	-10.0	-55.6	18.2	32.6	-21.2	14.0	21.8	29.2
	P2	7.8	-0.2	-0.2	18.3	-65.4	94.3	43.6	-157.4

Source: Calculated by the author.

Table 2

Calculated Values of Accelerations (Decelerations) of the Components of the Aggregate Economic Development Process in the Public Transport Subsystem of the Murmansk Transport System

Structure of the Aggregate Economic Process		2015	2016	2017	2018	2019	2020	2021	2022
Core Subprocesses	M1	-1.4	-13.4	17.1	5.8	-25.7	-66.6	56.7	125.4
	M2	10.6	-28.2	8.6	38.3	-35.5	-74.1	97.0	-12.3
	M3	-17.5	11.6	3.6	-23.4	-17.1	-6.4	16.2	-5.7
Supporting Subprocesses	S1	-0.4	3.1	-4.0	0.4	5.5	-11.8	-64.9	17.6
	S2	7.0	-4.6	1.4	-4.9	-3.2	10.6	5.4	-1.3
	S3	110.2	-100.2	-28.7	-7.1	33.8	0.0	3.7	44.4
Life-Supporting Subprocesses	LS1	22.8	-23.0	-0.2	1.2	-1.0	-5.8	-46.6	34.5
	LS2	-3.8	5.5	-7.7	6,2	-2.3	-1.4	2.3	3.4
	LS3	13.1	1.8	-2.7	-12.1	-4.9	8.0	2.5	2.9
Subprocesses Hindering Development	P1	-19.7	3.3	-0.1	7.5	-15.1	-0.7	10.0	10.5
	P2	-10.0	-55.6	18.2	32.6	-21.2	14.0	21.8	29.2
	P3	7.8	-0.2	-0.2	18.3	-65.4	94.3	43.6	-157.4

Source: Calculated by the author.

vector, reflecting the objective of achieving a synergistic effect from agglomeration processes and changes in the length and structure of the public transport route network.

This is evident from the data presented in Table 3, which shows the actual and target rankings of subprocesses within the aggregate economic process underlying the development of the public transport subsystem. The slowdown in the acceleration of electricity prices for the industrial consumers (P3) had a positive effect, alleviating some of the constraints that had been hindering the development of the city's trolleybus network. At the same time, the positive trend observed in previous years, associated with the deceleration of motorization, came to an end: the growth of private car ownership per 1,000 residents (P1) began to accelerate again. Moreover, the acceleration of regional inflation rates (P2) continues to impede the development of public transport within the city's transport system. This trend is inconsistent with the target vector, which reflects progress toward achieving Sustainable Development Goal No. 11.

The quantitative assessment of the synchronicity of changes in the subprocesses of the public transport subsystem in Murmansk (*Fig. 1*) was conducted by comparing the actual and target structures of indicator dynamics used to model the aggregate economic process of this subsystem. Two rank correlation coefficients — Spearman's and Kendall's — were applied. The target vector reflects the desired positive changes in public transport, both in terms of passenger volumes and average trip length, including the total length of the route network. The attractiveness of public transport is largely determined by the quality of services provided.

Table 3

Actual and Target Ranking of Subprocesses in the Aggregate Economic Development Process of the Public Transport Subsystem of the Hero City Murmansk

Структура совокупного экономического процесса		2015	2016	2017	2018	2019	2020	2021	2022	Целевой вектор
Основные подпроцессы	M1	8	8	2	6	10	11	3	1	1
	M2	4	10	3	1	11	12	1	10	2
	M3	11	1	5	12	8	10	6	9	3
Вспомогательные подпроцессы	S 1	7	6	4	8	6	3	2	11	4
	S 2	6	7	6	9	4	4	8	8	5
	S 3	1	12	12	10	1	6	9	2	6
Жизнеобеспечивающие подпроцессы	LS 1	2	9	9	7	2	9	12	3	7
	LS 2	9	2	11	5	3	8	11	6	8
	LS 3	3	4	10	11	5	5	10	7	9
Подпроцессы, препятствующие развитию	P1	12	3	7	4	7	7	7	5	10
	P2	10	11	1	2	9	2	5	4	11
	P3	5	5	8	3	12	1	4	12	12

Source: Calculated by the author.

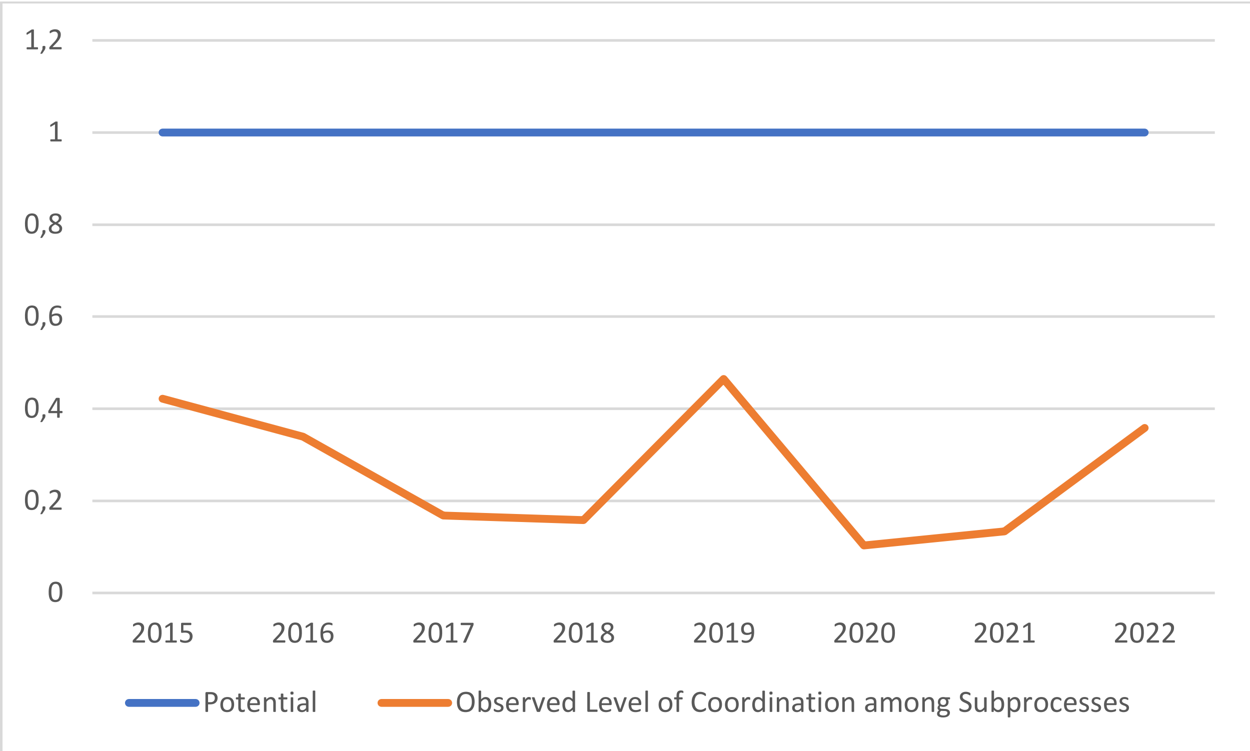

Fig. 1. **Transport Subsystem of the Murmansk Transport System in Utilizing Its Potential**

Source: Modelled by the author.

In this model, this condition is accounted for indirectly through indicators of supporting subprocesses. The fourth position in the target vector is occupied by indicator S 1, which characterizes the average age of the vehicle fleet operating on routes. The renewal of this fleet, which began in 2021, is reflected in the 2022 model. A substantial increase in budgetary financial support for this process (S 3), combined with a slowdown in the growth of public transport employment (S 2) (*Table 2*), distorted the actual indicators dynamics relative to the target values and affected the efficiency of utilizing the potential of the city's transport system. The group of life-supporting subprocesses (LS 1–LS 3) ranks third in terms of priority for indicators acceleration, as it reflects the long-term development goals of Arctic territories. Their implementation, despite the critical importance of demographic policy, depends on the creation of a favorable living environment over the short term.

Murmansk is characterized by a high level of motorization, elevated electricity prices for industrial consumers, and noticeable inflation. Therefore, it appears reasonable to explore ways to curb the growth of these indicators, which occupy positions 9–11 in the target ranking.

Considering the ranking logic and the actual structure of indicator dynamics by subprocess groups over the period from 2013 to 2022, the average effectiveness of the decisions taken, in accordance with goal priorities, reached only about one-third of the potentially achievable level (0.356). Consequently, the efforts of the city's main public transport operators, together with support from municipal, regional, and federal authorities, proved insufficient to counteract adverse migration trends, increasing private car ownership, and rising electricity costs for industrial consumers. As a result, the synergistic effect of interactions among the stakeholders included in the model, as well as the organizational and individual decisions made during the study pe-

Table 4

Qualitative Assessment of the Aggregate Economic Process in the Public Transport Subsystem of the Murmansk Transport System

Acceleration (+) / Deceleration (–) of Subprocesses	Core Subprocesses	Supporting Subprocesses	Life-Supporting Subprocesses	Subprocesses Hindering Development	Dynamic Structure of Economic Processes	Type of Development	Type of Aggregate Economic Process
2015	-1.846	28.864	12.818	-10.282	MS>LS>P	Stable Growth	Effective with Development Improvement
2016	-11.566	-27.039	-8.863	-14.396	LS>P>MS	Unstable Decline	Ineffective with Development Improvement
2017	11.415	-4.681	-2.958	5.120	MS>P>LS	Unstable Growth	Effective with Maintenance of Development Level
2018	8.027	-3.307	-0.601	17.310	P>MS>LS	Unstable Decline	Ineffective with Maintenance of Development Level
2019	-26.407	4.678	-2.306	-29.033	LS>MS>P	Unstable Growth	Effective with Decline in Development Level
2020	-54.180	8.616	-1.197	26.490	P>LS>MS	Unstable Decline	Ineffective with Decline in Development Level
2021	58.464	33.079	-20.716	21.483	MS>P>LS	Unstable Growth	Effective with Maintenance of Development Level
2022	54.289	2.056	17.989	-24.769	MS>LS>P	Stable Growth	Effective with Development Improvement

Source: Calculated by the author.

riod, remained relatively low, ranging from 10% to 40% of the maximum achievable level.

It should be noted that, during the period from 2019 to 2021, all cities faced the consequences of measures aimed at preventing the spread of COVID-19, which significantly reduced the utilization of the potential of their public transport subsystems.

Figure 2 presents models of the dynamic structure of the economic subprocesses underlying the development of Murmansk's public transport subsystem, supplemented by a qualitative assessment of the direction of the synergistic effect resulting from stakeholder interactions (*Table 4*). Based on the analysis of the acceleration or deceleration of indicator movements in each subprocess, it is

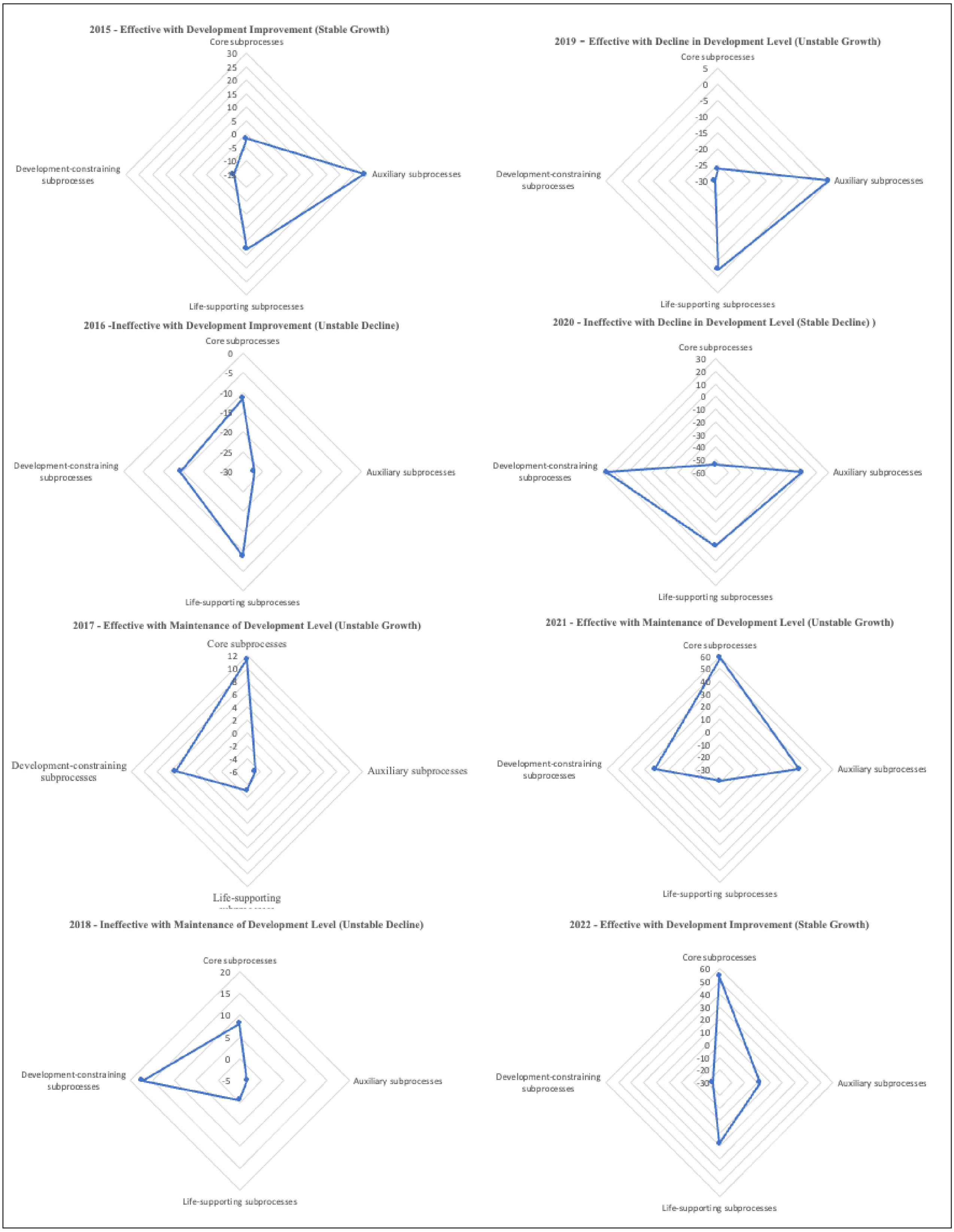

Fig. 2. **Models of the Dynamic Structure of Economic Subprocesses in the Public Transport Subsystem of the Hero City Murmansk Transport System**

Source: Modelled by the author.

possible to draw conclusions about the type of development of the public transport subsystem and the effectiveness of its operational regime in each year of the study period.

The analysis of the dynamic structure of economic subprocesses revealed significant fluctuations between unstable decline and growth within the aggregate economic process of the public transport subsystem. Improvement in performance became noticeable only from 2021 onwards. This finding is consistent with city-level rankings of public transport service quality [9], according to which Murmansk rose from 17th place in 2022 (61.5 points out of 100) to 10th place (71.8 points out of 100). According to SIMETRA data, between 2022 and 2023 improvements were observed in indicators such as public transport sustainability and safety (from 44 to 55), fare affordability (from 51 to 68), transport network functionality (from 59 to 76), and comfort and convenience (from 70 to 77).

RESULTS OF STRUCTURAL MODELING OF ECONOMIC PROCESSES IN URBAN PUBLIC TRANSPORT SYSTEMS

At the same time, physical accessibility deteriorated, decreasing from 80 80 in 2022 to 77 in 2023, reflecting a slight reduction in route network coverage and an increase in travel time to stops and destinations.

Within the group of supporting subprocesses, the average age of the rolling stock (S 1) was selected as one of the key parameters for analyzing service quality in Murmansk's public transport system. The study assumes a significant correlation between S 1 and the quality of services provided by the key operators — JSC "Electrotransport" and JSC "Murmanskavtotrans[5]" — such that a decrease in the average age of rolling stock corresponds to an improvement in service quality. In line with the Federal Project "Modernization of Passenger Transport in Urban Agglomerations,[6]" approximately 50% of the buses and trolleybuses serving the Murmansk agglomeration were renewed. This trend is reflected in the 2021 and 2022 models. Although the expert community recognizes the average age of rolling stock as a valid indicator [5], a more precise assessment of supporting subprocesses quality would require the use of fleet technical readiness as a model parameter. However, the current level of data disclosure in published statistical sources does not allow this indicator to be calculated.

The second indicator within the group of supporting subprocesses — the number of employees in public transport (S 2) — indirectly reflects the level of development and intensity of use of the city's route network. However, S 2 has limitations in capturing the degree of route duplication, which is a key factor for refining the structural modeling of economic processes in public transport systems of cities and urban agglomerations, as it indicates the synchronicity of transport service development between central and peripheral areas.

The complexity of the route network, as well as the reliability of technological accessibility of public transport services for the population, is determined by the number of routes, their length, and service frequency. These characteristics reflect the degree of self-organization of the public transport subsystem and its capacity to adapt to changes in passenger demand and the city's spatial development. At the same time, the public transport route network is characterized by a high degree of inertia, as changes in its structure require substantial capital investment and long-term planning. This constrains the ability of public transport systems to respond rapidly to shifts in passenger demand and urban development priorities.

The third indicator within the group of supporting subprocesses is the level of budgetary financial support allocated for public transport development (S 3). An increase in S 3 reflects the active involvement of public authorities in supporting the public transport system; however, the effectiveness of such support depends on the de-

[5] URL: https://транспортсевера.рф/#/

[6] The federal project profile "Modernization of Passenger Transport in Urban Agglomerations" file:///Users/tatana/Downloads/FP_Passazhirskij_transport.pdf

gree of coordination between financial inputs and other supporting and core subprocesses. In the absence of such coordination, additional budgetary funding may distort the dynamic structure of economic subprocesses rather than contribute to the achievement of the target development vector. This effect is particularly evident in the 2021 and 2022 models, where a substantial increase in budgetary support was not accompanied by a proportional acceleration of core performance indicators. Throughout the study period in the Murmansk agglomeration, insufficient funding for public transport development coincided with high rates of private car ownership, indicating the substitution of public transport services by private mobility. This relationship is captured in the dynamic structure models through the inclusion of indicator P1 (private passenger cars per 1,000 residents) among the subprocesses hindering public transport development.

The compensation of lost revenue from passenger transportation observed in 2015–2017 was followed by an almost complete absence of budgetary support in 2018–2020. The co-financing mechanism for fleet renewal through infrastructure loans provided by VEB.RF began operating in 2021. This change is reflected in the 2021 and 2022 models through a shift in the type of aggregate economic process — from "effective with maintenance of the development level" to "effective with development improvement." In 2020, a trend toward a transition from stable decline to stable growth began to emerge. This shift was facilitated by a decrease in electricity costs for industrial consumers (P3). As a result, the effectiveness of public transport potential utilization in the Murmansk agglomeration began to recover, reaching 36% of the maximum achievable level. Despite rising regional inflation (P2) and the continuing trend of population decline (LS 1), real wages (LS 2) and the cost of the consumer basket (LS 3) increased at an accelerated rate.

State policy concerning the territories and settlements of the Russian federation Arctic Zone (RFAZ), as well as the instruments for its development, is undergoing significant transformation. In the case of public transport in the Murmansk agglomeration, a key implication of this shift is that future development will no longer be determined solely by population-based criteria. Instead, it will increasingly depend on the functional role of the territories within the agglomeration in ensuring national security, including their significance as the base of Russia's largest Arctic international port, a northern supply hub, and one of the country's two maritime search and rescue coordination centers. In addition, large-scale infrastructure and logistics projects, together with the development of major educational and scientific centers of the Russian Arctic,[7] are expected to exert a substantial influence on the trajectory of public transport development.

At present, transport activity within the Murmansk agglomeration remains highly concentrated within the city boundaries, while peripheral territories exhibit substantially lower levels of accessibility and service intensity. This spatial imbalance limits the potential for sustainable development of the agglomeration as an integrated transport system. In this context, indicator M3—the total length of public transport routes — plays a critical role, as it reflects the capacity of the route network to ensure territorial coverage and connectivity between central and peripheral areas.[8] The expansion and restructuring of the route network, combined with the coordination of traffic management regimes and parking policies, can enhance the attractiveness of public transport and reduce dependence on private vehicles. Such measures are particularly important for Arctic agglomerations, where climatic conditions and settlement patterns amplify the costs of spatial fragmentation.

[7] Key settlement as the backbone of the Russian Arctic URL: https://nashsever51.ru/storage/temporary/24/03/06/156462/47cdd109–1303–48df-a944–0d4ae3334461.pdf

[8] By the end of the modeling period, coordinated measures for regulating public transport operating regimes in the Murmansk agglomeration had not yet been implemented.

Improvements in the efficiency of public transport can be achieved by involving local self-government bodies and residents in the development of corporate and regional strategic plans for the Murmansk agglomeration. An analysis of accumulated experience in this area [17] revealed a low level of effectiveness in attempts to coordinate the actions of key stakeholders (see Figures 1 and 2). According to studies on the social sustainability of Arctic cities, including those by A. D. Volkov [18], one of the key drivers of population outflow is the decline in the social embeddedness of major city-forming companies and the decreasing role of social benefit agreements. A critical contributing factor has been the growing trend toward extraterritorial management of city-forming enterprises during the 2010s. The relocation of decision-making centers outside Arctic cities and the implementation of restructuring programs — often involving workforce reductions — frequently resulted in income losses for local residents, with no available compensation mechanisms other than relocation outside the Arctic [19].

As a result, insufficient collinearity between the business objectives of key stakeholders and the interests of the local community contributes to a decline in both the effectiveness of public transport utilization and the development potential of this subsystem. At the same time, the identified shortcomings form a basis for further development in this area. This is evidenced by emerging examples of socio-economic partnerships involving major vertically integrated companies in the Russian Arctic Zone, as well as by coordinated priority projects included in the strategic plan "The North is a Place to Live![9]" and in the master plans for Far Eastern and Arctic cities developed on its basis. The effects of these initiatives are expected to be reflected in models for subsequent observation periods.

[9] Strategic Plan "The North is a Place to Live!". URL: https://nashsever51.ru/projects/pnszh

CONCLUSION

The study has demonstrated that the effectiveness of public transport development in Arctic cities and urban agglomerations depends not only on quantitative indicators of demand and funding, but also on the degree of coordination among key stakeholders involved in the aggregate economic process. Using the example of the Murmansk agglomeration, the results of structural modeling revealed a persistent misalignment between the target and actual dynamics of economic subprocesses, limiting the realization of the system's development potential.

The application of the structural process modeling approach made it possible to assess the synchronicity of changes across heterogeneous subprocesses, identify factors hindering development, and evaluate the magnitude of the resulting synergistic effect. The findings indicate that, during the study period, this effect remained relatively low, reflecting insufficient collinearity between the strategic objectives of public authorities, transport operators, business actors, and the local community.

At the same time, the results highlight the presence of institutional and managerial prerequisites for improving the effectiveness of public transport systems in Arctic agglomerations. In particular, the expansion and restructuring of route networks, the coordination of operating regimes, and the involvement of local self-government bodies and residents in strategic planning processes can contribute to enhancing system coherence and reducing dependence on private mobility.

The proposed methodological framework can be applied to the analysis of public transport systems in other cities and urban agglomerations characterized by complex spatial structures and high sensitivity to external socio-economic factors. Further research may focus on extending the observation period, refining indicators of service quality and institutional coordination, and assessing the long-term effects of emerging socio-economic partnerships and strategic development initiatives.

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