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DEVELOPMENT OF AN AUDIT-INTEGRATED CONCEPTUAL MODEL FOR SUSTAINABLE INNOVATION MANAGEMENT IN MOTOR TRANSPORT ENTERPRISES: A VIABLE SYSTEMS APPROACH

The object of this research is the system of sustainable innovation management in motor transport enterprises (MTEs). The problem addressed concerns the lack of integrated frameworks that combine sustainability, innovation, and audit mechanisms, which limits adaptability, resilience, and strategic alignment in MTEs, particularly under volatile markets and post-conflict recovery conditions in Ukraine. The research develops and establishes an audit-integrated conceptual model based on the viable systems approach (VSA) and the viable system model (VSM). The model aligns strategic, tactical, and operational subsystems with dual-loop regulation, combining deviation-based operational control with disturbance-based adaptive control. Internal audit functions are embedded to ensure accountability, transparency, continuous monitoring, and systemic integration of sustainable innovations. A comparative analysis with existing approaches, including the triple bottom line concept, circular economy principles, ISO 14001, and ESG frameworks, was conducted using the fuzzy analytic hierarchy process (Fuzzy-AHP). This method enabled a multi-criteria expert evaluation under conditions of uncertainty and provided quantitative validation of the advantages of the proposed VSM-based model. The results confirmed that the model ensures comprehensive systemic integration, positions innovation as a structural driver of development, enhances organizational resilience, and institutionalizes internal audit as a governance mechanism. The practical significance is the applicability of the model in ecological modernization, digital transformation, and post-conflict recovery of transport enterprises, particularly in developing economies with resource constraints. In practice, it supports managers and policymakers in designing adaptive strategies, embedding audit into business processes, and improving resilience, competitiveness, and sustainability performance.

Keywords: *sustainable innovation, business processes, viable system model, audit, regulation, resilience, adaptability, recovery.*

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1. Introduction

In the context of motor transport enterprises, sustainable development has become a critical strategic priority. Faced with environmental challenges, evolving regulatory frameworks, and shifting consumer expectations, transportation organizations must pursue innovation not only to enhance financial performance but also to fulfill ecological and social responsibilities. Integrating sustainability principles into innovation strategies is therefore essential for ensuring long-term viability and competitiveness in a dynamic industry environment.

The ongoing military conflict in Ukraine has exacerbated ecological, social, and economic vulnerabilities, resulting in widespread disruption. Key transportation infrastructure, industrial facilities, and transport enterprises have sustained substantial damage, alongside residential, commercial, and industrial assets.

The displacement of a significant portion of the population further underscores the magnitude of the humanitarian and operational challenges. Economic assessments by the Kyiv School of Economics (KSE) indicate that as of January 2024, direct losses amount to approximately 155 billion USD, encompassing damages to residential structures, infrastructure, transportation assets, and industrial enterprises [1]. Additional indirect effects have propagated across multiple sectors – including energy, agriculture, and education – generating estimated secondary losses exceeding 43 billion USD. Critical infrastructure, including airports, bridges, and over 25,000 kilometers of road networks, has been heavily affected, while at least 426 private and state-owned enterprises have experienced severe operational impairments [2]. Beyond economic disruption, environmental degradation has intensified, with damages over the two years of hostilities estimated at 2.2 trillion hryvnias (approximately 56 billion USD) [2]. These disruptions particularly affect the operational and strategic capacities of MTEs, highlighting the urgent need for systemic innovation management to ensure resilience and continuity of transport services [3].

These disruptions particularly affect the operational and strategic capacities of motor transport enterprises, highlighting the urgent need for systemic innovation management to ensure resilience and continuity of transport services.

The necessity for sustainable transport solutions is increasingly recognized, given the sector's environmental impact. International organizations, including ICAO, IRU, and IMO, advocate for the development of environmentally responsible transport systems. As a member state, Ukraine has committed to adhering to these ecological standards within its transportation sector. In this context, motor transport enterprises play a pivotal role in the recovery and long-term sustainability of national infrastructure. There is therefore a growing imperative to embed sustainable innovation within enterprise operations to ensure resilience and facilitate post-conflict reconstruction [4].

Sustainable innovation represents a critical driver for motor transport enterprises in addressing the multifaceted challenges posed by the ongoing crisis and in supporting the long-term recovery and resilience of the Ukrainian economy. Previous research has approached this topic from different perspectives. A systematic review outlines the conceptual foundations of sustainable innovation and stresses the role of strategic integration with corporate responsibility and environmental management [5]. This provides theoretical clarity but does not offer tools for enterprise-level implementation. Other studies argue that sustainability requires not only technological but also organizational and social changes [6]. While this broadens the scope of analysis, it leaves open the question of how to embed such changes into operational management systems. Sectoral evidence also enriches the discussion. In the construction industry, even incremental innovations in environmental sustainability create measurable financial and strategic value [7]. However, the findings are limited to event-based cases and do not translate into systemic approaches. In supply chains, scholars highlight the role of emotions, values, and daily practices in the diffusion of innovations [8]. This underlines important behavioral dimensions but does not address organizational integration. A complementary stream of research introduces multi-criteria decision-making methods for evaluating sustainable innovations [9]. Such tools improve assessment but do not provide a framework for managing innovation processes.

Empirical work in the automotive sector shows that green products and processes strengthen environmental, social, and economic outcomes, driven by regulation, market demand, and firm-level initiatives [10]. Yet, the evidence is highly context-specific. Case studies confirm that firms embedding sustainability in business models achieve competitiveness and environmental benefits [11]. These insights are valuable but remain fragmented and case-oriented. Despite these contributions, current research reveals a lack of a consolidated framework for managing sustainable innovations within enterprises. A systematic review has categorized sustainable business models, highlighting their common features and research gaps [12]. Subsequent studies have examined the organizational design and dynamic capabilities that determine the barriers and drivers of sustainable business model innovation [13]. Further contributions have advanced a unified perspective on sustainability-oriented business model innovation, aiming to consolidate diverse approaches into a coherent framework [14]. Other research has investigated circular business model innovation, identifying structural and contextual barriers that hinder its practical implementation [15]. Although these contributions advance theoretical understanding, they are not integrated into a comprehensive system of innovation management. Finally, research on sustainable innovation orientation proposes a conceptual framework [16]. This research extends this discourse by examining antecedents and outcomes of sustainable innovation orientation, yet a comprehensive methodology for operationalizing sustainable innovation at the enterprise level is still absent. Having analyzed existing approaches to sustainable innovations, it becomes evident that the current body of knowledge is fragmented and mostly sector-oriented. Despite providing valuable conceptual contributions, these studies do not converge into an integrated framework that could guide enterprises in managing innovations systematically and resiliently. This gap necessitates a broader look at the sustainability literature to understand which frameworks are commonly applied in organizational practice.

Several established approaches provide useful foundations for embedding sustainability into management. The triple bottom line introduces an integrated view of balancing social, environmental, and economic dimensions of business activity [17]. More recent studies extend this framework to Industry 4.0, showing how digitalization interacts with triple bottom line objectives in small and medium-sized firms [18]. The circular economy is framed as a new paradigm that promotes resource efficiency, waste reduction, and closed-loop production processes [19]. Policy research highlights regulatory frameworks and EU lessons, showing how circular principles can be embedded in multilevel governance [20]. Other studies emphasize the socio-economic benefits of circular strategies, stressing their potential for resilience and long-term sustainability [21]. ISO 14001-based systems provide structured mechanisms for environmental compliance and operational control [22]. However, further analyses reveal mixed outcomes, as effectiveness depends on broader organizational commitment and governance integration [23]. The ESG paradigm advances sustainability discourse through accountability, transparency, and reporting practices [24]. Yet ESG remains mainly assessment-oriented, relying on disclosure metrics rather than embedding innovation as a driver of adaptability. Although these frameworks provide foundational principles, they often remain compliance- or assessment-oriented and do not incorporate innovation as a systemic driver of organizational resilience and adaptability. These limitations are particularly relevant for MTEs operating under volatile markets, environmental challenges, and post-conflict recovery contexts such as Ukraine. Internal audit is widely applied as a compliance tool, but its integration into systemic sustainability and innovation management frameworks remains underexplored, highlighting the need for audit-integrated approaches.

There is a need for an approach that unites the normative principles of sustainability with a systemic, innovation-oriented perspective. Stafford Beer's viable system model (VSM) [25] and the subsequent viable systems approach (VSA) [26]. VSA provides a holistic and cybernetically grounded perspective on managing complex systems. It emphasizes adaptability, resilience, and long-term viability. Applied to motor transport enterprises, VSA allows systematic coordination of sustainable innovations, identification of strategic leverage points, and continuous monitoring of practices. It also helps enterprises integrate sustainability into core operations, ensuring that innovation initiatives contribute to ecological stewardship, social responsibility, and economic performance simultaneously.

Traditional approaches to sustainable innovation management [14–16] often exhibit limitations in addressing the flexibility, self-organization, and dynamic adaptation required in contemporary enterprise environments. These methods generally focus on isolated operational or strategic aspects and fail to integrate cross-functional, systemic perspectives. Consequently, there is a need for a conceptual framework capable of coordinating sustainable innovation across strategic, tactical, and operational levels, while simultaneously integrating auditing functions and adaptive control mechanisms.

Developing such a framework requires a comprehensive and interdisciplinary approach, drawing on sustainable development, innovation management, and systems thinking. One strand of research emphasizes the combination of structural, systemic, and enabling strategies, showing that fragmented solutions are insufficient for addressing complex challenges [27]. In innovation management, the concept of "open and sustainable" innovation highlights the need to embed sustainability into the logic of innovation creation and diffusion, rather than treating it as an external add-on [28].

Systems thinking provides a foundation for sustainability management, enabling the identification of interdependencies and unintended consequences within socio-ecological systems [29].

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Applied methodologies further extend this perspective by offering practical tools for managing change in organizational and socio-technical contexts [30]. From this standpoint, motor transport enterprises can be understood as complex adaptive systems, where systemic analysis helps identify interrelations among subsystems and supports management under dynamic and unstable conditions.

The VSA provides a structured lens for analyzing organizational viability and its integration with sustainability. Earlier studies emphasize the importance of systemic equilibrium and the interrelations among multiple dimensions for achieving sustainable territorial development [31]. Subsequent research has extended this perspective through system dynamics, underlining feedback loops and recursive processes as key mechanisms for sustainable value creation [32]. More recent contributions highlight the transition from viability to sustainability, proposing that ecological, social, and economic dimensions should be embedded within the viability architecture rather than treated as external elements. This approach underscores the necessity of aligning organizational survival with the sustainability of its broader context [33]. While these studies demonstrate the conceptual strength of VSA, its application to the management of sustainable innovations in motor transport enterprises remains limited, leaving room for further research and model development.

Within VSA, the viable system model emerges as a powerful tool for analyzing and managing complex organizational structures and processes [26]. Its recursive nature allows modeling of organizational dynamics at multiple levels of abstraction, supporting the consideration of both strategic objectives and operational processes. By incorporating external and internal factors, VSM enhances the understanding and visualization of organizational functions, enabling more effective management. Its focus on long-term viability makes VSM particularly suitable for developing models to manage sustainable innovations in MTEs, where strategic planning and adaptability are crucial [34].

The proposed audit-integrated VSM framework aims to provide MTEs with a systemic methodology for embedding sustainable innovations across business processes. By combining cybernetic principles with adaptive management mechanisms, this framework facilitates the alignment of innovation initiatives with organizational strategy, improves responsiveness to environmental and market dynamics, and strengthens enterprise resilience and long-term growth. This approach addresses a critical research gap, offering a structured pathway for operationalizing sustainability in post-conflict reconstruction contexts and providing actionable guidance for managers in ecological modernization.

Although this research is primarily conceptual due to limitations in wartime data, methodological rigor is ensured through logical consistency and adherence to systems theory principles. VSM has been applied to design flexible and adaptive municipal waste management systems [35]. It has also been used to support digitalization and diagnostic functions in short food supply chains [36]. Further studies demonstrate VSM's utility as a holistic tool for managing sustainable development [37]. Additionally, VSM supports social responsibility initiatives and related organizational practices [38]. These applications confirm VSM's relevance for addressing complex sustainability challenges, providing empirical support for its use in managing organizational viability, adaptability, and resilience. The specific potential of VSM for sustainable innovation in sector-specific domains like MTEs remains underexplored, highlighting the necessity for a conceptual adaptation integrating operational auditing and strategic adaptation to enhance innovation implementation, ecological modernization, and long-term competitiveness.

Thus, *the aim of this research* is to develop an audit-integrated conceptual model for sustainable innovation management in motor transport enterprises based on the viable system model, aimed at enhancing the effectiveness and viability of existing management systems.

The VSM provides a holistic, cybernetically grounded framework for managing complex adaptive systems, emphasizing organizational viability, adaptability, and resilience – qualities that are particularly critical in the context of post-conflict reconstruction in Ukraine.

2. Materials and Methods

The object of this research is the system of sustainable innovation management in motor transport enterprises. The research follows a conceptual research design and employs Stafford Beer's viable system model [25] within the broader viable systems approach (VSA) as the methodological foundation. The choice of VSM is justified by its capacity to represent organizations as adaptive and recursive systems that must continuously balance stability with innovation in order to remain viable in dynamic environments [26]. Such qualities are particularly relevant for MTEs, which operate under volatile market conditions and face additional challenges related to ecological modernization and post-conflict recovery.

The methodology proceeded through three interrelated stages.

First, the structural and functional principles of the VSM were examined to establish their suitability for sustainable innovation management. The recursive architecture of the model, encompassing five interconnected subsystems (Systems 1–5), enables enterprises to balance autonomy and coordination while ensuring viability across multiple organizational levels [39]. Information flows within this structure allow each operational unit (System 1) to function independently, while higher-level systems (2)–(5) manage integration, control, and strategic adaptation [40] (Fig. 1).

The model consists of five recursive subsystems (S1–S5) that collectively ensure organizational viability:

– System 1 – operational units carrying out core activities;
– System 2 – coordination and conflict resolution between operations;
– System 3 – integration and optimization of resources at the tactical level;
– System 4 – strategic adaptation and environmental scanning;
– System 5 – policy, identity, and long-term direction.

This structure provides the foundation for integrating sustainable innovations into operational processes, promoting synergy between innovation and business operations, and enhancing long-term resilience and adaptability of MTEs.

Fig. 1 illustrates the viable system model as a recursive cybernetic control structure demonstrating how an organization maintains viability through interconnected management functions and regulated information flows. The diagram is read from bottom to top. The lower part (System 1) represents autonomous operational units that interact with the external environment and carry out the enterprise's core activities. These units are recursively connected and coordinated through the stabilizing mechanisms of System 2, which dampen fluctuations and resolve conflicts. System 3 performs tactical control and resource optimization, while System 3* provides direct audit and monitoring, bypassing coordination channels to detect hidden inefficiencies or critical deviations in real time. When such deviations threaten system stability, an algedonic signal is triggered – an alert that rapidly escalates to higher management levels to initiate corrective action.

The middle and upper layers of the model represent strategic and policy functions: System 4 is responsible for environmental scanning and strategic adaptation, whereas System 5 defines organizational identity, values, and long-term direction. Elements such as "springs" in the diagram symbolize regulatory mechanisms that stabilize information flows by amplifying critical signals or damping excessive variability. Arrows represent feedback loops of information, coordination, and control, collectively illustrating how operational autonomy is balanced with centralized strategic governance to sustain long-term viability.

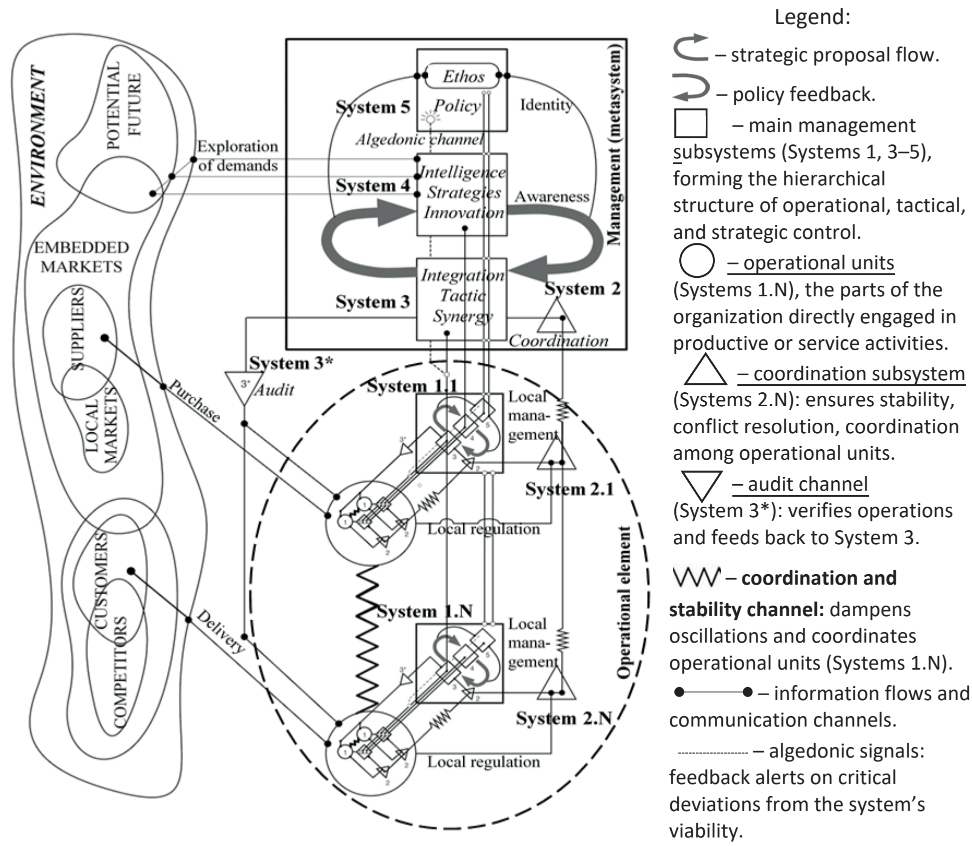

Fig. 1. Generic structure of the viable system model (VSM) (modified and adapted from [40])

Second, these principles were adapted to the specific requirements of MTEs. The adaptation involved incorporating dual-loop regulation mechanisms:

1) deviation-based operational control to stabilize ongoing processes;

2) disturbance-based adaptive control to ensure long-term resilience under external shocks.

Additionally, recursive information flows were introduced to connect strategic, tactical, and operational decision-making levels, supported by algedonic signals for rapid escalation of critical issues.

Third, a conceptual model of sustainable innovation management was developed on the VSM basis. This model integrates innovation processes directly into governance structures, positioning innovation not merely as a by-product of sustainability initiatives but as a systemic driver of organizational resilience. The approach also embeds internal audit and monitoring mechanisms, ensuring continuous alignment with environmental, social, and economic sustainability goals. At this stage, a methodological toolkit was employed, comprising:

– systemic-structural analysis, used to decompose innovation management processes and identify points of integration with sustainability objectives;

– cybernetic modeling, applied to the design of dual-loop regulation mechanisms and algedonic feedback channels;

– conceptual validation, employed to ensure logical consistency of the model and its alignment with sustainability standards and sectoral policy frameworks;

– fuzzy analytic hierarchy process (Fuzzy-AHP), integrated to quantitatively assess the proposed VSM-based model against established sustainability frameworks.

The Fuzzy-AHP procedure [41] enabled systematic multi-criteria evaluation under uncertainty while preserving the recursive and adaptive logic of the viable system model. Evaluation criteria were defined to capture core dimensions of enterprise viability and sustainability governance (systemic integration, adaptability, innovation orientation, governance logic, and learning capacity). A purposive group of ten experts with extensive experience in sustainability, transport management, and policy performed pairwise comparisons, providing linguistic judgments (very low to very high), which were converted into triangular fuzzy numbers. Individual judgments were then aggregated using the geometric mean, and fuzzy numbers were defuzzified into crisp values via the centroid method:

$$\tilde{a}=\left(\prod_{k=1}^{n}\tilde{a}_{ij}^{(k)}\right)^{\frac{1}{n}}, \quad (1)$$

$$C\left(\tilde{a}_{ij}\right)=\frac{l_{ij}+m_{ij}+u_{ij}}{3}, \quad (2)$$

where $\tilde{a}_{ij}^{(k)}$ denotes the fuzzy judgment of expert k, and n is the number of experts; l_{ij}, m_{ij}, u_{ij} are the triangular fuzzy number parameters, and $C\left(\tilde{a}_{ij}\right)$ is the defuzzified value.

A consistency check of pairwise matrices was conducted using Saaty's consistency ratio (CR) to ensure logical coherence.

Data sources comprised secondary materials, included peer-reviewed literature on sustainability and innovation management, international standards such as ISO 14001, and sectoral reports (e. g., Kyiv School of Economics, World Bank, EU transport directives), which provided contextual grounding for the model's development.

The choice of VSM as the methodological foundation is consistent with its proven applicability in sustainability-oriented studies (e. g., [35–38]). The methodological design ensured both conceptual rigor and contextual relevance. This grounding not only strengthens the theoretical robustness of the research but also ensures its practical applicability in designing adaptive sustainability-oriented governance for MTEs. The results of this methodological process are presented in the following section.

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3. Results and Discussion

In sustainable innovation management, enterprises adopt a holistic approach that integrates innovative practices beyond environmental concerns to encompass social and economic dimensions. This approach emphasizes responsible resource utilization, adherence to ecological safety standards, and the implementation of sustainable innovations across business operations to foster environmental responsibility, promote social well-being, and ensure long-term competitiveness and sustainability. This holistic perspective integrates sustainable practices across all business operations, focusing on resource efficiency, environmental stewardship, social responsibility, and economic viability. By promoting a comprehensive outlook, sustainable innovation management aims to address environmental, social, and economic challenges concurrently while fostering innovation. At the core of this approach is the alignment of economic goals with ecological and social objectives. Enterprises strive to enhance their competitive edge while minimizing their environmental impact, promoting social equity, and ensuring long-term economic viability. Achieving this requires integrating sustainable innovations throughout the entire value chain, from supply chain management and financial strategies to human resource development and waste management.

Motor transport enterprises, in embracing sustainable innovation management principles, must transition from reactive to proactive strategies to address sustainability challenges systematically. This involves systematically adopting sustainable innovations across organizational activities and integrating social and economic considerations into strategic decision-making processes (Fig. 2).

Through the sustainable orientation of management elements, a shift in the overall culture of management within the motor transport sector is initiated, rooted in an extended philosophy of management towards sustainability. Within this framework, there arises a need to modify the goals, strategies, and tools of classical management, as well as to change the enterprise management system.

In this paper, proposed employing a conceptual model of viable systems to develop a sustainable innovation management system in motor transport enterprises. This choice stems from the comprehensive structure of the viable systems approach, which offers insights into organizational dynamics and viability. Unlike traditional management approaches, which often prioritize short-term profitability and efficiency, the viable systems approach provides a deeper perspective.

Implementing a management system based on the viable systems approach integrates sustainable development principles into enterprise core processes, yielding several advantages. Firstly, it aligns innovative initiatives with strategic goals, ensuring sustainability integration into overall strategy. Secondly, it cultivates an innovation culture and continuous improvement, embedding sustainability into daily operations. Thirdly, it boosts resilience and adaptability, enabling effective responses to market changes and regulatory demands while preserving competitiveness and long-term viability. The proposed management system prioritizes integrating sustainable innovations directly into business processes, unlike existing approaches. This integration enables organizations to realize environmental, social, and economic benefits while enhancing competitiveness and long-term viability. This approach ensures sustainability is incorporated into strategy and operations, fostering innovation and value creation across all organizational activities.

Building upon the structural logic of the viable system model presented in Fig. 1, the proposed dual-loop control diagram (Fig. 3) specifies the dynamic mechanisms of information exchange and feedback regulation that operationalize the generic VSM structure for sustainable innovation management. In this model, Systems 1–5 of the original framework are transformed into a functional cybernetic control scheme that integrates deviation-based and adaptive feedback loops, enabling continuous alignment between operational innovation processes and strategic sustainability objectives.

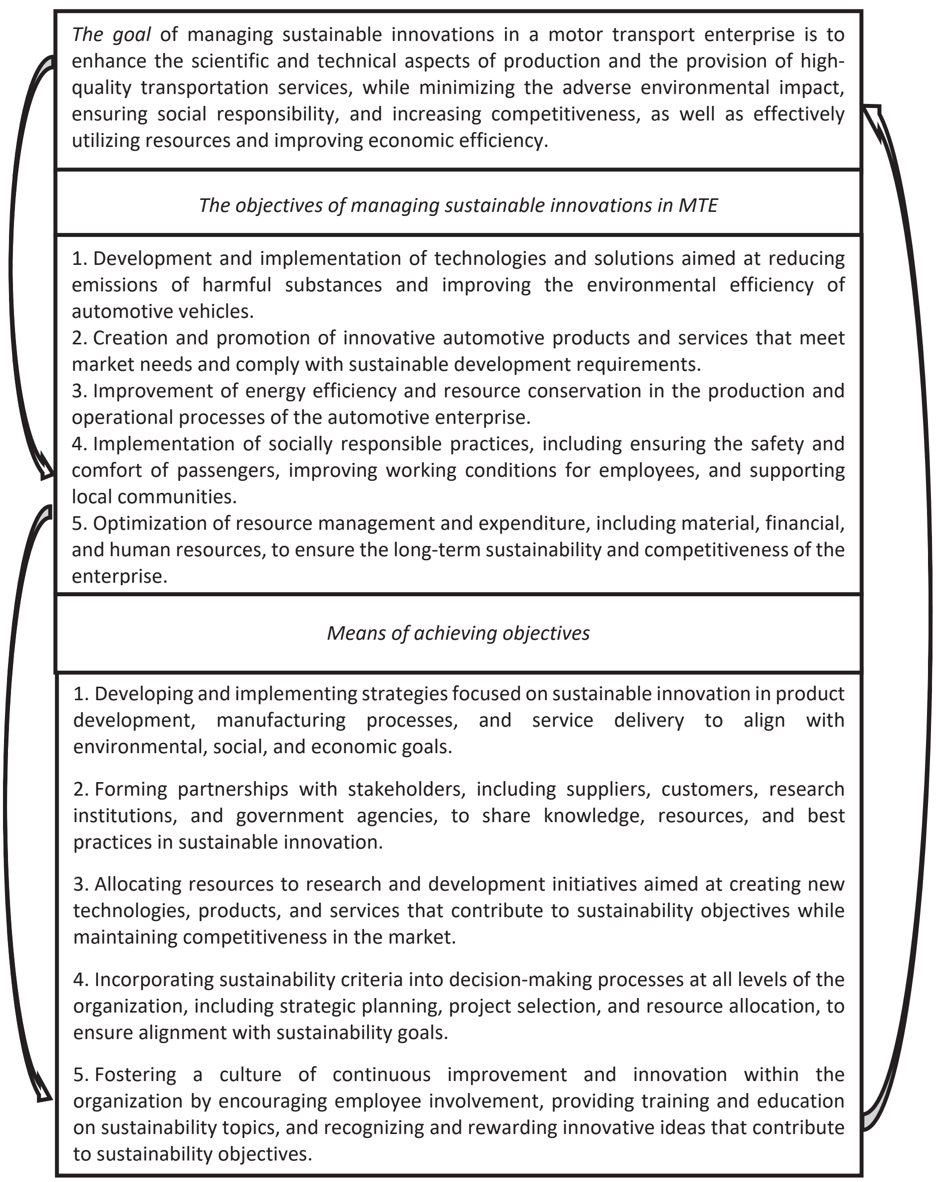
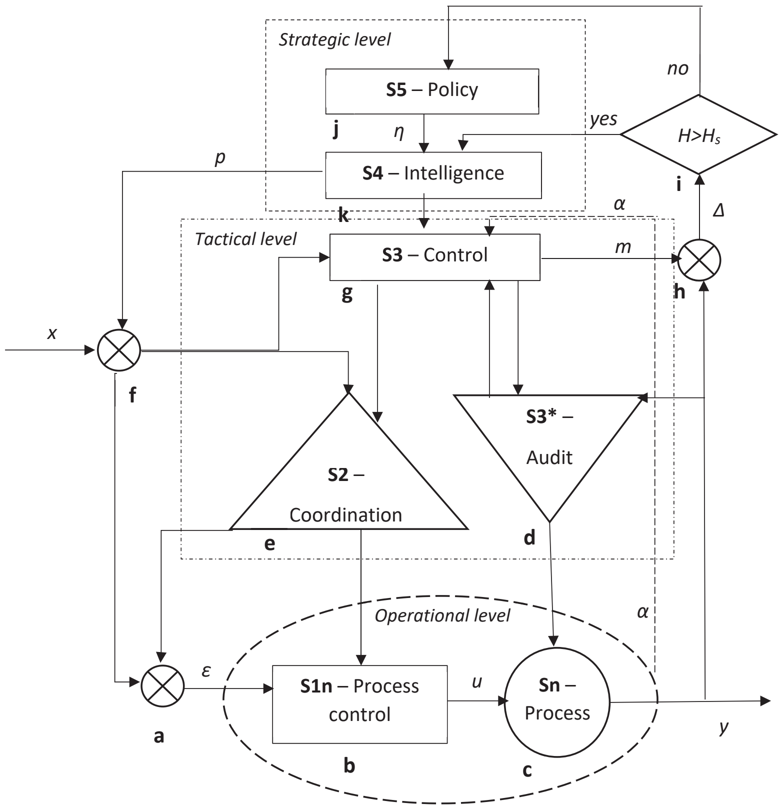


Fig. 2. Goal and objectives of sustainable innovation management in MTE



Legend:

Functional subsystems: S1n, Sn, S2, S3, S3*, S4, S5.

Signals and channels: x – input vector; y – output vector; u – control action; p – development plans; η – strategic goals; α – algedonic information (risk signals); Δ – deviation function; H, H_s – self-organization criterion and its critical threshold; ε – deviation; m – reference output.

Nodes and loops: a, f, h – comparator nodes (⊗ – standard cybernetic symbol for summation or comparison of signals); a, b, c, d, e – first (deviation-based) feedback loop; f, g, h, i, j, k – second (adaptive) feedback loop.

Fig. 3. Dual-loop control block diagram of the viable system model for sustainable innovation management in MTE

This model, grounded in S. Beer's viable system model (VSM) [25, 26], reflects the cybernetic principles of organizational viability, allowing for the integration of sustainable innovation processes within a complex, adaptive management system. This model reflects the interaction between the meta-management and operational components of the enterprise, ensuring adaptability, coherence, and long-term sustainability. The dual-loop structure enables both proactive adaptation to environmental changes and reactive management of internal deviations, supporting a holistic approach to sustainable innovation management.

The input vector x represents the set of requirements and conditions for the innovative development of the enterprise, including regulatory prescriptions, market demand for transport services, technological capabilities, and economic constraints. In addition, strategic goals η are defined by subsystem S5, while development plans p are elaborated by subsystem S4. The output vector y characterizes the results of innovative activities, such as improved transport efficiency, reduced operational costs, enhanced environmental performance, and increased safety.

The first control loop, corresponding to the sequence $a \to b \to c \to d \to e \to a$, implements the classical deviation-based regulation. In node a, the deviation vector $\varepsilon = x - y$ is generated, reflecting the degree of correspondence between achieved and required performance indicators. Based on this signal, block b produces the control action u, which is applied to block c where the core innovation processes are executed, including technology deployment, fleet renewal, and digitalization of operational management. The results of these processes are monitored in block d, representing the audit subsystem, and then passed to block e, the coordination subsystem, which ensures the harmonization of unit activities and transmits the corrective signal back to node a. Hence, the negative feedback of the first loop provides real-time self-organization of innovative processes and stabilization of the required operational parameters.

Deviation-based regulation alone does not enable the identification of underlying causes of discrepancies, whether originating from internal constraints or external disturbances. To address this limitation, the second loop of adaptive control is applied, corresponding to the sequence $f \to g \to h \to i \to j \to k \to f$. In block f, the input parameters x and plans p are integrated, forming the basis for constructing a reference model of enterprise innovation development. In block g, a scenario-based model is generated, resulting in a reference output vector

$$m = M(u_M, x, \eta, p), \tag{3}$$

where u_M denotes the reference control action reflecting strategic managerial decisions.

The reference outputs are compared with actual performance data aggregated in block h. At this stage, additional non-analytical information α, transmitted via the algedonic channel, is incorporated; this may include risk signals, customer complaints, equipment failures, and other critical incidents. In block i, the deviation function is computed as $\Delta = \Delta(m - y, \alpha)$, providing a comparative assessment of forecasted and actual system states. On this basis, the self-organization functional is determined as $H = H(\Delta)$ and compared with the critical threshold Hs.

If the condition $H > Hs$ is satisfied, the system demonstrates sufficient self-organizing capability, and the management response is limited to corrective adjustments of current plans in block i. These revised parameters are then transferred through block k back to f, closing the loop. If, however, $H \le Hs$, a feedback signal is directed to block j, initiating a revision of the enterprise mission and the formulation of new strategic goals η. Updated goals and plans are subsequently transmitted via blocks j and k to block f, completing the adaptive loop.

In this way, the dual structure integrates deviation-based operational regulation with disturbance-based strategic adaptation. The first loop stabilizes ongoing sustainable innovation processes in MTE, while the second ensures their alignment with long-term challenges and environmental dynamics. The interaction of both loops provides consistency between local innovative actions and overall strategic development, thereby enhancing enterprise viability and sustainability in the context of complex and rapidly changing conditions.

This dual-loop configuration forms the systemic basis for the organizational distribution of functions across subsystems 1–5. The conceptual model of sustainable innovation management at a MTE, presented in Fig. 4, reflects this distribution and demonstrates the hierarchical arrangement of the strategic, tactical, and operational levels of management. It integrates the external environment, the management megasystem, and the managed object, thereby linking the dual-loop regulatory mechanisms with the organizational structure of the enterprise.

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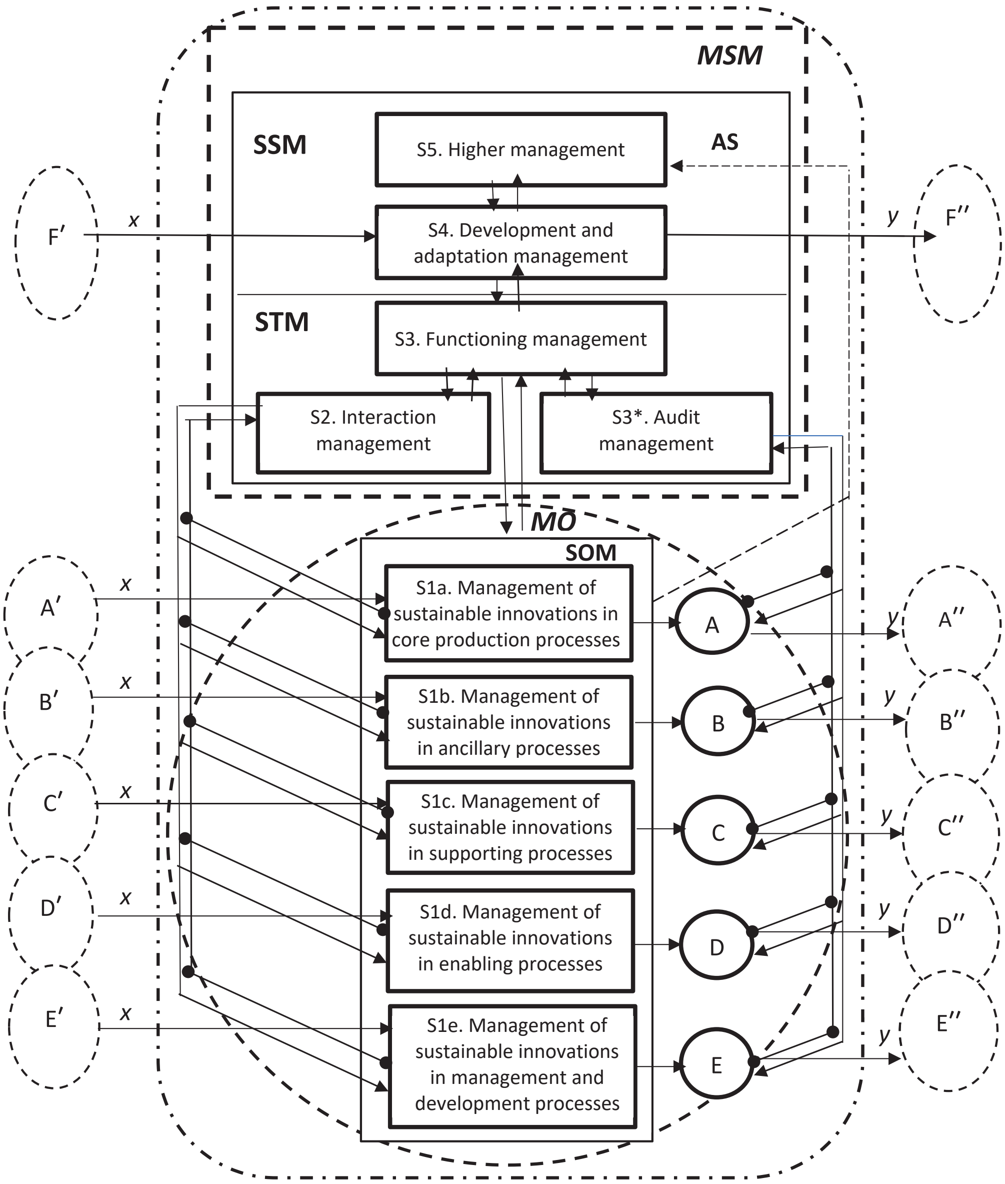

Legend:
A′–F′ and A′′–F′′ – areas of the external environment; *x* – resources (inputs); *y* – results (outputs); MO –managed object; SOM – system of operational management (subsystems S1a,..., S1e); A–E – business processes; MSM – management megasystem; STM – system of tactical management (subsystems S2, S3*, S3); SSM – system of strategic management (subsystems S4, S5); AS – algedonic signal.

Fig. 4. Conceptual model of sustainable innovation management at the MTE

The conceptual model of sustainable innovation management at a motor transport enterprise consists of the external environment (EE), the system (S), including the management megasystem (MSM) and the managed object (MO). The MSM incorporates the system of strategic management (SSM) and the system of tactical management (STM).

The SSM comprises two subsystems: System 5, responsible for establishing the mission, vision, and strategic objectives of sustainable innovation activities, and System 4, which ensures strategic planning, modeling, and adaptation to the external environment. The System of Tactical Management (STM) reflects immediate managerial activities within the enterprise. It includes three key subsystems. System 3 is responsible for optimizing the overall functioning of the enterprise and coordinating the allocation of resources. System 3* performs monitoring and auditing tasks, as well as environmental control of sustainable innovation processes. Finally, System 2 ensures harmonization in the interaction of divisions and regulates their performance.

The managed object (MO) implements the business processes that ensure the fulfillment of the main goal of the motor transport enterprise. Since the enterprise's sustainable development objectives decompose into sub-goals, the MO block contains five fractal subsystems *A–E*.

These correspond to the integration of sustainable innovations into core production, ancillary, supporting, enabling, and management and development business processes.

The system of operational management (SOM) is represented by subsystems *1.a–1.e*, which governs the implementation of sustainable innovations within each type of business process. The areas of the external environment associated with these processes are denoted as *A′*, *B′*, *C′*, *D′*, *E′* and *A′′*, *B′′*, *C′′*, *D′′*, *E′′*. The input and output parameters of the model are designated as x and y. A specific feature of the model is the algedonic signal (*AS*), which provides direct communication between operational and strategic levels, allowing higher management to respond promptly to urgent issues identified at the lower levels.

The graphical representation of subsystems in the proposed model is aimed at visualizing not only their functional roles but also the interaction between them (Fig. 5).

The notation follows the principles of cybernetic modeling as developed within Stafford Beer's VSM and subsequently adapted in systems research. Each subsystem is depicted by a geometric figure that corresponds to its function in the control loop.

Hexagons are used for subsystems 1, 3, and 4, symbolizing complex adaptive blocks with multiple input and output channels responsible for the operational, tactical, and strategic levels of management.

Parallelograms are applied for subsystems 2 and 5, highlighting their role as coordinating and policy-setting entities with a more linear and directive control structure. An inverted triangle is employed for subsystem 3*, emphasizing its special function as an independent monitoring and filtering mechanism, separate from direct operational control.

This symbolic differentiation makes it possible to clearly present the interaction of subsystems through control actions (C_i), feedback (FB_i), direct connections (D_i), algedonic signals (AS), as well as input and output parameters (x, y). Such representation improves readability of the model, clarifies the systemic distribution of functions across subsystems, and provides a visual language consistent with both classical VSM theory and modern applications in innovation management.

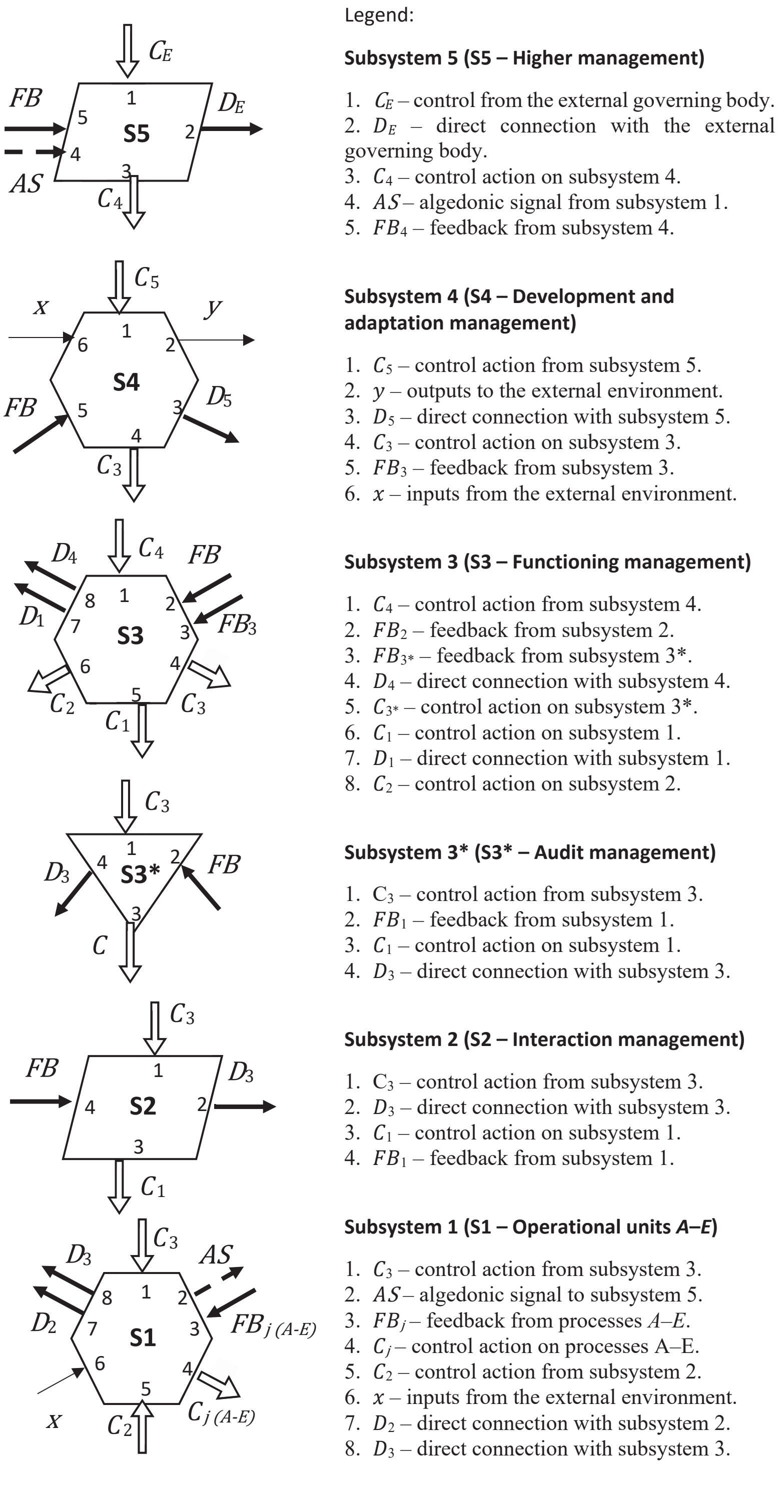

Fig. 5. Interaction of structural elements of the conceptual model

Subsystem 5 formulates the mission, strategic objectives, and policies of sustainable development at the MTE. The control input (CE) represents regulatory requirements and strategic directives from external governing bodies (e. g., national sustainability policies, transportation regulations). The direct connection (DE) denotes communication with stakeholders such as owners, investors, and governmental authorities. The algedonic signal (AS) enables critical issues from operational units (e. g., failure to achieve environmental targets or safety incidents) to be transmitted directly to the highest level of management. Feedback from subsystem 4 (FB_4) provides analytical information about adaptation and external trends, while the control action (C_4) sets directions for strategic planning and innovation priorities.

Subsystem 4 ensures strategic adaptation of the enterprise through innovation. Its control input (C_5) derives from higher management, setting long-term innovation and sustainability goals. The output (y) represents innovation strategies and development programs directed toward the external environment F'' (partners, customers, regulators). Feedback from subsystem 3 (FB_3) provides information on current performance and innovation implementation. The control action (C_3) communicates strategic requirements back to subsystem 3 to align operations with innovation objectives. The direct connection with subsystem 5 (D_5) reflects the exchange of information on external environment dynamics (e. g., new technologies, market demands). Inputs (x) from the external environment F' include technological trends, sustainability standards, and customer expectations.

Subsystem 3 coordinates the functioning of all operational units (subsystem 1) to ensure that innovation projects are implemented effectively.

The control action from subsystem 4 (C_4) translates strategic innovation goals into operational tasks. The direct connection (D_4) ensures quick adaptation to changes in strategic plans. Control actions toward subsystem 3* (C_{3^*}) and subsystem 2 (C_2) guarantee oversight of auditing and coordination functions, while feedback (FB_{3^*}, FB_2) provides monitoring information. Control on subsystem 1 (C_1) establishes rules for resource allocation, quality standards, and innovation priorities. The direct connection with subsystem 1 (D_1) ensures access to real-time data on process execution, crucial for evaluating innovation performance.

Subsystem 3* is responsible for independent audit and monitoring of innovation implementation.

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The control action from subsystem 3 (C_3) sets the scope of audits and reporting requirements. The direct connection (D_3) facilitates operational access to process data. Feedback from subsystem 1 (FB_1) provides monitoring information, such as environmental indicators, safety performance, or cost efficiency of innovations. The control action on subsystem 1 (C_1) addresses corrective measures based on audit results, ensuring compliance with sustainability objectives. The audit subsystem plays a pivotal role in validating sustainability indicators, ensuring reliability of information flows, and supporting continuous organizational learning. This differentiates the model from established sustainability frameworks.

Subsystem 2 harmonizes activities between operational units to prevent conflicts during the integration of innovations. The control action from subsystem 3 (C_3) provides rules for coordination, while the direct connection (D_3) ensures immediate interaction. Feedback from subsystem 1 (FB_1) includes data on process interdependencies and conflicts (e. g., resource competition between innovation projects). Control action on subsystem 1 (C_1) promotes synchronization of timelines and alignment of innovation-related tasks among different departments.

Subsystem 1 represents the core business processes of the MTE (*A* – core production, *B* – ancillary, *C* – supporting, *D* – enabling, *E* – management and development). The control action from subsystem 3 (C_3) regulates the operational execution of innovations, while the algedonic signal (*AS*) escalates critical sustainability-related issues (e. g., environmental accidents, failure of innovative technology) directly to subsystem 5. Control action on processes *A*–*E* (C_j) ensures structured innovation management. Feedback (*FB*) from processes communicates performance results, such as reduced emissions, improved efficiency, or customer satisfaction. Control action from subsystem 2 (C_2) guarantees coordinated functioning, while direct connection (D_2) enables immediate resolution of conflicts. Input parameters (x) represent resources, technologies, and regulatory requirements, while outputs (y) are innovative services, sustainable performance indicators, and customer value.

On this basis, a viable system model for managing sustainable innovations within the motor transport enterprise is proposed (Fig. 6). The model integrates strategic, tactical, and operational subsystems into a coherent cybernetic framework, where their interaction is ensured through control actions, feedback loops, direct connections, and algedonic signals. Such representation highlights the recursive nature of enterprise management, providing both vertical and horizontal coordination of sustainable innovation processes.

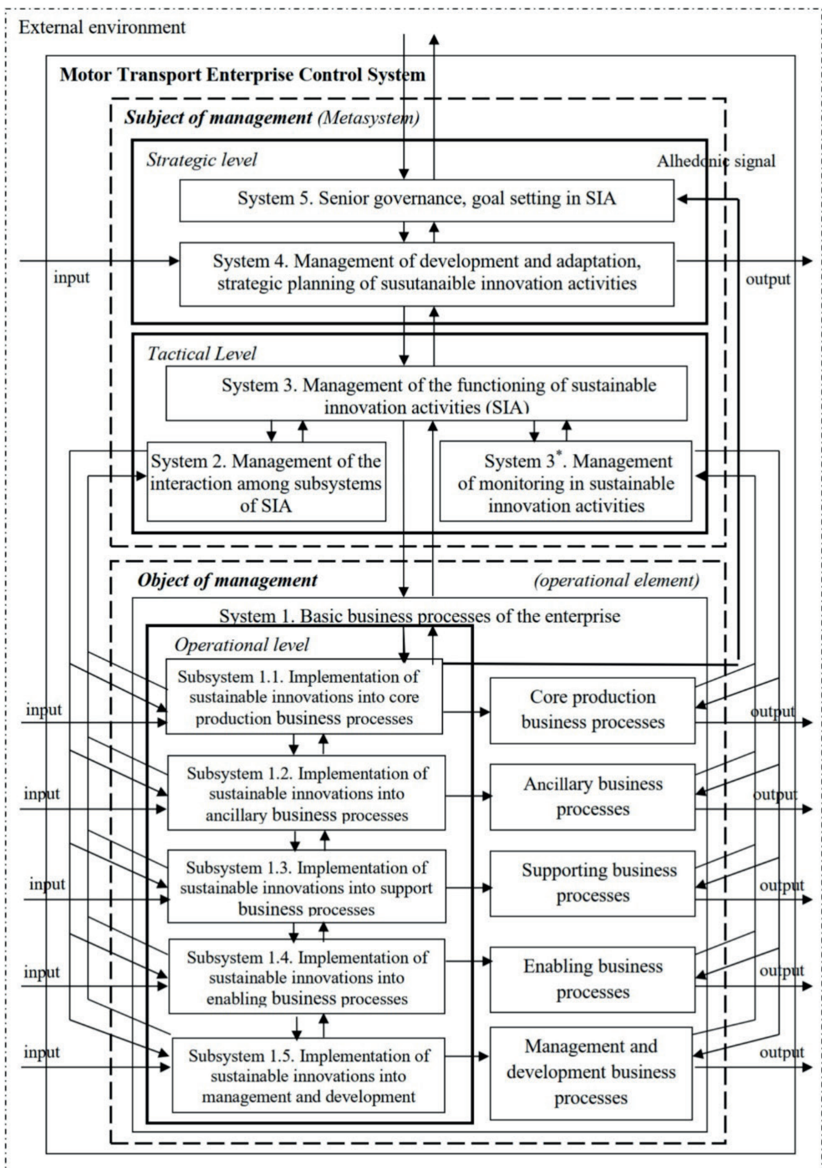

Fig. 6. Viable system model for sustainable innovation management in MTE

The proposed model includes the following elements: the external environment, the enterprise management system, consisting of a meta-management system and an operational element (subject and object of management). The meta-system contains two levels of management: strategic and tactical.

The strategic management system comprises two subsystems: System 5 for higher-level control and System 4 for development and adaptation management. System 5 is responsible for establishing objectives for sustainable innovation activities, developing strategic goals, missions, visions, and policies. System 4 handles decisions related to strategic planning of sustainable innovation activities, developing models, and adapting to the external environment. At the tactical management level, which entails immediate managerial activities, three subsystems are involved. System 3 optimizes the overall system functioning, coordinates the allocation of efforts and resources among departments, and ensures necessary synergy. This system forms the basis for a directorate overseeing current activities, comprising various managers in specific areas, deputy directors, or department heads. System 3* oversees auditing, conducting monitoring, control, and internal audits of the integration of sustainable innovations into the enterprise's operations and environmental monitoring of the motor transport enterprise. This oversight of plan execution involves evaluating indicators that characterize the development of various areas of activity and, if necessary, assigning tasks to lower subsystems to address disparities between planned and actual indicators. System 2 orchestrates interactions, harmonizing the collaboration among divisions in the development and implementation of sustainable innovation projects. It either encourages or restricts their operations, serving as the central regulator of enterprise activity and conducting interim reviews of the work of all subsystems 1. At the subsystem 2 level, business process managers coordinate and align decisions among themselves.

The management object implements business processes to ensure the attainment of the main goal of the motor transport enterprise's operation. System 1 comprises the enterprise's fundamental business processes and the subsystem for operational management of these processes. The operational element of the VSM for managing sustainable innovations is aimed at integrating innovation activities into the core business processes of MTEs. It encompasses several functional areas:

– *core production* – enhancement of transportation services through the introduction of new technologies and service improvements;
– *ancillary processes* – adoption of more efficient methods for loading and unloading operations, as well as freight forwarding;
– *support processes* – application of innovative maintenance technologies and fleet management systems for vehicle repair;
– *enabling processes* – development of innovative approaches to resource allocation and the use of financial management tools for energy and resource supply;
– *management and development* – improvement of strategic, tactical, and operational planning, alongside the modernization of management processes and technologies. These activities are implemented as portfolios of sustainable innovation projects.

At the level of subsystem 1, business process managers lead their respective areas of activity, develop, and implement innovative projects with a sustainable focus. At the level of subsystem 2, they also coordinate and align decisions made among themselves. In cases where direct coordination is impossible due to conflicting interests of different processes, coordination occurs at the level of subsystem 3, under the guidance of the directorate of current operations. Subsystem 2 is considered an information channel or even information support, which allows identifying problems and transmitting information about them and methods of their resolution to interested subsystems.

Subsystems 1–3 carry out operational management of the sustainable innovation activities of the motor transport enterprise and actively adapt to the influences of the external environment. At the same time, they also have some responsibilities for passive adaptation, in terms of compiling elements of the strategic innovation development plan considering sustainable aspects. The subsystem for strategic decision-making on development management (Subsystem 4) performs the main part of the processes of passive adaptation. Strategic goals for determining in which directions to assess the need for sustainable innovations and what resources can be allocated to achieve these goals are set by the goal-setting subsystem (Subsystem 5). The algedonic signal facilitates communication between operational and strategic management levels, allowing higher-level managers to promptly address issues within lower-level departments. This feature is crucial for sustainable innovation management in MTE, enhancing responsiveness and efficiency in addressing sustainable risks and innovations.

The proposed research introduces the integration of an internal audit system within the VSM to develop a sustainable innovation management system in motor transport enterprise. This system performs comprehensive audits and monitors key performance indicators (KPIs) to ensure alignment with sustainability standards and objectives, supporting proactive management and continuous improvement. It facilitates both vertical and horizontal information circulation across the management system, fostering collaboration and synergy among departments. Prioritizing sustainable innovations is essential for ensuring overall sustainability and competitiveness, positioning the enterprise as a leader in innovative transportation solutions and contributing to comprehensive sustainable development.

The proposed VSM-based framework for sustainable innovation management in motor transport enterprises provides a systematic and adaptive approach to integrating sustainability principles into business operations. The results of this research demonstrate that embedding innovation processes into the core management structure enhances organizational resilience, strategic flexibility, and long-term competitiveness. Unlike traditional management approaches, which primarily focus on financial efficiency and short-term objectives, the VSM framework incorporates environmental, social, and economic dimensions, thus enabling enterprises to balance sustainability goals with operational priorities.

Compared with existing studies on sustainable innovation models [5–11, 14–16], our approach offers a higher degree of adaptability through recursive management structures and internal audit mechanisms. For instance, while prior works highlight the importance of innovation diffusion and sustainability integration in supply chains [8, 10], they often lack systemic tools for coordinating multiple levels of decision-making. Our model addresses this gap by enabling vertical and horizontal information flows across strategic, tactical, and operational levels, supported by real-time performance monitoring.

To clarify the originality and added value of the proposed framework, it is important to position it against existing approaches to sustainable management. Widely recognized frameworks include the triple bottom line (TBL) [17, 18], circular economy (CE) models [19–21], and ISO 14001-based environmental management systems [22, 23]. Another widely adopted framework is the ESG (environmental, social, governance) reporting system [24], which has gained prominence as a benchmark for corporate sustainability performance. ESG practices often remain assessment-oriented, focusing on disclosure and compliance with investor-driven indicators rather than embedding systemic adaptability, innovation, and organizational learning into enterprise governance structures.

The TBL approach emphasizes the balance between economic, environmental, and social dimensions ("people, planet, profit"), but it primarily functions as an assessment tool rather than a management mechanism, lacking dynamic integration processes and learning capabilities. CE frameworks provide valuable principles for resource efficiency and closed-loop processes, yet remain largely confined to material flows and ecological aspects, with limited applicability to broader governance, adaptability, and organizational learning challenges.

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ISO 14001, while widely adopted, offers standardized compliance procedures but does not conceptualize enterprises as adaptive systems or embed innovation and knowledge integration into management structures. The more recent ESG paradigm has gained global prominence as a benchmark for assessing corporate sustainability performance. However, it primarily functions as a disclosure and reporting tool driven by external stakeholders. As a result, environmental, social, and governance aspects are often considered separately, rather than being integrated into a dynamic and adaptive management system.

In contrast to conventional sustainability frameworks, the proposed VSA/VSM-based model conceptualizes motor transport enterprises as viable and adaptive systems. Its recursive structure and dual-loop regulation mechanism ensure continuous alignment between strategic and operational processes. At the same time, it integrates innovation, sustainability, governance, and organizational learning into a coherent system, positioning innovation and knowledge dynamics as core drivers of long-term resilience. This systemic perspective addresses the key gaps left by existing approaches, which often remain descriptive, compliance-oriented, or limited to specific dimensions of sustainability.

To ensure the comparability and analytical rigor of the proposed framework, five qualitative criteria were selected based on established studies in systems thinking, sustainability governance, and innovation management [25–30]. These criteria – systemic integration, dynamic adaptability and resilience, innovation as a structural element, governance logic, and capacity for learning and knowledge integration – collectively reflect the core dimensions of viability identified in Beer's viable system model and subsequent developments within the VSA.

Each criterion captures a distinct aspect of enterprise sustainability and organizational viability:

– *systemic integration* reflects the degree to which sustainability dimensions are embedded into the enterprise's structural and functional architecture;

– *dynamic adaptability and resilience* indicate the capability to respond to internal and external disturbances;

– *innovation as a structural element* measures whether innovation is institutionalized rather than episodic;

– *governance logic* assesses the orientation of management processes (compliance-, performance-, or learning-based);

– *capacity for learning and knowledge integration* evaluates the enterprise's ability to absorb, diffuse, and institutionalize new knowledge.

This framework of criteria establishes a robust basis for both conceptual comparison and empirical advancement in subsequent research, employing a hybrid qualitative–quantitative assessment design. Based on the authors' synthesis of prior studies in sustainability governance, circular economy, and systems thinking, Table 1 provides a structured comparison across the five analytical dimensions identified.

The comparative synthesis presented in Table 1 indicates that the proposed VSA-based model provides a more integrated and adaptive representation of enterprise sustainability. Unlike the established frameworks, it embeds innovation and learning as structural governance components rather than supplementary elements. To substantiate these conceptual advantages through empirical evaluation, a fuzzy analytic hierarchy process (Fuzzy-AHP) analysis [41] was conducted. The method was selected due to its suitability for multi-criteria decision-making under uncertainty, particularly when expert judgments are expressed in linguistic rather than numerical terms.

A group of ten experts representing academia, environmental policy, transport management, and sustainable development participated in the evaluation. Experts were selected based on ≥ 10 years of professional experience in sustainability and transport management. Their judgments were aggregated using the geometric mean to ensure balanced representation. They conducted pairwise comparisons among five frameworks (TBL, CE, ISO 14001, ESG, and the proposed VSA-based model) using five decision criteria: systemic integration, dynamic adaptability, innovation orientation, governance logic, and learning capacity. The evaluation followed the procedure described in Section 2, ensuring comparability and analytical rigor.

Individual assessments were converted into triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij}) according to the linguistic scale in Table 2.

Table 1

Comparative positioning of the proposed VSA-based model against existing sustainability frameworks

Criterion	Triple bottom line (TBL)	Circular economy (CE)	ISO 14001	ESG	Proposed VSA-based model
Degree of systemic integration	Partial, three dimensions treated separately	Partial, primarily oriented toward material and ecological flows	Limited, procedural compliance without systemic integration	Partial, fragmented by reporting categories	Full, recursive systemic structure integrating all subsystems
Dynamic adaptability and resilience	Weak, relies on static indicators	Limited, adaptation confined to ecological efficiency	Weak, compliance-driven with low flexibility	Weak, reactive to investor / regulatory pressure	Strong, dual-loop regulation enabling continuous environmental scanning and response
Innovation as a structural element	Not explicit, innovation treated indirectly	Indirect, mainly through eco-design and resource efficiency	Absent, innovation not embedded in the framework	Not explicit, focused on disclosure	Explicit, innovation conceptualized as a subsystem driver and governance principle
Governance logic	Assessment-oriented, focused on reporting balance	Resource-oriented, eco-efficiency driven	Normative / procedural, compliance with standards	Reporting and disclosure-driven	Systemic and adaptive governance based on feedback and recursive control
Capacity for learning and knowledge integration	Minimal, descriptive in nature	Limited, technology- and process-focused	Minimal, compliance documentation-oriented	Minimal, oriented to external reporting	Strong, supports organizational learning, digitalization, and continuous improvement

Table 2

Linguistic scale and corresponding triangular fuzzy numbers

Linguistic term	Triangular fuzzy number		
	lower boundary (l_{ij})	most probable value (m_{ij})	upper boundary (u_{ij})
Very low (VL)	0.0	0.1	0.3
Low (L)	0.1	0.3	0.5
Moderate (M)	0.3	0.5	0.7
High (H)	0.5	0.7	0.9
Very high (VH)	0.7	0.9	1.0

Aggregation of expert opinions was performed through the geometric mean method, and the defuzzification process used the centroid technique to obtain crisp values of priority weights. After aggregation and normalization, the results revealed distinct variations in the sustainability logic of each framework. As shown in Table 3, the model performs consistently across all five evaluation criteria.

Criterion weights (column 2) were derived from a separate pairwise comparison matrix evaluated by the same expert group and represent the global importance of each criterion. The subsequent columns show normalized performance scores of each framework under each criterion (defuzzified and scaled within [0, 1]). Normalized values were derived after defuzzification and synthesis using the geometric mean and centroid methods, with normalization performed across all frameworks to ensure comparability. The findings indicate that the VSA-based model demonstrates the highest overall priority (0.342), confirming its superior integrative and adaptive capacities compared to other frameworks. These results provide quantitative, empirically grounded support for the conceptual claims presented earlier. The consistency ratio, computed from the defuzzified matrix using Saaty's formula equaled 0.078 (< 0.1), confirming acceptable logical consistency. Overall, the results validate that the VSA-based model integrates systemic, adaptive, and innovative principles more effectively than established sustainability frameworks, enabling recursive feedback control and continuous learning mechanisms within complex organizational environments.

While Table 3 provides a detailed criterion-based comparison, Fig. 7 complements this analysis by offering a conceptual visualization. The figure highlights the relative limitations of existing frameworks (TBL, CE, ISO 14001, ESG) and underscores the systemic adaptability of the proposed VSA/VSM model.

As illustrated in Table 1 and Fig. 7, the proposed VSA/VSM framework addresses the main limitations of existing approaches. Unlike the TBL framework, which separates the economic, environmental, and social dimensions without capturing their dynamic interactions, VSA integrates them through recursive loops and systemic feedback.

Compared to the circular economy, which emphasizes resource cycles but provides limited adaptability to external shocks, VSA explicitly incorporates mechanisms for resilience and strategic adaptation. ESG frameworks, while increasingly adopted as a global benchmark, remain primarily disclosure- and reporting-oriented, often fragmenting sustainability dimensions instead of embedding them into an adaptive governance logic. Although ISO 14001 ensures procedural compliance with environmental standards, it lacks systemic innovation orientation and knowledge integration, both of which are embedded as structural drivers in the VSA-based model.

While ESG and ISO 14001 are primarily disclosure- and compliance-oriented, they lack embedded audit functions as systemic drivers of adaptability. By contrast, the proposed framework institutionalizes audit as a governance mechanism, reinforcing accountability and resilience.

Table 3

Weighted evaluation by criteria (Fuzzy-AHP synthesis)

Criterion	Weight	TBL	CE	ISO 14001	ESG	VSA-based model
Degree of systemic integration	0.247	0.12	0.21	0.15	0.17	0.35
Dynamic adaptability and resilience	0.198	0.10	0.19	0.14	0.16	0.41
Innovation as a structural element	0.204	0.09	0.17	0.10	0.15	0.49
Governance logic	0.152	0.11	0.20	0.14	0.18	0.37
Capacity for learning and knowledge integration	0.199	0.13	0.22	0.16	0.17	0.32
Overall normalized weight	1.00	0.113	0.215	0.146	0.184	0.342
Rank	-	5	2	4	3	1

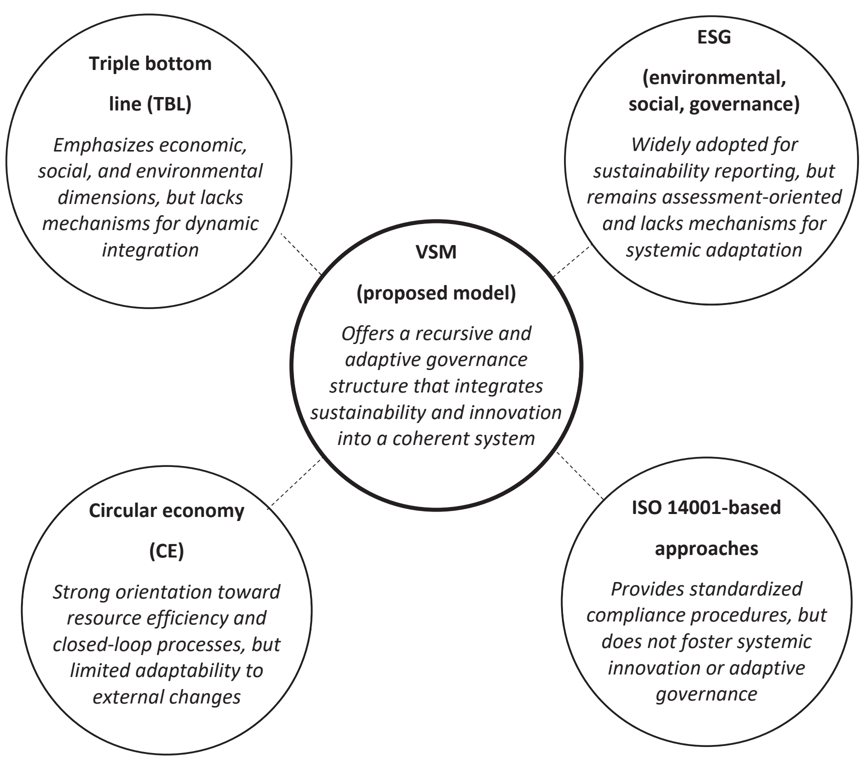

Fig. 7. Conceptual visualization of existing sustainability frameworks and the proposed VSA-based model

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A distinctive contribution of the proposed framework lies in its explicit capacity for organizational learning and knowledge integration. This feature enables motor transport enterprises to go beyond reactive adaptation, fostering continuous transformation of internal processes, assimilation of emerging technologies, and institutionalization of best practices. Such a knowledge-based orientation enhances not only short-term adaptability but also long-term resilience and competitiveness, particularly under conditions of uncertainty, post-crisis recovery, and rapid technological change.

By embedding learning and innovation into its recursive systemic structure, the VSA-based model complements and extends existing sustainability frameworks. Whereas established approaches remain largely descriptive, assessment-driven, or compliance-oriented, the proposed framework reconceptualizes sustainable innovation management as an adaptive governance paradigm. Within this paradigm, innovation is not treated as an external add-on but institutionalized as a structural driver of resilience, sustainability, and strategic renewal. In doing so, the model contributes to advancing both the theoretical discourse on viable systems and the practical toolkit available to enterprises operating in volatile and transformative environments.

The practical relevance of the findings lies in their applicability for post-conflict recovery and modernization of motor transport enterprises in Ukraine. The model can guide managers in designing adaptive strategies for digitalization, ecological modernization, and sustainable logistics planning. For example, practical implementation may involve restructuring enterprise processes to reduce environmental impacts, optimizing energy consumption, and developing socially responsible transportation services for local communities affected by war. While this research primarily addresses the Ukrainian context, the proposed model is equally relevant for enterprises in other regions undergoing transformation, post-crisis recovery, or modernization processes.

The research has several limitations: the model has not yet been empirically validated using large-scale datasets from motor transport enterprises, and its implementation depends on the availability of reliable environmental and economic indicators, which may be difficult to obtain under unstable economic conditions and in the crisis-affected context of Ukraine. Additionally, the model does not explicitly address sector-specific technological barriers, and its conceptual nature with reliance on secondary sources prevents empirical generalization at this stage.

The conditions of martial law in Ukraine significantly influenced the scope and methodology of this research. Limited access to primary enterprise data, restrictions on field studies, and disruptions in transportation infrastructure constrained empirical testing, highlighting the urgent need for adaptive, sustainability-oriented models capable of operating under uncertainty and post-conflict recovery scenarios.

Future research should focus on empirical validation of the proposed model using case studies and simulation experiments. Comparative analyses across different industries and countries could provide additional insights into the model's adaptability. Furthermore, integrating emerging technologies such as artificial intelligence, big data analytics, and digital twins could enhance predictive capabilities, audit efficiency, and sustainability performance of motor transport enterprises under dynamic environmental and economic conditions.

The proposed VSA/VSM-based framework advances the theoretical discourse on sustainable innovation management and provides a practical methodology for managers of motor transport enterprises to implement adaptive, resilience-oriented, and sustainability-driven strategies in complex, uncertain, and dynamic environments.

4. Conclusions

This research has developed a VSM-based framework for sustainable innovation management in motor transport enterprises, grounded in the broader VSA and explicitly integrating internal audit mechanisms. The proposed five-level model aligns strategic, tactical, and operational subsystems with audit-based feedback loops and sustainability indicators, ensuring vertical and horizontal information flows across the enterprise. By embedding internal audit mechanisms into the recursive structure, the framework ensures not only adaptability and innovation integration, but also accountability, transparency, and reliability of sustainability governance.

The originality of the framework lies in its systemic and recursive architecture. Through dual-loop regulation, algedonic signaling, and meta-management subsystems, the model enables both stabilization of ongoing processes and proactive adaptation to external shocks. Internal audit serves as a structural control mechanism within this architecture, supporting continuous verification of sustainability performance and innovation integration. As a result, the framework enhances organizational resilience, strategic flexibility, and the capacity to embed sustainable innovations into core business processes, while simultaneously fostering organizational learning and knowledge integration.

The contributions of this research are threefold. First, it extends the application of VSA to the underexplored field of sustainable innovation management in motor transport enterprises, advancing the theoretical discourse. Second, it offers a systemic alternative to widely used frameworks such as the triple bottom line, circular economy, ISO 14001, and ESG by addressing their limitations and emphasizing adaptability, innovation integration, audit-driven accountability, and continuous learning. The comparative evaluation using the fuzzy analytic hierarchy process (Fuzzy-AHP) empirically confirmed the model's integrative and adaptive performance under conditions of uncertainty. Third, it provides a practical governance tool for MTEs, particularly in contexts of post-conflict recovery, ecological modernization, and digital transformation. For example, enterprises can apply the model to optimize fuel and energy consumption, implement low-emission technologies, and integrate socially responsible transport services while maintaining competitiveness.

The findings highlight that sustainable innovation management should not be treated as a mere assessment or compliance exercise but as an adaptive governance paradigm, in which innovation and audit jointly function as structural drivers of resilience, sustainability, and long-term viability. The proposed model is particularly relevant for enterprises operating under uncertainty, as it supports continuous organizational renewal and systemic alignment of strategic, tactical, and operational levels.

The VSA/VSM-based framework contributes both theoretically and practically to the field of sustainable innovation management. By embedding internal audit into a recursive system architecture, it provides a structured pathway for motor transport enterprises to transition toward adaptive, innovation-driven governance systems, enabling them to meet contemporary sustainability challenges while enhancing resilience, accountability, and competitiveness in dynamic environments.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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