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A STATE REGULATION MODEL FOR ATVS AND SSVS IN UKRAINE

Summary. *This study examines the current state of government regulation of all-terrain vehicles (ATVs) and side-by-side (SSV) vehicles in Ukraine. Based on an analysis of Ukrainian legislation, the regulatory experience of the European Union, the United States, and Australia, as well as contemporary research in the field of safety, the study identifies the principal shortcomings of the existing regulatory framework governing this category of vehicles.*

A model of state regulation is proposed based on mandatory vehicle registration, the establishment of minimum technical requirements, driver training, compulsory third-party liability insurance, official recording of road traffic accidents, and government oversight of vehicle operation.

The proposed model may be used to improve Ukrainian legislation and public policy on ATVs and SSVs.

The research employs comparative legal analysis, systems analysis, generalization, and analysis of international regulatory experience.

Key words: *state regulation, all-terrain vehicles (ATVs), side-by-side (SSV) vehicles, vehicle registration, road safety, public administration.*

Problem Statement. In recent years, Ukraine has experienced a steady increase in the use of ATVs and SSVs in active tourism, recreation, motorsports, agriculture, and other sectors of economic activity. At the same time, the number of business entities engaged in the import, sale, rental, and maintenance of such vehicles has been increasing.

Despite the growth of this market segment, the system of state regulation governing ATVs and SSVs in Ukraine remains incomplete. Current legislation does not establish a procedure for their state registration, requirements for their participation in public road traffic, a specific driver's license category, or a system for the official recording of road traffic accidents involving these vehicles.

The absence of a comprehensive regulatory framework creates risks to road safety, limits the effectiveness of government oversight, prevents the collection of reliable statistical data and the identification of vehicles and their owners, and reduces the state's ability to administer the relevant regulatory mechanisms.

Accordingly, the development of a model of state regulation for ATVs and SSVs in Ukraine represents a relevant objective of public administration.

The object of the study is the system of state regulation governing ATVs and SSVs.

The subject of the study comprises the mechanisms of state regulation related to vehicle registration, authorization for operation, and government oversight.

Literature Review. The safe operation of ATVs and SSVs has been extensively studied in the international scientific literature. Most studies focus on the causes of road traffic accidents, injury prevention, driver training, and the improvement of technical safety requirements for these vehicles.

According to the **U.S. Consumer Product Safety Commission (CPSC)**, approximately **100,000 ATV-related injuries** and **700–800 fatalities** are recorded annually in the United States [1]. Studies conducted by the **American Academy of Pediatrics** and systematic reviews have demonstrated that the most significant contributors to severe injuries include inadequate driver training, excessive speed, violations of operating rules, and the failure to use personal protective equipment [2–4].

In addition to safety issues, considerable attention has been paid to mechanisms of state regulation in the European Union, the United States, and Australia. These include vehicle registration systems, technical regulation, driver licensing requirements, compulsory insurance, and government oversight of vehicle operation [5–7].

At the same time, the review of the available literature indicates the absence of comprehensive studies devoted to developing an integrated model of state regulation for ATVs and SSVs that would combine safety, administrative, and economic mechanisms within a unified regulatory framework. In particular, the adaptation of such approaches to the legal and institutional environment of Ukraine remains insufficiently explored, which determines the relevance of the present study.

Main Body

Current State of Government Regulation of ATVs and SSVs in Ukraine

The current system of state regulation governing ATVs and SSVs in Ukraine does not ensure the full implementation of public administration functions with respect to this category of vehicles. Certain aspects are regulated by the **Law of Ukraine "On Road Traffic"**, regulatory acts governing vehicle registration, technical regulation, customs procedures, and other legal instruments [8–12]. However, these provisions do not constitute an integrated system of state regulation.

As a result, ATVs and SSVs remain largely outside the scope of comprehensive public administration. The absence of mandatory vehicle registration, clearly defined driver licensing requirements, a unified vehicle registration system, and effective government oversight mechanisms prevents the state from fully performing its regulatory, administrative, statistical, and safety-related functions.

From the perspective of public administration, this situation prevents the collection of reliable statistical data, the evaluation of public policy effectiveness, and the effective exercise of government oversight with respect to this category of vehicles.

The principal differences between the current regulatory framework in Ukraine and the approaches applied in most developed countries are presented in **Table 1**.

Assessing the Impact of the Absence of State Regulation on Safety, Public Administration, and the Economy

According to the **U.S. Consumer Product Safety Commission (CPSC)**, approximately **100,000 ATV-related injuries** and **700–800 fatalities** are recorded annually in the United States [1]. Studies conducted by the **American Academy of Pediatrics** and systematic reviews indicate that the primary factors contributing to severe injuries are inadequate driver training, violations of operating rules, excessive speed, and the failure to use personal protective equipment [2–4].

In countries where the operation of ATVs is subject to state regulation, these risks are mitigated through the combined application of vehicle registration, driver licensing, technical regulation, compulsory insurance, and government oversight [5–7]. In Ukraine, most of these regulatory mechanisms do not apply to ATVs and SSVs, which adversely affects not only safety but also the effectiveness of public administration.

From the perspective of public administration, a vehicle should be regarded as an object of state regulation throughout its entire life cycle. At each stage of this life cycle, the state performs specific regulatory, administrative, and information-related functions that ensure the lawful operation of the vehicle, promote road safety, and contribute to public revenue generation.

The proposed approach demonstrates that vehicle registration is not an isolated administrative procedure but rather a fundamental mechanism for implementing other public administration functions. Without it, government oversight, official statistical reporting, road traffic accident analysis, public policy evaluation, and the administration of procedures related to vehicle operation become significantly more difficult.

Table 1

Comparison of Selected Elements of State Regulation for ATVs and SSVs

Criterion	Ukraine	EU	USA	Australia
Vehicle registration	—	✓	✓	✓
Vehicle and owner identification	—	✓	✓	✓
Technical requirements	Partial	✓	✓	✓
Driver licensing	—	✓	✓	✓
Mandatory insurance	—	✓	✓	✓
Official accident records	—	✓	✓	✓
Government oversight	Limited	✓	✓	✓

Note: ✓ — regulated; Partial — partially regulated; — no specific legal regulation

Source: developed by the author based on [5–12]

Table 2

Functions of State Regulation Throughout the Life Cycle of an ATV or an SSV

Life Cycle Stage	Government Function	Outcome
Import	Customs control	Lawful importation of the vehicle
Certification	Conformity assessment	Authorization for operation
Vehicle registration	Identification and state registration	Registration of the vehicle and its owner
Driver training	Qualification control	Authorization to operate the vehicle
Insurance	Protection of property interests	Third-party liability insurance coverage
Operation	Government oversight	Compliance with legal requirements
Transfer of ownership	Updating the state register	Registration of a new owner
Deregistration	Removal from the state register	Maintenance of an up-to-date register

Source: developed by the author

Thus, the absence of a comprehensive system of state regulation results in increased safety risks, reduced effectiveness of public administration, and the loss of administrative and economic benefits that are provided by an integrated regulatory framework.

Proposed Model of State Regulation for ATVs and SSVs

The findings of this study provide a basis for proposing a model of state regulation for ATVs and SSVs that ensures the interconnection of the principal public administration functions throughout the entire life cycle of these vehicles.

The proposed model integrates vehicle registration, technical regulation, driver licensing, compulsory insurance, official road traffic accident recording, and government oversight into a unified system of public administration. The implementation of each of these regulatory mechanisms enhances the effectiveness of the others, thereby ensuring a comprehensive approach to state regulation.

The proposed model considers vehicle registration not as an independent administrative procedure but as a fundamental mechanism for implementing other public administration functions. Its implementation creates the conditions necessary for establishing an integrated system of state regulation for ATVs and SSVs in Ukraine.

Conclusions. The study has demonstrated that the current system of state regulation governing ATVs and SSVs in Ukraine does not ensure the full implementation of public administration functions related to road safety, government oversight, official record-keeping, and the administration of this category of vehicles.

Based on an analysis of international experience and the current legislative framework of Ukraine, a model of state regulation has been proposed that integrates vehicle registration, technical regulation, driver licensing, compulsory insurance, official road traffic accident recording, and government oversight into a unified public administration system.

The scientific novelty of the study lies in substantiating an approach according to which vehicle registration should be regarded not as an isolated administrative procedure but as a fundamental mechanism for implementing other public administration functions necessary for effective government oversight, the maintenance of official statistics, public policy evaluation, and the safe operation of ATVs and SSVs.

Table 3

Key Mechanisms of the Proposed State Regulation Model

Regulatory Mechanism	Main Content	Expected Outcome
Vehicle registration	Registration of vehicles and maintenance of the state register	Identification of vehicles and their owners
Technical regulation	Establishment of minimum technical requirements and conformity assessment	Authorization for safe operation
Driver licensing	Driver training and qualification assessment	Improved road safety
Insurance	Compulsory third-party liability insurance	Protection of the property interests of road users
Official record-keeping	Recording of road traffic accidents and statistical data collection	Information support for public policy
Government oversight	Monitoring compliance with legal requirements	Improved effectiveness of public administration

Source: developed by the author

The proposed model may serve as a theoretical and practical basis for the development of regulatory legal acts, the improvement of Ukrainian legislation, and the formulation of public policy in the field of regulating ATVs and SSVs.

Future research should focus on developing mechanisms for the practical implementation of the proposed model and evaluating its impact on road safety, the effectiveness of public administration, and the development of the legal ATV market.

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INTEGRATED SUPPLY AND FABRICATION MODEL IN STEEL CONSTRUCTION: A CASE STUDY OF SMALL AND MEDIUM ENTERPRISE OPERATIONAL PRACTICE

Summary. *Small and medium enterprises in steel construction typically specialize in a single function, specifically trading, fabrication, or installation, creating information and quality gaps between supply chain stages that increase defect risk and reduce client accountability. Integrated models combining these functions within a single organizational structure have been documented for large corporations but remain under-represented in academic literature for SME contexts where resource constraints and management concentration create different operational dynamics. A longitudinal case study of Kharkiv Stal LLC (Kharkiv, Ukraine), documenting the enterprise's twelve-year evolution (2013–2025) from a steel trading startup to an integrated supply-fabrication-service (ISFS) operation encompassing certified material procurement, structural steel fabrication, profiled sheeting production, and post-delivery client support. Operational data spanning four development phases demonstrate that vertical integration of supply and fabrication functions within a single SME enabled 100% certified material sourcing, repeat client revenue exceeding 60% of annual turnover, and revenue growth from startup levels to over UAH 40 million annually with a diversified portfolio spanning trading, fabrication, and finishing services. As a contribution, the ISFS model is proposed as a potentially transferable framework, subject to validation in other SME contexts, identifying the preconditions, integration mechanisms, and performance indicators relevant to small enterprises pursuing vertical integration strategies in steel construction markets.*

Key words: *steel construction, small and medium enterprise, supply chain integration, fabrication management, quality assurance, case study, vertical integration, client service model.*

Introduction. Global steel production reached 1.9 billion tons in 2023, with construction applications consuming over 50% of total output [12]. Structural steelwork, metal cladding, and associated fabrication services serve industrial, commercial, agricultural, and infrastructure sectors across every national market. In most countries, the sector is populated by a large number of small and medium enterprises that collectively process most of the structural steel tonnage, even where a few large fabricators dominate high-profile project segments. Ukraine's steel construction market follows this pattern: alongside several large fabricators with capacities exceeding 10,000 tons per year, hundreds of SMEs operate in the 500–5,000 ton range, serving regional demand for warehouses, workshops, agricultural buildings, commercial premises, and light industrial structures [13; 14].

A distinguishing feature of the SME segment is functional fragmentation. Steel trading companies purchase material from mills and distributors, maintaining inventory for resale to fabricators and construction firms. Fabrication workshops receive material from trading companies or directly from mills, converting it into structural components through cutting, welding, and assembly operations. Installation contractors erect the fabricated structures at construction sites. Each entity operates within its own commercial and quality management boundaries, and the interfaces between them represent points where information is lost and accountability is diluted. A trading company delivering steel to a fabricator transfers a mill certificate; whether that certificate is consulted during welding procedure selection depends on the fabricator's internal practices. A fabricator shipping structural components to an installation site provides dimensional drawings; whether those drawings account for actual (rather than nominal) member dimensions depends on the fabricator's measurement discipline. At each handover point, quality information degrades unless formal protocols preserve it; a pattern the author has observed consistently across two decades of professional engagement with the steel supply chain.

Published research on supply chain integration in manufacturing draws extensively on value chain theory originated by Porter [1], who identified primary and support activities as the building blocks of competitive advantage. Womack and Jones [2] extended this framework through lean thinking, emphasizing the elimination of waste across the value stream from raw material to end customer. Gunasekaran et al. [3] developed performance measurement frameworks for supply chain management, identifying metrics at strategic, tactical, and operational levels. More recent research has refined these foundations: Mittal et al. [15] examined enabling factors for smart manufacturing in SMEs, while Chiarini [8] linked sustainable manufacturing practices to supply chain configuration. All of these works, however, address supply chain integration primarily from the perspective of enterprises with dedicated functional departments and formalized inter-organizational relationships, leaving the SME configuration, where a single owner-manager may simultaneously oversee procurement, production, sales, and quality, largely outside their analytical scope.

Individual case studies of steel enterprises have examined lean implementation in large-scale steel production [5], quality management systems as organizational frameworks [10], and digital transformation pathways for manufacturing [15], but none has documented the operational mechanics and performance outcomes of an integrated supply-fabrication-service model in an SME context over a multi-year development trajectory. Yin [4] identifies the "revelatory case" as a legitimate rationale for single-case study design: a situation where the researcher has access to a phenomenon previously unavailable for scientific observation. An SME founder documenting the complete operational history of an enterprise from inception through twelve years of growth, diversification, and wartime adaptation constitutes such a case.

Kharkiv Stal LLC (Kharkiv, Ukraine), founded in 2013, provides the empirical basis for this study. Starting as a steel trading operation with minimal initial capital, the enterprise evolved through four distinct development phases over twelve years into an integrated operation with certified supplier relationships, in-house fabrication capacity, and a client base generating over UAH 40 million in annual revenue. Having served as both founder-director and researcher enables the author to have access to complete operational records from inception, while also requiring explicit methodological safeguards against confirmation bias, which are addressed in the Methods section. Operations spanned a period that included rapid market growth (2017–2021), the full-scale military conflict beginning in February 2022, and subsequent wartime adaptation, a trajectory that tested the resilience of the integrated model under conditions that no controlled study could replicate.

Presented here is a documentation and systematization of the Integrated Supply-Fabrication-Service (ISFS) model as implemented at Kharkiv Stal LLC, analyzing its operational structure, quality assurance mechanisms, client interaction patterns, and quantitative performance over the 2013–2025 period. Results and Discussion sections are presented separately to distinguish factual operational data from their interpretation. Scientific novelty lies in the formalization of a vertically integrated SME operational model in steel construction, documented through longitudinal data from a single enterprise across multiple market conditions including peacetime growth and wartime adaptation. Practical contribution consists in identifying the preconditions, integration mechanisms, and measurable performance outcomes that other SMEs can evaluate when considering similar vertical integration strategies.

Literature review. Supply chain integration as a competitive strategy has been studied across manufacturing sectors for over three decades, generating theoretical frameworks, empirical evidence, and prescriptive models at varying scales of enterprise. For the steel construction SME context examined in this study, four research streams are directly relevant: vertical integration theory and its application to manufacturing, supply chain quality management, SME operational models, and industry-specific case studies in steel and metalworking.

Vertical integration refers to the extent to which a firm owns or controls successive stages of the value chain for its products. Harrigan [17] distinguished between full integration (complete ownership of adjacent stages), taper integration (partial ownership supplemented by market transactions), and quasi-integration (long-term contracts or equity stakes without full ownership). For manufacturing SMEs, full vertical integration is typically constrained by capital requirements: owning a steel mill, a fabrication workshop, and a construction crew simultaneously exceeds the financial capacity of most small enterprises. What becomes feasible is selective integration of adjacent stages, for example, combining trading and fabrication, or fabrication and installation, where the capital requirement for adding the adjacent function is proportionate to the enterprise's existing resource base. A strategic question is which combination of stages generates the greatest competitive advantage for a given investment, and the answer depends on where in the value chain the most significant quality and information losses occur [1; 2].

Supply chain quality management (SCQM) examines how quality practices extend beyond the boundaries of a single firm to encompass supplier relationships, inter-organizational information flows, and customer feedback loops. Kuei et al. [18] identified six dimensions of SCQM: leadership commitment, strategic planning, human resource focus, supplier focus, customer focus, and quality information availability. Their empirical analysis of 214 firms in Taiwan found that quality information availability, specifically the degree to which quality data flows freely across organizational boundaries, was the strongest predictor of supply chain performance. Robinson and Malhotra [19] conducted a comprehensive literature review of SCQM, concluding that the field had evolved from a narrow focus on supplier quality auditing toward a broader view encompassing collaborative quality planning, joint problem-solving, and shared performance metrics. For steel construction, where material quality at the procurement stage propagates through fabrication into the finished structure's performance over decades of service, the availability and continuity of quality information across supply chain stages is particularly consequential.

ISO 9001:2015 [10] provides the management system architecture within which SCQM operates at the firm level, requiring documented processes for supplier evaluation, incoming material verification, in-process control, and customer feedback management. ISO 3834–2:2021 [11] adds welding-specific quality requirements that link material properties (chemical composition, mechanical characteristics) to fabrication process parameters (welding procedures, preheat temperatures, interpass constraints). EN 1090–2:2018 [9] establishes execution classes that determine the minimum levels of material traceability, dimensional tolerance, and inspection intensity for steel structures. Individually, these standards define what must be controlled at each stage; collectively, they create a quality framework that spans the material-to-structure chain. For a fragmented supply chain where different enterprises hold different certifications, compliance is verified at organizational boundaries through document exchange. For an integrated enterprise holding all three certifications, compliance is verified through internal processes with no inter-organizational information gaps.

SME operational models in manufacturing have been characterized by several distinguishing features that differentiate them from large-enterprise models. Ghobadian and Gallear [20] compared total quality management implementation between large and small firms, identifying that SMEs benefit from shorter communication lines, faster decision cycles, and direct owner involvement in quality, but suffer from limited specialist expertise, informal documentation, and vulnerability to key-person dependency. Srinivasan et al. [5] applied Lean Six Sigma methodology to a steel industry context using Yin's case study approach, demonstrating that structured improvement frameworks originally developed for automotive and electronics manufacturing can be adapted to steel processing environments with measurable gains in cycle time and defect reduction. Their study, conducted at a galvanizing line within a larger steel operation, documented a 42% reduction in non-value-added time and significant improvement in process cycle efficiency through targeted application of value stream mapping and statistical process control.

Distinctions between SME integration in stable markets and in volatile or conflict-affected environments has received limited academic attention. Ates et al. [16] noted that emerging economy SMEs face institutional voids, specifically gaps in market infrastructure, regulatory enforcement, and financial services, that simultaneously constrain growth and create opportunities for enterprises willing to internalize functions that market institutions would otherwise provide. Such dynamics resonate with the Ukrainian steel construction context, where supply chain fragmentation is partly a consequence of market immaturity: the institutional mechanisms that enable reliable inter-firm quality coordination in mature markets (industry-wide certification bodies, established reputational networks, enforceable quality warranties) are less developed, creating an incentive for individual enterprises to integrate functions rather than depend on external coordination.

Digital transformation offers SMEs potential tools for achieving integration benefits without full vertical ownership. Moeuf et al. [6] found that SMEs adopting Industry 4.0 technologies tended to implement cloud-based ERP systems, basic IoT sensors, and digital quality records before attempting more advanced technologies like digital twins or artificial intelligence. Matt and Rauch [7] proposed an SME 4.0 framework emphasizing that technology adoption in small firms follows a pragmatic path driven by immediate return on investment rather than comprehensive digital strategy. For steel construction SMEs, ERP-based integration of procurement, inventory, production, and delivery data represents the most accessible digitalization pathway, enabling information continuity across supply chain stages without requiring the sensor infrastructure and data analytics capability that large-enterprise Industry 4.0 implementations demand [15].

Figure 1 positions the ISFS model within Porter's value chain framework, illustrating which primary and support activities are internalized within the integrated SME versus outsourced or absent in the fragmented model.

In the fragmented model, inbound logistics (material procurement and inventory) resides with the trading company, operations (fabrication) with the workshop, outbound logistics and service with the installation contractor, and quality information transfers between entities through documents that may or may not be consulted at the receiving end. In the ISFS model, all primary activities from procurement through service reside within a single enterprise, enabling continuous quality information flow, unified performance metrics, and direct feedback from client experience to procurement and fabrication decisions. Support activities (firm infrastructure, human resource management, technology) similarly operate under unified management rather than being distributed across independent entities with potentially conflicting priorities.

Across the reviewed literature, supply chain integration theory provides the strategic rationale for combining adjacent value chain stages. SCQM research identifies quality information continuity as the critical enabler of supply chain performance. SME studies document the specific constraints and opportunities that small enterprises face when pursuing integration. Steel industry case studies demonstrate that structured improvement methodologies can deliver measurable gains in metalworking environments. No identified source, however, documents the complete operational trajectory of a steel construction SME that progressively integrated trading, fabrication, and service functions over a multi-year period, tracking the preconditions for each integration step, the mechanisms through which integration produced operational benefits, and the quantitative performance outcomes across changing market conditions. Such a longitudinal integration gap defines the contribution of the present case study.

Materials and methods. This study employs a single-case embedded design following Yin's [4] case study methodology. Yin identifies five rationales for single-case design: the critical case (testing a well-formulated theory), the extreme or unique case, the representative case, the revelatory case (previously inaccessible to observation), and the longitudinal case (same case at multiple time points). By combining the revelatory and longitudinal rationales: the author's position as founder and director of Kharkiv Stal LLC provides access to complete operational data from the enterprise's inception, data that would be unavailable to an external researcher, while the twelve-year observation period (2013–2025) enables analysis of the enterprise's evolution across distinct market phases.

An embedded design with three units of analysis corresponding to the three components of the ISFS model: the supply component (procurement practices, supplier relationships, material quality assurance), the fabrication component (production capabilities, process organization, in-process quality control), and the service component (client interaction patterns, post-delivery support, feedback mechanisms). Each unit is analyzed through its own set of data sources and performance indicators, while cross-unit analysis examines how integration between components generates outcomes that the individual components could not achieve independently.

Data sources comprise four categories. Operational records include procurement logs (supplier, product, quantity, certification type, and price for every incoming shipment), production records (order specifications, cutting plans, welding protocols, inspection results, and delivery documentation), and client records (order history, delivery dates, complaint logs, and repeat purchase patterns). Financial summaries include annual revenue, cost structure breakdowns, and margin

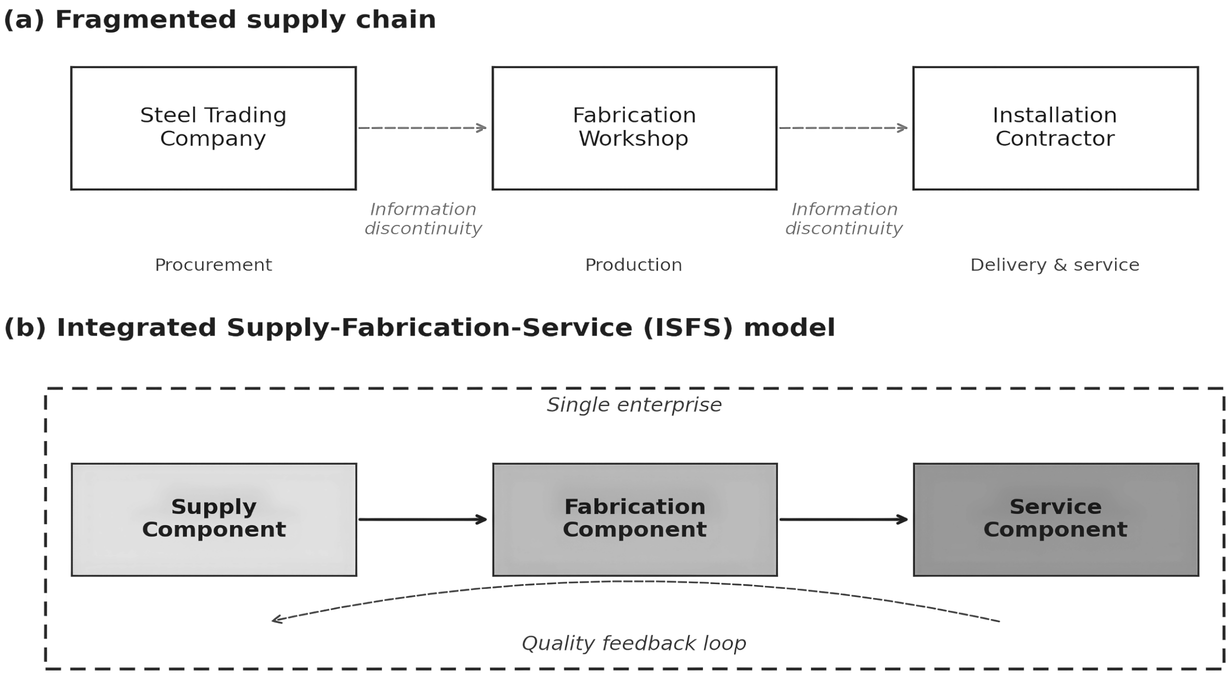

Fig. 1. Porter's value chain adapted: fragmented supply chain versus integrated ISFS model in steel construction SME
Source: developed by the author based on Porter [1] and operational practice

analysis aggregated from the enterprise's accounting system (data are presented in ranges rather than exact figures to maintain commercial confidentiality while preserving analytical value). Quality records include incoming material inspection results, in-process rework logs, final inspection outcomes, and post-delivery client feedback collected since the formalization of the quality management system in 2017. Contextual records include supplier correspondence, client meeting notes, and the author's contemporaneous observations documented in operational notes maintained since 2013, formalized into structured journals from 2015 when the enterprise's operational complexity warranted systematic documentation.

Analytically, the approach follows a pattern-matching logic [4], comparing the observed enterprise trajectory against two alternative theoretical predictions: (a) that vertical integration in an SME creates bottlenecks and management overload that limit growth beyond a certain threshold, and (b) that vertical integration creates synergies that enable sustainable growth through quality differentiation and client retention. Performance indicators were selected to discriminate between these predictions: revenue trajectory (growth versus plateau), client retention rate (increasing versus stable versus declining), quality metrics (improving versus stable versus deteriorating), and product portfolio breadth (expanding versus static). Convergent evidence across multiple indicators toward prediction (b) would support the proposition that the ISFS model generates sustainable competitive advantage for the SME; mixed or contradictory evidence would suggest conditional applicability.

Methodological limitations require explicit acknowledgment. A dual role as enterprise founder and researcher creates inherent risk of confirmation bias: a natural tendency to interpret ambiguous data in ways that validate the model one has built. Three safeguards mitigate this risk without eliminating it. First, quantitative performance data (revenue, order counts, rejection rates, client retention percentages) are drawn from accounting and quality management records that were created for operational purposes before the research was conceived, reducing the possibility of retrospective data selection. Second, negative evidence is actively reported: instances where integration created problems (management overload during peak periods, capital concentration risk, wartime supply disruptions) are documented alongside successes. Third, the Discussion section explicitly addresses alternative explanations for observed outcomes, including market conditions, geographic advantages, and competitive dynamics that may have contributed to the enterprise's trajectory independently of the ISFS model. No causal proof is claimed that the ISFS model produced the observed results; it documents the co-occurrence of the model's implementation with specific performance outcomes and proposes the integration mechanisms through which the model may have contributed to those outcomes.

Results

1. Company profile and evolution

Kharkiv Stal LLC was registered in Kharkiv, Ukraine in 2013 as a steel trading enterprise. With over a decade of prior experience in the metal products market, having worked in steel procurement and sales since the early 2000s. Initial operations comprised purchasing structural steel from regional distributors and reselling it to construction firms and small fabrication workshops in the Kharkiv region. Starting capital was minimal, the team consisted of the founder and one assistant, and the enterprise operated without its own warehouse, arranging deliveries directly from distributor stock to client sites.

Development over the subsequent twelve years can be characterized through four distinct phases, each marked by a qualitative shift in operational capability and market positioning. Table 1 summarizes these phases.

Phase 1 (2013–2015) established the commercial foundation. Revenue grew steadily during this phase, driven by the founder's existing relationships in the regional construction market. During this phase, the enterprise functioned as a pure intermediary: purchasing steel at wholesale prices and reselling with a trading margin. Quality control was limited to verifying

Table 1

Development phases of Kharkiv Stal LLC (2013–2025)

Phase	Period	Primary activity	Key capability milestones
1. Trading startup	2013–2015	Steel resale from distributor stock	First direct mill contracts; client base formation; first leased warehouse
2. Trading + basic fabrication	2015–2017	Steel trading with cutting and light fabrication	Plasma cutting equipment; first production zone; EN 10204 type 3.1 policy
3. Integrated supply-fabrication	2017–2020	Certified trading, structural fabrication, profiled sheeting	3 production zones; ISO 3834 welding; sheeting line; 5 certified suppliers
4. Full ISFS + wartime adaptation	2020–2025	Integrated supply, fabrication, service, support	ERP order management; wartime restructuring; geographic expansion

Source: compiled by the author based on operational records, Kharkiv Stal LLC. Revenue, staff, and other quantitative indicators are consolidated in Table 5 (Section 4.6) delivery documentation against order specifications. In retrospect, two operational patterns during this phase created the conditions that motivated subsequent integration. First, the enterprise had no control over the quality of material it sold: when a client reported that the delivered plate did not match the specified grade, the trading company could only relay the complaint to the distributor, with resolution depending on the distributor's willingness to investigate. Second, margins on pure trading were thin and vulnerable to price competition from other traders offering identical products from the same distributors at marginally lower prices.

Phase 2 (2015–2017) added basic fabrication capability. Initial production space (~800 m²) was leased, and the enterprise acquired production space (~800 m²) and acquired plasma cutting equipment, enabling it to offer cut-to-size plates and sections alongside standard trading inventory. Two consequences followed from this capability shift. Commercially, it allowed the enterprise to capture fabrication margin on top of trading margin, increasing gross margins on orders that included cutting services (specific margin data are reported in Table 5). Operationally, it created the first direct contact between the enterprise and the physical properties of the material it handled: operators cutting steel plates discovered dimensional inconsistencies and surface defects that were invisible in the documentation-only trading model. This hands-on quality feedback motivated the decision in 2017 to adopt a 100% certified sourcing policy, requiring EN 10204 type 3.1 mill certificates for every incoming shipment of structural steel, and transitioning supplier relationships from ad hoc purchasing to formal agreements with five certified mills and primary distributors.

Phase 3 (2017–2020) represented the core integration period. Production capacity expanded to three working zones totaling approximately 4,100 m². The product portfolio expanded from steel trading with cutting services to include fabricated structural components (trusses, frames, platforms, canopies, stairways), custom metalwork (conveyor supports, equipment frames, agricultural structures), and profiled sheeting in multiple profiles and coatings. Welding quality was formalized under ISO 3834 requirements, and execution class EXC2 per EN 1090–2 became the standard for structural work. By the end of Phase 3, the enterprise was processing 5–8 concurrent orders across its three zones, with annual throughput of approximately 800–1,200 tons of structural steel and 150,000–200,000 m² of profiled sheeting.

Phase 4 (2020–2025) added the service dimension and tested the model under extreme conditions. Client interaction evolved from transactional (deliver and invoice) to relational (consult, specify, fabricate, deliver, follow up). An ERP-based order management system replaced manual tracking, enabling real-time visibility of order status from material procurement through production to delivery. When full-scale military conflict began in February 2022, the enterprise's operations were directly affected: Kharkiv experienced sustained shelling, supply routes were disrupted, some clients suspended construction activity, and several employees were mobilized.

The integrated model proved more adaptable than a fragmented alternative would have been: because the enterprise controlled its own material inventory rather than depending on just-in-time deliveries from external traders, production could continue using existing stock during periods when incoming supply was interrupted. Supplier relationships were restructured to accommodate altered logistics (western routing replacing disrupted eastern corridors), and the product mix shifted toward military-adjacent construction (fortification elements, rapid-assembly shelters, repair components for damaged structures). By 2024–2025, revenue had recovered to pre-conflict levels and the enterprise was serving clients across a wider geographic area than before the conflict, having established delivery capability beyond the Kharkiv region.

2. Supply component: procurement and material management

The supply component of the ISFS model encompasses supplier selection, procurement execution, inventory management, and incoming quality verification. Since Phase 3 (2017 onward), five certified suppliers have constituted the core procurement portfolio, each contributing specific product categories. Table 2 presents the supplier structure.

The current product range exceeds 2,000 SKU spanning seven categories: structural plate and sheet (S235JR through S355J2, thickness 3–20 mm), structural sections (angles, channels, I-beams from 50 mm to 400 mm), profile tubes (rectangular, square, and circular, 15×15 mm to 200×200 mm), rebar and

Table 2

Supplier portfolio: product categories, certification, and relationship duration

Supplier	Product categories	Certificate type	Relationship since
Metinvest-SMC	Hot-rolled plate, sections, rebar, wire	EN 10204 type 3.1	2015
ArcelorMittal Kryvyi Rih	Structural sections, merchant bar	EN 10204 type 3.1	2016
Cascade	Hot-rolled and cold-rolled coil, sheet	EN 10204 type 3.1	2017
Slavsant	Galvanized and polymer-coated coil	EN 10204 type 3.1	2017
AV Metal Group	Profile tubes, hollow sections	EN 10204 type 3.1	2018

Source: compiled by the author based on procurement records, Kharkiv Stal LLC reinforcing mesh (diameter 6–32 mm), galvanized and polymer-coated coil (0.35–0.85 mm, zinc coating Z100–Z275, polymer in RAL color range), welding consumables (wire, electrodes matched to base material grades), and fasteners (bolts, nuts, washers, anchor assemblies for structural connections).

Incoming quality verification follows a standardized protocol for every shipment. Mill certificates are checked against order specifications before unloading: supplier name, steel grade, heat number, chemical composition, and mechanical test results are verified against EN 10025 requirements. Dimensional verification includes spot thickness measurements at 4–6 points per plate or coil using a calibrated ultrasonic gauge. Surface condition is assessed visually during unloading, with any material showing corrosion, mechanical damage, or coating defects segregated for evaluation before acceptance. Since the transition to 100% certified sourcing in 2017, incoming rejection rates have remained below 1% of deliveries, with rejections primarily attributable to transport damage rather than material non-conformance.

Inventory management balances two competing objectives: maintaining sufficient stock to enable rapid order fulfillment (clients in construction frequently require material within 1–3 days rather than the 2–4 week lead time for mill orders) and minimizing capital locked in inventory. The enterprise maintains a rolling stock valued at approximately UAH 5–8 million, comprising high-turnover items (S235/S275 plate 4–10 mm, profile tubes 40×40 through 100×100, rebar 10–16 mm, galvanized coil 0.45–0.55 mm) that account for 70–80% of order volume. Lower-turnover or project-specific material is procured against confirmed orders.

3. Fabrication component: production capabilities and processes

Fabrication operations occupy three production zones that were established progressively as the enterprise's capability expanded. Cutting capability, acquired in Phase 2 with the lease of initial production space, grew into a dedicated zone of approximately 1,200 m² housing plasma cutting equipment (capacity up to 40 mm carbon steel), oxy-fuel cutting stations for heavy plate, and mechanical cutting tools (band saws, shears) for sections and tubes. Welding and assembly capability, added during Phase 3, occupies approximately 1,800 m² containing MIG/MAG and manual arc welding stations, assembly jigs, and overhead crane capacity for handling structural assemblies up to 5 tons. The finishing zone, also established in Phase 3, encompasses approximately 1,100 m² incorporating the profiled sheeting line, surface preparation equipment (grinding, primer application), and the dispatch area. Combined production area of approximately 4,100 m² represents a facility that was built incrementally through reinvested operating cash flow rather than designed as a greenfield layout.

The production flow from material receipt to dispatch follows six stages, with quality verification integrated at each transition. Figure 2 presents this flow schematically.

Stage 1 (material receipt and incoming inspection) verifies identity, grade, dimensions, and surface condition against the order specification and mill certificate. Stage 2 (cutting) converts raw material into components per cutting plans; cut parts are checked for dimensional accuracy against tolerances specified in the order. Stage 3 (welding and assembly) joins cut components into structural assemblies per welding procedure specifications matched to the base material grade and thickness; visual inspection of every weld and dimensional verification of completed assemblies occur before the assembly advances. Stage 4 (surface treatment) applies primer, paint, or other protective coating as specified; coating thickness is verified by gauge measurement. Stage 5 (final inspection) conducts a comprehensive check covering dimensions, weld quality, surface treatment completeness, and documentation accuracy. Stage 6 (packaging and dispatch) prepares the product for transport with appropriate protective measures.

The profiled sheeting line operates as a parallel production stream, converting galvanized or polymer-coated coil into finished roofing tiles, corrugated wall panels, and flat profiled sheet. Machine parameters (roller pressure, forming speed, cut length) are verified

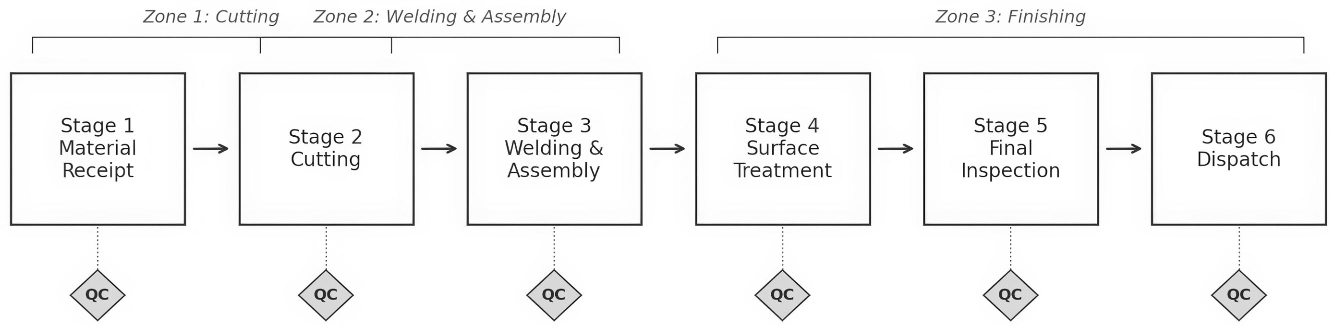

Fig. 2. Production flow: six stages with integrated quality checkpoints
Source: developed by the author based on operational practice, Kharkiv Stal LLC

at the start of each production run using sample pieces inspected for coating integrity at all bend radii before full production proceeds.

Production capacity allows concurrent processing of 5–8 fabrication orders and continuous sheeting production during standard working hours. During peak demand periods (typically spring and early summer in the Ukrainian construction season), capacity utilization reaches 85–90%. During the wartime period (2022 onward), production scheduling adapted to intermittent electricity supply and periodic operational pauses during active shelling. A diesel generator maintained power for critical operations (plasma cutting, welding, crane systems), and flexible shift patterns concentrated production during periods of stable grid supply.

4. Quality assurance across the supply-fabrication chain

Quality assurance at Kharkiv Stal operates through four sequential levels spanning the material-to-delivery chain. Rather than describing inspection procedures at each level (which follow standard industry practice per EN 1090–2 [9] and ISO 3834–2 [11]), this section focuses on the integration-specific advantages that arise from conducting all four levels within a single enterprise.

At Level 1 (incoming material quality), the critical integration benefit is that quality information gathered during inspection, specifically actual thickness readings, chemical composition from the mill certificate, surface condition observations, transfers directly into production planning within the same organization. A fabricator purchasing material from an external trader receives a mill certificate as a document; an integrated enterprise receives the same data as operational input already embedded in its quality system.

At Level 2 (in-process fabrication quality), the integration benefit operates bidirectionally. When a production issue is detected, for example, inconsistent weld penetration on a plate that met all incoming specifications, the quality system traces backward to the specific shipment, supplier, and heat number, and forward to any other orders using material from the same batch. In a fragmented chain, backward tracing requires cross-organizational communication that may take days; in the integrated model, it takes minutes.

At Level 3 (final product quality), integration ensures that inspection criteria reflect actual material properties rather than nominal specifications. Final dimensional checks account for the actual thickness measured at incoming (Level 1), not the nominal thickness on the drawing, because the same system holds both data points.

At Level 4 (post-delivery quality and client feedback), integration closes the information loop. Client feedback on structural performance, assembly fit, and coating durability during service feeds back into procurement decisions (supplier performance rating), production adjustments (process parameter refinement), and product development, creating a continuous improvement cycle that spans the entire supply-fabrication-service chain.

Table 3 presents quantitative quality metrics across the four levels for the most recent three-year period (2023–2025).

The complaint rate of 0.4 per 100 deliveries merits contextual interpretation. During Phase 1 (2013–2015), when the enterprise functioned as a pure trader without fabrication capability, complaint resolution depended on the upstream distributor's cooperation and could take weeks. During Phase 4 (2023–2025), complaints are resolved internally within 1–3 working days because the enterprise controls the full production chain and can identify whether the issue originated in material (Level 1), fabrication (Level 2), inspection (Level 3), or transport/handling (post-Level 3). This resolution speed is itself a competitive advantage: construction clients operating under tight schedules value rapid problem resolution over zero-defect promises that cannot be verified until after the project deadline.

5. Client interaction and market development

The service component of the ISFS model encompasses client acquisition, order specification, delivery logistics, post-delivery support, and long-term

Table 3

Quality metrics by assurance level (2023–2025 averages)

Quality level	Metric	Target	Actual (2023–2025)
Level 1: Incoming	Shipment rejection rate	< 2%	0.8%
Level 1: Incoming	Certificate non-conformance	0%	0%
Level 2: In-process	Rework rate (cutting)	< 3%	1.8%
Level 2: In-process	Rework rate (welding)	< 5%	2.9%
Level 2: In-process	Rework rate (assembly)	< 3%	1.4%
Level 3: Final	First-pass inspection rate	> 90%	94.2%
Level 3: Final	Documentation completeness	100%	99.6%
Level 4: Post-delivery	Complaint rate (per 100)	< 2	0.4
Level 4: Post-delivery	Repeat order rate	< 50%	62%

Source: compiled by the author based on quality management records, Kharkiv Stal LLC, 2023–2025 relationship management. Evolution of this component parallels the enterprise's four development phases, shifting from transaction-based interaction (Phase 1–2) to relationship-based engagement (Phase 3–4).

During the trading-only period (Phase 1), client interaction was transactional: price quotation, order acceptance, delivery, and invoicing. Differentiation from competing traders was limited to delivery reliability and personal relationships, with no quality or technical advantage available.

Addition of fabrication capability (Phase 2–3) transformed the client interaction model. Clients could now request material as well as processing services, including cut-to-size plates, welded assemblies, custom brackets, and complete structural components designed to their specifications. Technical consultation became part of the sales process: the enterprise's production staff could advise clients on material selection (which grade and thickness for a given structural application), connection design (welded versus bolted, detail geometry), and surface protection (appropriate coating system for the intended service environment). This consultative capability attracted a different client profile, specifically construction companies and industrial enterprises that valued engineering input alongside material supply, and shifted the competitive basis from price per ton to value per project.

Client segments span industrial enterprises, construction companies, agricultural enterprises, and individual clients. Industrial and construction segments generate approximately 75% of annual revenue.

Geographic market reach expanded progressively from the immediate Kharkiv area (Phase 1) to the broader Kharkiv Oblast (Phase 2–3) and, following wartime disruption, to a national scope including central and western Ukrainian regions where the enterprise had no prior presence.

Repeat client revenue grew from an estimated 25–30% of annual turnover in Phase 1 (when the enterprise was new and client relationships were forming) to over 60% in Phase 4. This growth trajectory developed in parallel with the enterprise's expanding service scope, as the share of clients utilizing multiple services (trading + fabrication, or fabrication + delivery + consultation) grew relative to clients purchasing a single product category.

6. Quantitative performance assessment

Growth was not without setbacks. During the Phase 2–3 transition (2016–2018), concurrent management of expanding supplier negotiations, production scheduling, client quotations, and quality documentation created operational bottlenecks: client response times periodically exceeded 48 hours and scheduling conflicts resulted in delivery delays on an estimated 10–15% of orders during peak periods. The 2022 conflict onset produced a sharper disruption: revenue declined by an estimated 40–50% in the first six months before adaptation measures restored operational continuity.

Table 4 aggregates the key performance indicators across the enterprise's twelve-year trajectory, organized by development phase. Figure 3 visualizes the revenue and order volume trends.

Several patterns emerge from the longitudinal data. Revenue growth was not linear: Phase 1 showed rapid percentage growth from a low base (approximately 4× over three years), Phase 2 showed moderate growth (approximately 2× as fabrication margins supplemented trading), Phase 3 showed accelerating growth (approximately 2× as the integrated model attracted higher-value orders), and Phase 4 showed resilience and recovery (dip during 2022 conflict onset, followed by recovery to pre-conflict levels by 2024 and continued growth in 2025).

Gross margin expansion from 8–12% (pure trading) to 20–30% (integrated ISFS) reflects the progressive capture of value-added stages. Each integration step, from resale to cutting, from cutting to welding, from welding to complete fabrication, from fabrication to sheeting, from product delivery to technical consultation, added margin layers that cumulatively

Table 4

Key performance indicators by development phase (2013–2025)

Indicator	Phase 1 (2013–15)	Phase 2 (2015–17)	Phase 3 (2017–20)	Phase 4 (2020–25)
Revenue (UAH M)	2–8	8–15	15–30	30–45
Orders/year	50–150	150–400	400–800	600–1,000
Product categories	1	3	5	7
Staff (year-end)	2–4	5–10	10–20	15–25
Supplier certification	Mixed	~60% type 3.1	100% type 3.1	100% type 3.1
Gross margin	8–12%	15–22%	18–28%	20–30%
Repeat client share	25–30%	35–45%	50–58%	60–65%
Complaint rate (/100)	Not tracked	~3	~1	0.4
Capacity (tons/yr)	N/A	~200	800–1,200	1,000–1,500

Source: compiled by the author based on financial and operational records, Kharkiv Stal LLC. Revenue in ranges for commercial confidentiality

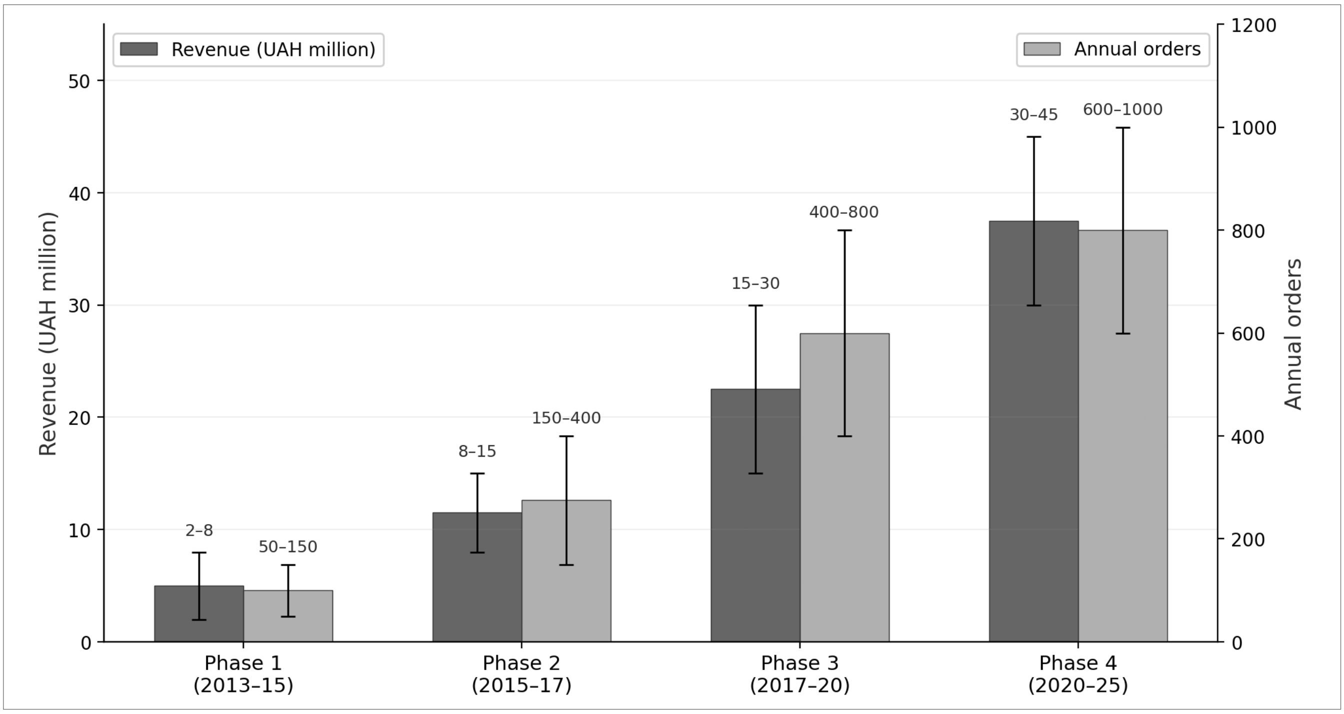

Fig. 3. Revenue trajectory and order volume growth (2013–2025) by development phase
Source: compiled by the author based on financial records, Kharkiv Stal LLC

transformed the enterprise from a low-margin intermediary into a differentiated service provider competing on capability rather than price alone.

Client complaint rate declined from approximately 3 per 100 deliveries in Phase 2 (when fabrication capability was newly established) to 0.4 per 100 in Phase 4, a trajectory that coincided with quality system maturation, supplier base stabilization, and workforce experience accumulation documented in Sections 4.2–4.4.

Discussion. The operational trajectory documented in Sections 4.1–4.6 can be interpreted through the theoretical lenses established in the literature review, while also identifying empirical findings that extend or qualify existing theoretical predictions.

Porter's value chain framework [1] predicts that competitive advantage arises from configuring primary and support activities in ways that create value for the buyer at acceptable cost to the firm. The ISFS model demonstrates a configuration where inbound logistics, operations, outbound logistics, and service are unified under single management within an SME structure. Harrigan's [17] integration typology classifies this as selective full integration: the enterprise fully owns and controls the trading-fabrication-service chain but does not extend into upstream steel production or downstream construction installation. The empirical data suggest that for SMEs in steel construction generally, this selective boundary is strategically rational: extending into steel production would require capital investment orders of magnitude beyond SME reach, while extending into construction installation would require a different workforce skill set and regulatory framework. This finding can be generalized to SMEs operating in fragmented manufacturing sectors: the trading-fabrication-service segment represents value chain territory where SME-scale capital and management capacity can achieve integration benefits without exceeding resource constraints.

Kuei et al. [18] identified quality information availability as the strongest predictor of supply chain performance among the six SCQM dimensions they studied. The present case provides a mechanism-level illustration of this finding. When procurement and fabrication reside within a single enterprise, quality information flows directly into production parameters without crossing an organizational boundary. In a fragmented chain, this transfer depends on multiple handoffs, each representing a potential failure point. The quality metrics documented in Section 4.4 are consistent with the SCQM prediction that information continuity reduces defect generation. This suggests that SMEs capable of internalizing the procurement-fabrication interface gain a quality advantage that is structural rather than dependent on individual vigilance. The decline in complaint rates from early fabrication to mature ISFS operation reflects concurrent quality mechanisms: system formalization, supplier stabilization, and experience accumulation. For other SMEs considering similar integration, this trajectory suggests that quality benefits compound over time rather than appearing immediately at the point of structural change.

Ghobadian and Gallear [20] characterized SMEs as benefiting from short communication lines and direct owner involvement but suffering from limited specialist expertise and key-person dependency. The Kharkiv Stal case confirms both sides of this characterization. Short communication lines enable direct owner oversight across procurement, production, and client relationships simultaneously, an integration capability that larger enterprises achieve only through formal coordination mechanisms. This concentration of quality authority in a single decision-maker accelerates quality culture development in ways that formal documentation alone cannot replicate, a pattern likely generalizable to owner-managed SMEs across manufacturing sectors. Conversely, key-person dependency is the model's primary vulnerability: during the most intense period of the 2022 conflict, when the founder was directly managing evacuation logistics, supply chain restructuring, and client communication simultaneously, production coordination suffered until additional management responsibility was delegated to senior production staff. The wartime period forced an acceleration of organizational development that had been deferred during peacetime growth, transitioning from founder-centric to team-distributed decision-making for routine operations while retaining founder oversight for strategic and quality-critical decisions. Repeat client share exceeding 60% suggests that integrated service offerings create relationship continuity through switching costs, a retention mechanism available to any SME that combines multiple value chain stages rather than specializing in one.

The competing prediction, that vertical integration creates bottlenecks limiting growth, found partial support. Phase transitions and the 2022 conflict exposed two stress points: management overload during capability expansion, and financial exposure from capital concentration during demand shocks. These findings suggest that SMEs pursuing vertical integration should anticipate management capacity constraints at each growth phase and build delegation mechanisms before they become urgent rather than after crisis forces the transition. The founder's initial resistance to delegating procurement and quality decisions, overcome by operational necessity during wartime, illustrates the key-person dependency risk that Ghobadian and Gallear [20] identified as characteristic of SME quality management.

Transferability of the ISFS model to other SMEs requires assessment of preconditions. The empirical evidence suggests four necessary conditions for successful implementation: (1) foundational market knowledge: the founder's pre-existing experience in steel trading provided client relationships and supplier contacts without which the startup phase would have been significantly longer; (2) incremental capital investment, each integration phase was funded from operating cash flow rather than external investment, making the model accessible to bootstrapped enterprises but requiring patience in the growth trajectory; (3) quality commitment preceding capability expansion, the transition to 100% certified sourcing in Phase 2, before full fabrication capability was established, created the quality foundation on which subsequent integration was built; and (4) management willingness to learn adjacent functions, the founder transitioned from trader to production manager to quality system designer to client relationship manager progressively, acquiring competencies that a specialist in any single function might not pursue. SMEs that lack any of these preconditions may find specific integration steps more difficult, though not necessarily impossible, to execute.

Conclusions. The Integrated Supply-Fabrication-Service model documented in this case study demonstrates that a steel construction SME can achieve competitive advantage through progressive vertical integration of trading, fabrication, and client service functions within a single organizational structure. Over twelve years and four development phases, Kharkiv Stal LLC evolved from a two-person steel trading startup into an integrated operation with certified supplier relationships, multi-zone fabrication capability, diversified product portfolio, and a service-oriented client model generating over UAH 40 million in annual revenue with repeat client share exceeding 60%.

Quality assurance across the integrated supply-fabrication chain represents the model's primary operational advantage. Continuous information flow from incoming material inspection through production stages to post-delivery client feedback, managed within a single quality management system without inter-organizational boundaries, produced measurable outcomes: incoming rejection rates below 1%, in-process rework rates of 1.4–2.9% depending on operation type, first-pass final inspection rate of 94.2%, and client complaint rate of 0.4 per 100 deliveries. These metrics are consistent with the supply chain quality management prediction that quality information continuity is the strongest driver of supply chain performance, and they provide SME-specific quantification that the SCQM literature has lacked.

Wartime adaptation (2022–2025) provided an unplanned but empirically valuable test of the model's resilience. The integrated structure offered specific advantages, specifically inventory buffering, prioritized supplier relationships, and product-mix flexibility, that enabled operational continuity under conditions that would have fragmented a non-integrated supply chain. While this finding is specific to the Ukrainian conflict context, the underlying principle, that enterprises controlling more stages of their value chain have more response options during disruption, is consistent with supply chain resilience theory and has implications for SMEs operating in any volatile market environment.

As a single-case study documenting one enterprise's trajectory in a specific market and conflict context, the findings represent a single data point rather than a generalizable law. The author's dual role as founder and researcher, while enabling unprecedented data access, introduces interpretation risks that the methodological safeguards described in Section 3 mitigate but cannot eliminate. Quantitative performance outcomes reflect the combined effect of the ISFS model and numerous concurrent factors (market conditions, competitive dynamics, macroeconomic trends, wartime disruption) that cannot be isolated through observational methodology.

Four preconditions for ISFS model implementation emerged from the longitudinal analysis: foundational market knowledge, incremental capital investment, quality commitment preceding capability expansion, and management willingness to acquire adjacent-function competencies. These preconditions define the boundary conditions within which the model is likely to be replicable, and they suggest that successful integration is a multi-year developmental process rather than a configuration that can be designed and implemented at a single point in time.

Further research should pursue three complementary directions: multi-case comparative studies examining whether the ISFS model produces similar outcomes at other steel construction SMEs in different market contexts; quantitative modeling of the relationship between integration depth and performance metrics across a sample of enterprises at varying integration levels; and longitudinal studies of SME adaptation in conflict-affected markets, where the interplay between supply chain structure and operational resilience can be examined with the analytical rigor that the single-case design of the present study cannot provide.

ДОДАТКОВА ІНФОРМАЦІЯ
ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.
КОНФЛІКТ ІНТЕРЕСІВ: Автори заявляють про відсутність конфлікту інтересів.

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REGULATORY HARMONIZATION ANALYSIS AND STRATEGIC RECOMMENDATIONS: A CASE STUDY ON THE IMPORT OF EUROPEAN HEAVY-DUTY TRUCK COMPONENTS AND THEIR IMPACT ON THE U.S. MARKET

Summary. *This article investigates the jurisprudential and technical divergence between the US self-certification regime (ex-post enforcement) and the EU type approval paradigm (ex-ante verification), identifying this discrepancy as the primary driver of market fragmentation. Employing a hybrid methodology that integrates comparative jurisprudence, systems engineering and economic impact assessment, the study exposes critical compliance gaps in photometric standards, chemical composition disclosure (REACH vs. TSCA) and certification markings. The analysis quantifies the compliance premium – excessive costs attributed to redundant validation and logistical friction, demonstrating how current protocols foster oligopolistic market structures and disrupt just-in-time supply chains. To resolve these inefficiencies, the article proposes a novel proposed framework. This model advocates for a paradigm shift from geometric prescription to functional equivalence, predicated on three pillars: harmonized cross-validation of testing facilities, blockchain-based digital product passports and conditional mutual recognition. Implementation of this mechanism is projected to reduce the landed cost of European components by 15–20%, eliminate bureaucratic latency and accelerate the adoption of safety-critical innovations within the US domestic market ecosystem.*

Key words: *harmonization, transatlantic, automotive market, supply chain, certification, divergence.*

Introduction. In the contemporary architecture of global trade, the automotive industry occupies a unique position, acting simultaneously as a driver of technological innovation and a hostage to archaic regulatory barriers [1]. Despite its substantial capacity and technological proximity, the transatlantic automotive component market remains fragmented due to profound regulatory contradictions. While engineers strive for platform unification, the legal systems of the United States and the European Union continue to function within isolated realities. Divergences in safety standards (FMVSS vs UNECE), environmental testing protocols (EPA vs WLTP), and labeling requirements create a paradoxical scenario wherein a technically superior and safe European component may be rendered legally illicit on the American market absent costly modification [2].

The jurisprudential bifurcation between conformity assessment regimes in the United States and the European Union represents one of the most persistent challenges to the harmonization of international technical regulation [3]. The significance of this study is anchored in the necessity to surmount the compliance premium — excessive economic costs stemming from procedural duplication and the absence of mutual recognition [4]. Consequently, this article undertakes a comprehensive analysis of regulatory divergence to identify critical non-conformance zones and assess their economic impact on pricing and logistics. Also it conducts a comparative analysis of the normative frameworks of both jurisdictions to detect specific vulnerabilities inherent in the importation of European components.

In response to these identified challenges, this article proposes a conceptual model designated as the Transatlantic Compliance Protocol (TCP). This framework is engineered to supersede obsolete geometric prescriptions with a modern system based on the principle of functional equivalence and the implementation of digital verification tools.

Materials and methods. This study employs a comprehensive qualitative research methodology, integrating comparative jurisprudence, systems engineering analysis and economic impact assessment to examine the transatlantic automotive regulatory landscape. The primary evidentiary basis for this research comprises the legislative and technical regulations governing vehicle homologation procedures within the United States and the European Union. The analysis focuses on the National traffic and motor vehicle safety act, the Code of federal regulations (specifically Title 49, Part 571 FMVSS), enforcement protocols of the National highway traffic safety administration (NHTSA), as well as environmental mandates from the EPA (Title 40 CFR) and California's Proposition 65 [5; 6; 7; 8]. Also the study examines the framework of the UNECE 1958 Agreement, specific UN Regulations (R112 for lighting systems, R43 for glazing), the EU Type Approval framework regulation (EU) 2018/858 and chemical safety standards under REACH [9; 10; 11].

A comparative review of SAE (Society of automotive engineers) standards and ISO (International organization for standardization) norms was conducted to identify specific engineering divergences. A dialectical comparison was applied to contrast the philosophy of ex-ante verification in the EU with the ex-post enforcement regime in the US [12]. This phase utilized legal hermeneutics to interpret how procedural differences transmute into non-tariff trade barriers. Supply chain management principles were applied to evaluate the impact of regulatory friction on just-in-time logistics. Qualitative economic analysis was utilized to decompose the landed cost structure, isolating specific cost multipliers associated with redundant certification and risk mitigation. Specific automotive components, namely lighting systems, glazing and hydraulic assemblies, were utilized as case studies to empirically ground the theoretical analysis.

In the final phase, the Transatlantic Compliance Protocol was designed using a systems engineering approach. This model was synthesized by integrating existing best practices in digital credentialing (blockchain technology) with the legal principle of functional equivalence, aiming to propose a theoretically viable mechanism for regulatory harmonization.

Juxtaposition of US regulatory frameworks and EU standardization protocols. Notwithstanding the pervasive globalization of the automotive industry, regulatory divergence persists as a formidable barrier between the United States and the European Union. While the overarching teleological objectives in both jurisdictions remain congruent, namely the assurance of road safety and the minimization of environmental impact, the jurisprudential pathways employed to achieve them exhibit a fundamental bifurcation [13]. The foundational distinction between the American and European systems lies less in technical granularity than in the legal philosophy of conformity assessment.

Pursuant to the National traffic and motor vehicle safety act, the United States operates under a self-certification regime. Under this framework, the manufacturer bears the sole burden of attesting that its components comply with the Federal motor vehicle safety standards (FMVSS), as codified in the Code of federal regulations (CFR). Conversely, federal regulatory bodies, such as the National highway traffic safety administration (NHTSA) and the Department of transportation (DOT), generally refrain from conducting pre-market testing. Instead, oversight is exercised through an ex-post enforcement mechanism, characterized by sporadic compliance audits following market entry and a rigorous liability framework encompassing mandatory recall campaigns and litigation risks [14].

In stark contrast, the European model affords significantly less autonomy to the manufacturer, relying on a stricter control paradigm. The European approach is predicated on ex-ante verification, technically termed as type approval (or homologation). Prior to market launch, components must undergo mandatory testing by accredited technical services and subsequently obtain certification from a competent authority — the KBA in Germany or the RDW in the Netherlands [15].

These systemic disparities constitute a primary impediment to the seamless transposition of European logistical algorithms onto American soil. The integration of supply chains is impossible without a nuanced understanding of these legal idiosyncrasies and systemic bottlenecks. Specifically, the possession of a full suite of European certifications (the E-mark) holds no statutory validity within the US jurisdiction, thereby necessitating a redundant cycle of internal validation by the importer to mitigate legal liability [16]. Technical standardization reveals a deep schism. The American framework frequently codifies SAE (Society of Automotive Engineers) standards directly into federal law (49 CFR). Modifications to these standards entail a labyrinthine rulemaking process, often resulting in regulatory inertia [17].

Conversely, the European system is harmonized with UNECE Regulations and ISO standards, facilitating a more agile adaptation to technological innovations. Critical discrepancies are evident in requirements regarding lighting systems, glazing, rearview mirrors and braking assemblies. For instance, European aspherical mirrors or matrix lighting technologies may fail to meet the rigid geometric prescriptions of FMVSS, notwithstanding their empirical efficacy, thus precluding direct importation and complicating supply chain dynamics [18].

The most acute contradictions, however, arise within the domain of environmental regulation concerning powertrains and exhaust systems. Given the global imperative for carbon neutrality and green performance metrics, environmental mandates have become integral to transatlantic logistical mechanisms. While both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) enforce stringent thresholds for nitrogen oxides (NOx) and particulate matter, the core conflict resides in the test cycles. American protocols (FTP-75) simulate specific driving conditions that diverge significantly from European WLTP or RDE (Real Driving Emissions) cycles [19].

Consequently, an emission control component optimized for European load profiles may exhibit deviations when subjected to EPA methodology, rendering it effectively illegal without profound technical modification, even if its actual ecological footprint is minimal.

Detecting critical compliance gaps in the US certification process for EU origin components. The transition from a theoretical juxtaposition of regulatory frameworks to the operational reality of importation exposes a series of critical compliance gaps, manifesting as specific technical or chemical parameters where the direct application of commercial off-the-shelf European components is rendered impossible without substantial modification.

One of the most insidious, yet frequently underestimated, risk zones concerns the regulation of chemical composition. While the European Union operates under the REACH regulation, which primarily focuses on the direct prohibition or restriction of hazardous substances, the United States framework relies heavily on the Toxic substances control act (TSCA) and, more critically for importers, California's Proposition 65 [20]. Unlike the European "prohibition" model, the American model often mandates "disclosure" and consumer warning. Hence, a European plastic component may be fully compliant within the EU. However, if it contains micro-traces of a substance listed under Proposition 65 without the requisite warning label, the entity is exposed to significant litigation risks. This enforcement is frequently driven by private enforcement litigants, colloquially known as bounty hunters, creating a regulatory paradox wherein a technically safe component becomes statutorily toxic solely due to the absence of a warning sticker [21].

Additionally, photometric incompatibility constitutes a formidable engineering barrier due to fundamental divergences in beam pattern geometry. SAE J standards in the US and ECE R regulations in Europe stipulate distinct requirements for light distribution: the European low-beam standard mandates a sharp cut-off gradient to prevent glare, whereas US standards specifically require a certain degree of upward light leakage to illuminate overhead gantry signs [22]. As a result, a European headlamp with focus characteristics that are considered ideal under ECE protocols may be deemed non-compliant under FMVSS 108 due to insufficient illumination of the upper sector, rendering the direct import of optical units impossible without a comprehensive re-engineering of the reflector or lens optics.

Beyond functional performance, the third tier of vulnerability pertains to safety-critical components where the lack of mutual recognition regarding certification markings creates absolute barriers to market entry. The European E-mark on automotive glass holds no validity in the US. Instead, glazing must bear the DOT certification and an AS (American standard) code, attesting to successful penetration and light transmissibility tests which differ methodologically from European norms [23]. Similarly, hydraulic assemblies such as brake hoses must feature an indelible DOT marking and a manufacturer identification code registered

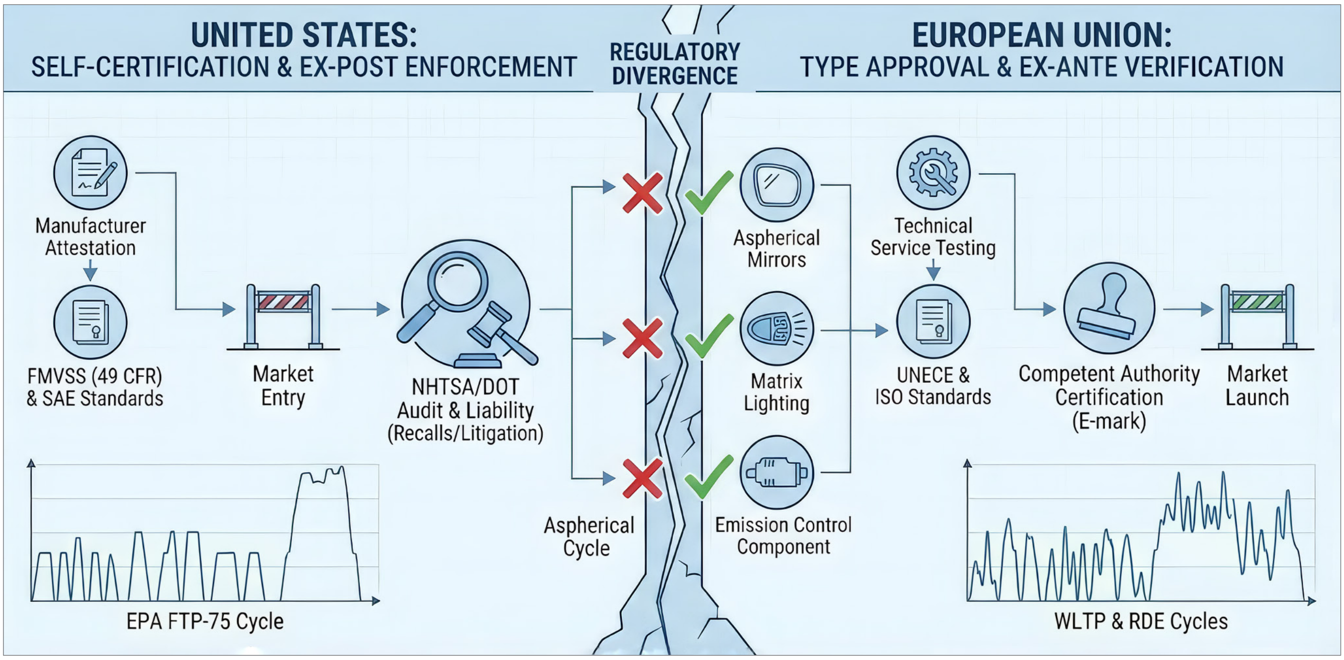

Fig. 1. Conceptual diagram of systemic regulatory divergence between the US and the EU

Source: generative artificial intelligence and prompt were used to create the image

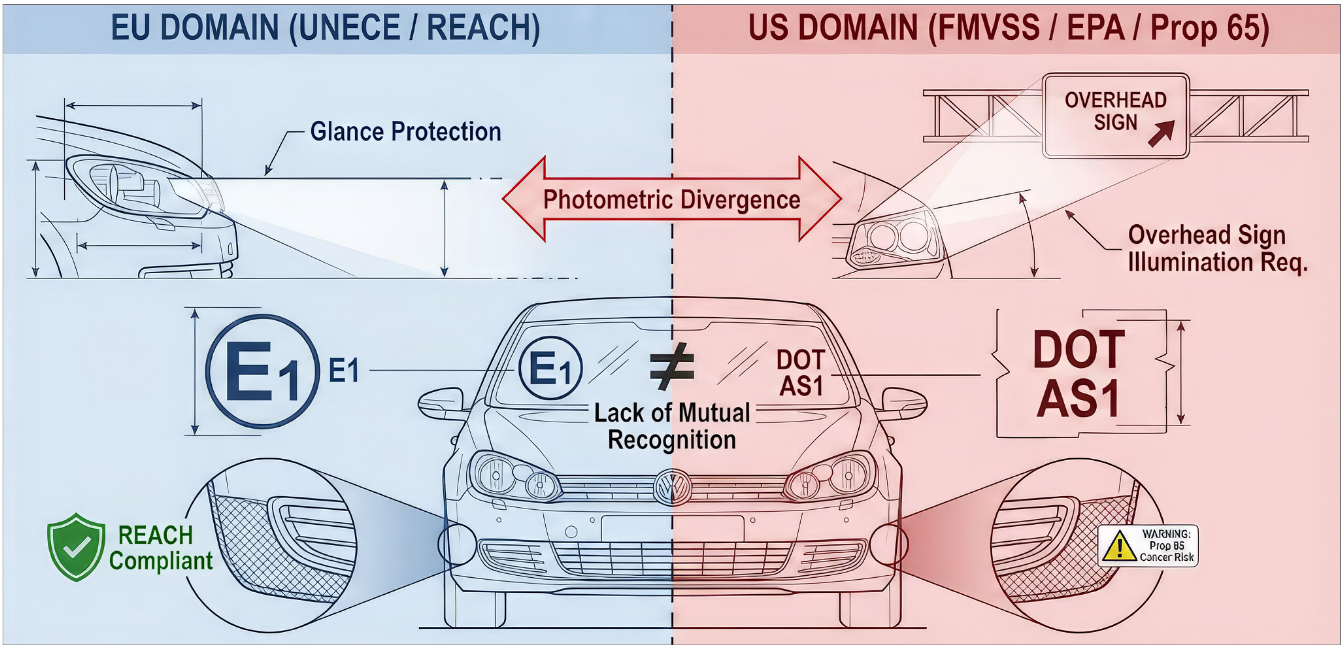

Fig. 2. Schematogram illustrating systemic compliance gaps between EU type approval and US self-certification requirements across photometric, material and marking domains

Source: generative artificial intelligence and prompt were used to create the image

directly with NHTSA. The absence of this specific code, regardless of the component's intrinsic quality or performance, serves as grounds for the immediate confiscation of the shipment, thereby confirming that technical excellence is insufficient without precise adherence to US statutory labeling requirements.

The economic and logistical implications of regulatory divergence on import dynamics, pricing strategies and lead time. The technical incompatibility of standards delineated in the preceding sections inevitably transmutes into quantifiable economic inefficiencies, fundamentally distorting the structure of transatlantic automotive trade. Regulatory divergence operates as a pervasive non-tariff barrier, creating a cost multiplier effect at every node of the supply chain [24].

The primary economic impact strikes the structure of the landed cost. The importer is compelled to factor in also the amortization of re-certification overhead, which serves as an absolute prerequisite for market access. The process of conducting redundant trials in US laboratories to corroborate compliance with FMVSS standards — even when identical European protocols exist, necessitates significant capital investment and temporal resources. These fixed costs are particularly deleterious for small and medium-sized consignments, effectively foreclosing the American market to niche European manufacturers unable to leverage economies of scale to dilute these expenses. Therefore, an oligopolistic market structure emerges, dominated exclusively by large multinational corporations capable of financing dual production standards. Meanwhile, small, medium or nascent enterprises remain marginalized in the shadows, although their quality and potential fully warrant entry into the transatlantic logistics and sales ecosystem.

The logistical dimension of this issue manifests in the destabilization of supply chains and the elongation of lead times. The absence of harmonized digital documentation precipitates substantial customs friction. Any discrepancy in labeling or manufacturer identification codes detected by NHTSA inspectors at the port of entry initiates cargo detention protocols that may persist for weeks. Under the contemporary just-in-time paradigm, such unpredictability compels American distributors to abandon efficient logistics in favor of accumulating excessive safety stock [25]. This defensive strategy immobilizes working capital in inventory and escalates warehousing costs, standing in direct contradiction to the principles of lean manufacturing.

Ultimately, this regulatory burden is transferred to the consumer via the pricing mechanism. The retail price of a European component in the US incorporates a "compliance premium" — a surcharge covering legal liabilities and localization costs. Moreover, the uncertainty regarding delivery timelines forces suppliers to embed additional risk margins, eroding the price competitiveness of high-quality European parts vis-a-vis cheaper, lower-quality alternatives from jurisdictions with more flexible or less monitored standards. Thus, the regulatory gap not only decelerates trade turnover, but also artificially drives inflation within the automotive component sector, diminishing overall market efficiency.

Development of a novel framework for regulatory harmonization.

Table 1

Structural decomposition of regulatory cost multipliers in transatlantic trade

Economic variable	Mechanism of inefficiency	Impact on supply chain + pricing
Certification overhead	Mandatory reiteration of identical technical tests (FMVSS vs. ECE) for market entry	Increases CAPEX requirements. Creates prohibitive entry barriers for SME, fostering an oligopolistic market structure
Inventory management	Disruption of just-in-time flows due to unpredictable customs detention risks (NHTSA holds)	Forces accumulation of excessive safety stock, immobilizing working capital and increasing warehousing OPEX
Liability mitigation	Necessity to insure against strict US liability laws and bounty hunter litigation (Prop 65)	Adds a significant risk premium to the wholesale price. Necessitates expensive legal counsel retention
Time-to-market	Delays caused by bureaucratic rulemaking and non-harmonized digital documentation	Erodes competitive advantage of new technologies and also increases the likelihood of obsolescence before retail sale

To surmount the established barriers and mitigate the consequent economic hemorrhage, a paradigm shift away from archaic, siloed regulatory methodologies is critically required. This section posits a proposed framework designated as the Transatlantic Compliance Protocol. The proposed architecture does not necessitate total legislative unification, a politically unfeasible objective, but rather establishes a mechanism of functional equivalence. The model is predicated on three integrated components: harmonized technical pre-attestation, digital ledger credentialing and conditional mutual recognition.

The first stratum involves the implementation of a harmonized pre-attestation mechanism through the cross-validation of testing facilities. Laboratories already accredited within the EU to conduct testing under UNECE standards should be granted "Trusted technical service" status by the NHTSA. This designation would facilitate the in-situ execution of US-mandated protocols (FMVSS 108 for optical systems) directly within European territories, obviating the need for the physical export of test samples to the United States. As a consequence, test results ratified by an accredited EU laboratory would be recognized by US regulators as legally binding substantiation for self-certification, thereby eliminating the redundancy of duplicative validation by the importer.

Concomitantly, the second tier addresses logistical friction through digital ledger certification. To resolve supply chain bottlenecks, the framework advocates

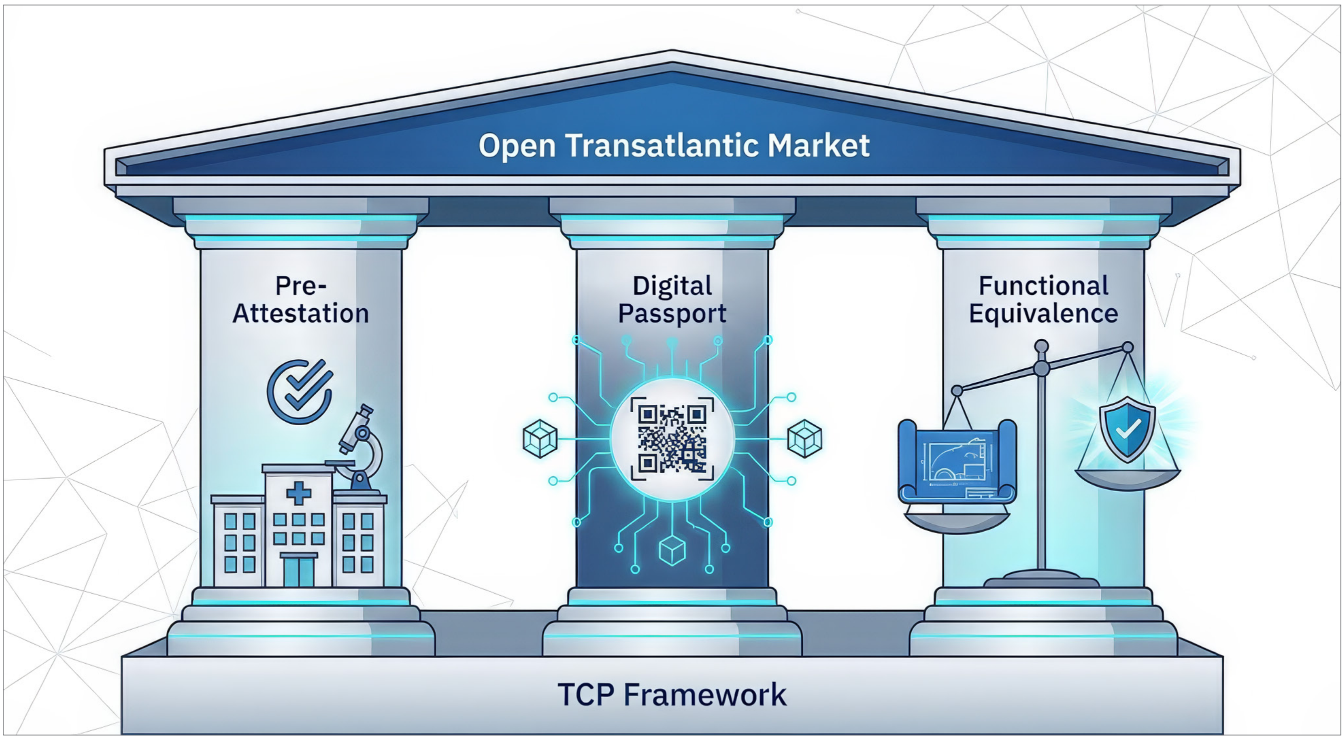

Fig. 3. Schematic representation of the proposed structure of the Transatlantic compliance protocol (TCP)
Source: generative artificial intelligence and prompt were used to create the image

for the abandonment of physical etching and paper-based documentation in favor of a digital product passport. Under this regime, every component batch is tagged with a unique QR code or RFID identifier linked to a secure, immutable blockchain ledger. Upon scanning, a customs officer or DOT inspector gains immediate access to verified test protocols, material declarations (spanning REACH and Proposition 65), and chain-of-custody data. This digitalization ensures absolute supply chain transparency and drastically reduces customs clearance latency from weeks to mere minutes, effectively eradicating the human factor risk, associated with manual label verification.

The third component is the agreement on mutual recognition of functional equivalence. This represents a fundamental transition from geometric prescriptive compliance to functional performance recognition. Rather than demanding identical design specifications, regulators must acknowledge the equivalence of safety outcomes. Specifically, if a European matrix headlight demonstrates road illumination and glare prevention capabilities that exceed the minimum safety thresholds of FMVSS, it must be deemed admissible to the US market via the MRA mechanism, even if it formally deviates from the obsolete geometric prescriptions of the 1970s.

This holistic architecture is engineered to resolve the multipolar crisis — encompassing economic, ecological, logistical and jurisprudential dimensions, ultimately unlocking the market for innovation and reducing the landed cost of technology for the end consumer.

Projected impact on the US domestic market ecosystem. The implementation of the proposed protocol framework precipitates a profound structural reconfiguration of the US automotive component market, extending far beyond the mere simplification of import procedures. The primary and most tangible effect is the exertion of deflationary pressure on retail pricing. The elimination of redundant certification expenditures and the mitigation of logistical risks are projected to reduce the landed cost of European products by approximately 15–20%.

The projected 15–20% cost reduction represents a cumulative estimate derived from three distinct economic vectors. The primary component involves the elimination of redundant certification overhead (3–5%), which encompasses the substantial expenses related to the transatlantic shipment of test samples, US-based laboratory fees and destructive testing protocols — fixed costs that disproportionately erode profit margins for small and medium-sized consignments. Additionally, logistical optimization contributes an additional 5–7% saving. Currently, the unpredictability of customs clearance compels distributors to maintain a safety stock covering two to three months of demand and halving this requirement through regulatory predictability significantly reduces carrying costs, which typically average 20–25% annually relative to the goods' value. Finally, the alleviation of the risk premium offers a potential reduction of 5–8%, as the implementation of the TCP mitigates the need for importers to hedge against recalls and liability litigation, allowing competitive pressure to erode this surcharge and yielding an aggregate conservative lower bound estimate of 15%.

This reduction will effectively dismantle the artificial compliance premium, rendering high-quality European original equipment manufacturer components price-competitive against budget-tier alternatives from the Asian region. The second vector of impact pertains to the democratization of technology and the erosion of oligopolistic barriers. Lowering the market entry threshold will grant access to European small and medium-sized enterprises specializing in niche, high-technology solutions — entities previously precluded from the market by the prohibitive capital requirements of FMVSS certification. This will result in a substantial diversification of supply: the American consumer will gain direct access to advanced active safety systems and environmentally sustainable technologies that were historically obstructed by regulatory gateways.

Finally, harmonization will engender enhanced supply chain resilience. The transition to digital credentialing and mutual recognition will eliminate the variable of delivery unpredictability, enabling American distributors and service centers to revert to efficient inventory management models. In the long term, the integration of standards will serve as a catalyst for the renewal of the national vehicle fleet, accelerating the transition toward carbon neutrality and elevating overall road safety standards through the adoption of proven global innovations without bureaucratic latency.

Conclusion. The comprehensive analysis undertaken herein underscores that the regulatory divergence between the US and EU automotive sectors constitutes an archaic constraint impeding technological advancement and economic efficiency, rooted in the dichotomy of ex-ante verification versus ex-post enforcement. As demonstrated, this bifurcation engenders barriers manifesting as chemical, photometric and administrative compliance gaps, which artificially inflate the landed cost of European components and stifle supply chain agility. The research has quantified the substantial compliance premium driven by the absence of mutual recognition, revealing how current certification protocols function as unintentional drivers of inflation and mechanisms of market exclusion for innovative SME.

The proposed Transatlantic Compliance Protocol demonstrates that contemporary technological instruments, specifically digital product passports and cross-validated pre-attestation are capable of resolving this systemic inefficiency. Consequently, the harmonization of standards is identified herein as a fundamental catalyst for restoring market equilibrium, reducing consumer expenditures and ensuring the unimpeded flow of vital automotive innovations across the Atlantic. By leveraging distributed ledger technologies to ensure transparency and shifting the regulatory paradigm toward functional equivalence, it becomes feasible to harmonize standards without compromising safety or environmental objectives. The implementation of such a framework constitutes a strategic imperative for fostering a sustainable, innovative and cost-effective transatlantic market. Ultimately, the trajectory of the transatlantic aftermarket depends on the willingness of regulators to embrace the principle of functional equivalence. This measure will also accelerate the adoption of critical safety systems and environmentally sustainable technologies, thereby accruing benefit to the ultimate stakeholder — the consumer.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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ПСИХОЛОГІЧНІ НАУКИ

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THE IMPACT OF DANCE MOVEMENT ON PSYCHOLOGICAL RESILIENCE FORMATION AND STRESS REDUCTION

Summary. *Dance movement is a recognized, scientifically based, and non-pharmacological intervention for stress reduction and psychological resilience development. The paper describes the neurophysiological and psycho-emotional pathways through which movement-based practices have an important role in self-regulation, emotional processing as well as adaptive functioning. Relying on recent studies on embodiment, interoception, emotion regulation and somatic therapies, this paper suggests that dance movement promotes the activation and integration of mind-body networks that increase resilience capacity. One important contribution of this study is the introduction of the Heart Crystal Method, an integrative, author-developed framework for somatic regulation, emotional release, embodiment practices, and change at the identity level. This method casts dance movement as a structured intervention that can impact intraindividual- and interindividual-level psychological factors. The results indicated that chronic participation in dance-based practices is associated with significant improvement in stress indicators, emotional regulation, and interoceptive awareness. Additionally, the inclusion of movement in a coaching framework facilitates sustainability of results. Discussion frames these findings in context while suggesting a conceptual expansion of resilience as an embodied, dynamic process. Through the combination of theoretical synthesis and actionable framework on sustained lifestyle changes, the article advances the concepts of health psychology, somatic therapy and wellness coaching.*

Key words: *dance movement, psychological resilience, stress reduction, embodiment, interoception, emotion regulation, somatic practices, dance movement therapy, health coaching, embodied mindfulness, nervous system regulation, identity transformation, Heart Crystal Method, non-pharmacological interventions, mental well-being.*

Introduction. Addressing the issues of stress-related disorders, psychological resilience and more are major requirements in current society, which requires efforts for interventions that are effective, universally available and non-invasive. Conventional methods of coping with stress have typically targeted cognition or pharmacology, but new research highlights the role of embodied strategies in emotion regulation and mental well-being [7; 20].

Dance movement now is considered a multidimensional intervention which encompasses three dimensions; physical, emotional and cognitive, and is increasingly recognised within the paradigm shift. Dance movement serves as an embodied activity that activates neurophysiological systems involved in stress response and self-regulation. Through coordinated movement, rhythm, and expressive action, individuals engage processes associated with interoception, proprioception, and affective processing [6; 2]. These processes contribute to the modulation of autonomic nervous system activity, facilitating a shift from stress-dominant states toward adaptive regulation.

The efficacy of dance movement interventions for psychological well-being is supported on the evidence base. Meta-analyses have shown decreases in depressive and anxiety symptoms, as well as improvements in overall mental health and emotional functioning [8; 9]. Furthermore, using movement practices has also been demonstrated to affect mood, cognitive performance, as well as identity-related processes through embodied involvement [2; 17].

Although movement-based interventions are becoming increasingly recognised, current work often approaches these interventions as standalone therapeutic tools rather than as elements of integrated systems of transformation. So little is known about how dance movement can be applied methodically to create lasting behavioral and psychological change.

In this article, the Heart Crystal Method, a unique integrative framework developed by the author, is proposed in light of this gap. By considering dance movement not only as a therapeutic technique but also as a structured mechanism for facilitating long-term transformation, the method includes stages such as regulation; emotional release; embodiment; and identity reconstruction.

The purpose of this study is to establish the effects of dance movement on stress reduction and resilience development, while also placing it within a broader integrative coaching perspective. Through a composite analysis of past research, and an original design-driven contribution, the article contributes to both theory and application of movement-based interventions in psychological health.

Literature Review

1. Embodiment and Interoception in Psychological Regulation

Embodiment theory proposes that cognitive and emotional processes are intimately tied to bodily experience. Research finds that posture, movement, and physical involvement significantly influence mood and cognitive functioning [2]. Interoception — the perception of internal bodily states — holds significance in emotional awareness and regulation, linking physiological signals with subjective experience [6; 13].

Mindfulness-based somatic frameworks also underscore the value of body awareness in reducing stress and enhancing resilience. This training teaches how to pay more attention to bodily sensations, helping one self-regulate emotional responses [25; 26]

2. Dance Movement as a Therapeutic Intervention

Dance movement therapy (DMT) has been extensively studied as a psychosocial intervention. Meta-analyses indicate its effectiveness at decreasing symptoms of depression, anxiety, and psychological distress [8; 9]. The therapeutic effects are attributed to the integration of movement, emotional expression, and social interaction.

Neurocognitive perspectives highlight that dance engages multiple brain systems, including those responsible for motor control, emotional processing, and social cognition [14]. This multimodal activation supports the development of adaptive coping mechanisms and resilience.

3. Emotion Regulation Mechanisms

Emotion regulation is one of the most important aspects of resilience. Adaptive regulation relates to the ability to manage the emotional response with cognitive and behavioral strategies [7]. Movement practices are part of this process as well, as they act as non-verbal channels for emotional expression and release.

Research of contemplative movement programs identified an increase in emotional regulation by greater awareness of the body and less reactivity [10; 22]]. These results are consistent with the work of trauma-informed practice based on somatic processing as a process of healing [15; 18].

4. Somatic Therapies and Trauma Processing

Somatic therapies concentrate on the body as the primary site of psychological experience. Trauma is embodied and stored in the body based patterns but is also accessible and modified through movement and sensory stimulation [5; 16]. Interventions using both interoception and proprioception have been found to strengthen resilience and lessen distress-related symptoms [12]. These strategies foster internal safety and self-regulation capacities.

5. Movement, Music, and Emotional Expression

Movement and music share structural features that are conducive to emotional expression and communication [21; 24]]. Dance is the perfect way to make use of those features and becomes an expressive medium and means to achieve and change emotional states. Research in the context of music and movement indicates that synchronous movement encourages emotional connection, motivation and the engagement of participation [23]. These elements are why dance is so helpful in promoting resilience.

6. Motivation and Behavioral Change

For behavioral change to last, it needs to come from within and be in line with who you are. Self-determination theory stresses the importance of autonomy, competence, and relatedness in boosting motivation [19]. Dance movement fulfills these needs by offering a self-directed, expressive, and socially interactive activity. Identity-based motivation theory posits that individuals are predisposed to engage in behaviors congruent with their self-concept [17]. Movement-based practices can promote identity transformation by facilitating embodied experiences of novel behavioral patterns.

7. Health Coaching and Integrated Approaches

Health coaching has been proved to result in long-lasting improvements in lifestyle behaviours and well-being [1; 11]. The incorporation of movement-based methods within coaching programs increases their impact on both cognitive and somatic aspects. Exploratory research suggests that interventions in which body-based practices are provided as a part of coaching practice are more likely to trigger deeper and long-lasting shifts [3]. This also underlies the need for integrative models integrating multiple modalities.

8. Research Gap

Although a body of literature has shown that dance movement and somatic practice work well, there is little that offers an integrative framework, either in

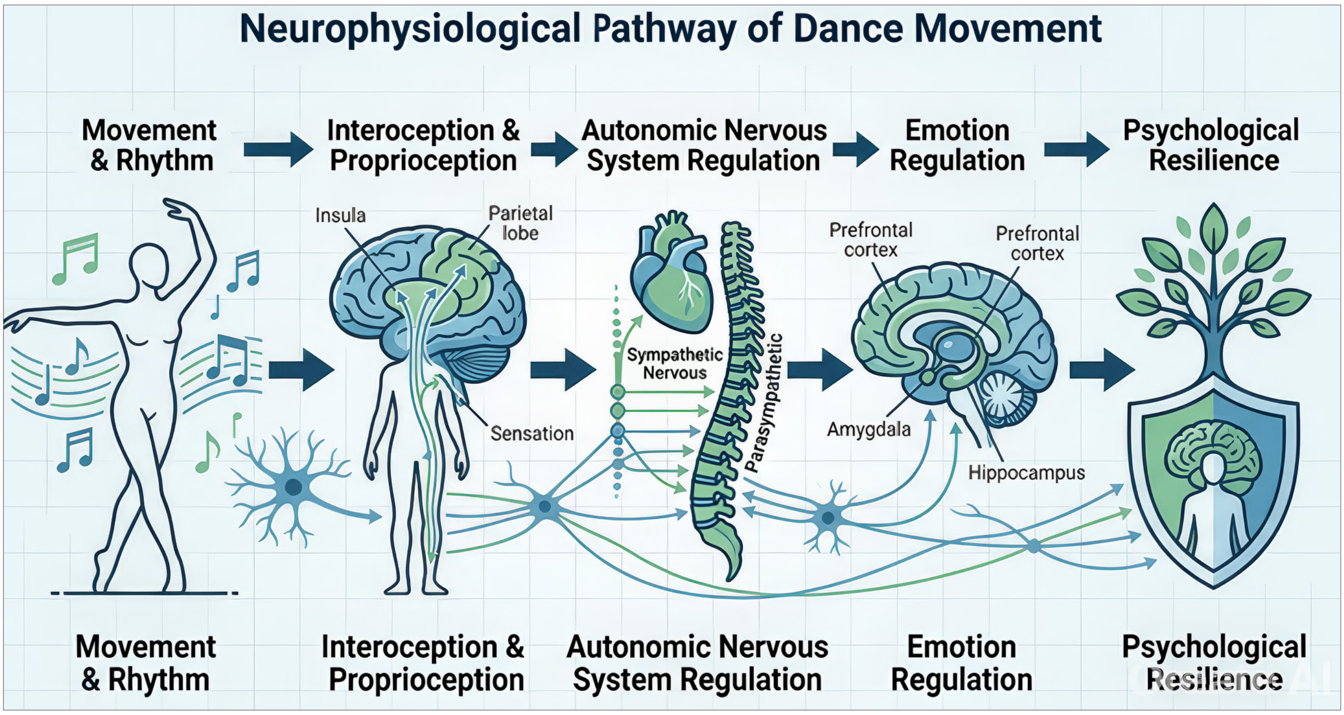

Fig. 1. Neurophysiological Mechanism of Dance Movement

terms of principles or in the way of organization, that can be implemented across multiple disciplines for long-term transformation. Studies currently available address short-term results only, without considering sustainability or identity-level change (See Fig. 1). This gap highlights the need for integrative methodologies that combine embodiment, emotional processing, and behavioral change mechanisms within a structured framework.

Methodology. This study takes a conceptual-analytical approach integrating extant empirical studies with the author-created framework, the Heart Crystal Method. It builds a framework between literature synthesis and theoretical framework construction to explore the impact of dance movement on stress reduction and mental resilience. The Heart Crystal Method is an iterative transformational process consisting of four major steps:

Nervous System Regulation — establishing safety of body through somatic awareness, grounding skills.

Emotional Release — to help move away from a sense of emotion of stored emotions: letting go of the heart and to process stored emotions through movement.

Embodiment Integration — integration of the brain and body organs and minds — the practice of interoceptive stimulation and inter-awareness.

Identity Reconstruction — reinforcing new habits of behaviour and emotions as it is enacted through physical behavior through repetition of embodied experience.

Table 1

Summary of Literature on Dance Movement and Psychological Outcomes

Study	Intervention Type	Key Mechanism	Outcome
Karkou et al. (2019)	Dance Movement Therapy	Emotional expression	Reduced depression symptoms
Koch et al. (2019)	Dance & Movement	Mind-body integration	Improved psychological health
Millman et al. (2021)	Neurocognitive DMT	Brain-body interaction	Enhanced emotional processing
Lee et al. (2021)	Contemplative Movement	Regulation practices	Improved emotion regulation
Spaccapanico Proietti et al. (2024)	Mindful movement	Interoception	Reduced stress
Zafeiroudi et al. (2025)	Dance-based interventions	Embodied awareness	Improved well-being
Awad et al. (2021)	Posture & embodiment	Cognitive-emotional link	Improved mood
Gibson (2019)	Interoception	Body awareness	Emotional regulation
Todd & Aspell (2022)	Mindfulness + body	Sensory awareness	Stress reduction
Weber (2022)	Somatic mindfulness	Embodiment	Psychological resilience

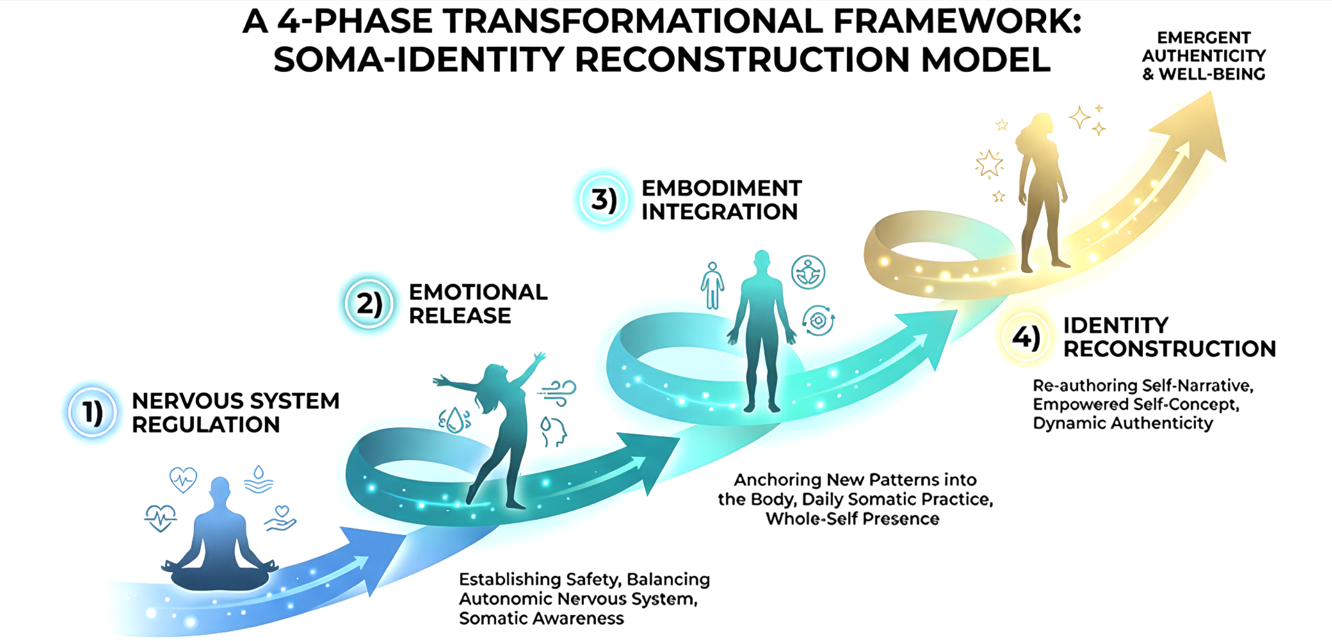

Fig. 2. Heart Crystal Method

At the same time, dance movement is presented as the key tool in different stages, which activates neurophysiological processes related to self-regulation and resilience. The models integrate aspects of embodiment, emotion processing, and identity-based motivation to make sense of the mechanisms that mediate performance. We are also mindful of the effects of intraindividual and interindividual dynamics which concur with contemporary models of psychology that call for a combination of both levels of analysis (See Fig. 2) [4].

Data interpretation is undertaken via cross-study contrast of outcomes attributed to movement-based interventions, focusing specifically on stress reduction, emotional regulation, and resilience measures (See Table 2). The approach also draws on principles of health coaching, to evaluate the feasibility of the results.

Findings. The analysis suggests that dance movement has a bearing on both physiological and psychological aspects of stress and resilience. Consistently across studies, evidence also appears that stress-related symptoms are reduced, as well as improvements in emotional regulation.

First of all dance movement facilitates autonomic nervous system regulation allowing for a state of equanimity when you are in the midst of stress. Movement practices focus on body awareness and interoception, essential skills for identifying and directing stress responses [6; 25].

Dance is also an effective medium to process and release emotions. People who participated in movement-oriented interventions stated that they are more emotionally transparent and suppressed less emotional states — thus promoting greater psychological well-being [9; 10].

The evidence also suggests that embodied practices contribute to resilience formation via adaptation and coping. Movement-based interventions increase flexibility of emotional reactions and assist the development of internal resources [22; 27].

Fourthly, a coaching-integrated framework significantly enhances the sustainability of the outcome. Evidence from health coaching shows that a combination of behaviourally based coaching and somatic interventions yields long-lasting well-being gains [1; 3].

Finally, the Heart Crystal Method approach suggests that integrating movement into transformation phases, as outlined, will have the desired impact. The staged method guarantees that physiological

Table 2

Heart Crystal Method: Phases, Mechanisms, and Outcomes

Phase	Core Focus	Mechanism	Expected Outcome
Nervous System Regulation	Safety & stabilization	Somatic grounding, breathwork	Reduced physiological stress
Emotional Release	Expression of stored emotions	Movement-based release	Emotional unloading
Embodiment Integration	Body awareness	Interoception, proprioception	Improved self-regulation
Identity Reconstruction	Behavioral transformation	Repetition & embodiment	sustained change

Table 3

Observed Effects of Dance Movement on Stress and Resilience

Dimension	Mechanism Activated	Observed Effect
Physiological	Autonomic regulation	Reduced stress response
Emotional	Expression & release	Lower emotional suppression
Cognitive	Attention & awareness	Improved clarity
Behavioral	Movement repetition	Adaptive coping patterns
Identity	Embodied experience	Strengthened resilience

regulation comes before emotional processing, and that stabilizes identity-level change (See Table 3).

Discussion. The findings of this study support the view that dance movement is a multidimensional intervention that activates neurophysiological, emotional, and cognitive systems simultaneously. And it's well-trod: previous research has been showing the interrelatedness of mind and body during psychological regulation [14; 20]. That the current analysis reinforces this understanding in the exploration of dance movement allows me to situate the movement within this structured integrative framework better able, within its scope, to enhance effectiveness and sustainability.

This paper addresses an important issue by introducing the notion of resilience as an embodied process as opposed to a cognitive or behavioural concept solely. Conventional perspectives of resilience tend to prioritize psychological factors or coping strategies to the detriment of physiological regulation. We propose here that resilience is an interplay between bodily phenomena and emotional experiences based on movement and interoceptive perception [12; 18].

The Heart Crystal Method offers a structured framework for putting this idea into practice. The arrangement of transformation through its stages allows the process to ensure that some basic physiological regulation is accomplished before moving into deeper emotional processing. This is a big limitation in many therapeutic methods where processing emotion early can result in dysregulation, not healing.

In addition, the inclusion of dance movement in each of the stages improves accessibility and effectiveness of the intervention by the inclusion of dance movement in each step. Movement is an accepted language that transcends resistance that can get past the cognitive resistance and enable the treatment of feelings into engagement with emotional states. This is especially applicable in trauma-informed environments, where verbal processing could be poor or even counterproductive [15; 16].

The importance of interoception is especially important in this process. Awareness of physiological sensations allows to sense the early signs of psychological distress for the adaptive response to overcome it. Such evidence is in keeping with previous literature showing the critical role of interoceptive awareness in the modulation of emotion and mental health [6; 13].

Another key idea is the relationship between movement and identity change. Sustained behavioral change is supported by identity-based motivation

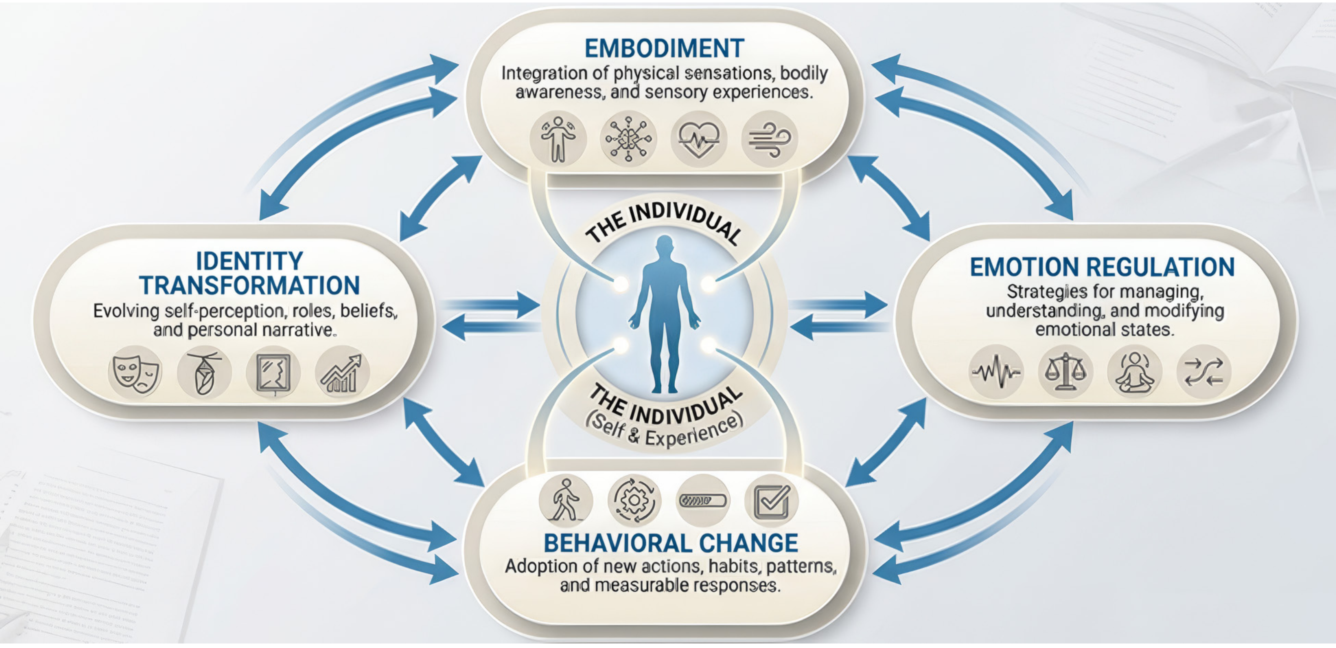

Fig. 3. Integrated Model: Movement, Identity, and Resilience

theory [17], which holds that a person needs to be congruent between their self and their behavior [17]. Dance helps bridge the gap by engaging a new pattern of movement through experiential situations, allowing movement to become a new avatar for behaviour as well as for emotion. These embodied experiences over time help to create an identity marked by resilience and self-regulation.

The incorporation of principles related to health coaching increases the practicalization of the process. Coaching provides structure, accountability and goals to help the move in meaningful ways by transferring movement-based experiences into lasting behaviour change [1; 11]. This combination counteracts the more common tendency to sustain intervention effects beyond initial engagement.

However, the study is also concerned with limitations of the existing literature. Most of the studies available in this area are short-term interventions with no longitudinal analysis of sustainability. Furthermore there's a need for more consistent tools of measurement for evaluating movement-based practices' effect on resilience.

Further studies should address the long-term effects of integrative frameworks such as Heart Crystal Method and how well they apply in all population segments. These research questions could be answered better by quantitatively measuring physiological and psychological measurements to further establish the evidence of this type of effect beyond treatment.

Conclusions. This article shows that dance movement is a rational and evidence-based, non-chemical alternative for the reduction of stress and an enhancement of psychological resilience. Movement-based practices promote self-regulation, emotional processing and adaptive functioning, by activating neurophysiological and psycho-emotional processes.

A new integrative framework with the Heart Crystal Method serves to systematically systematize dance movement use in the phases of transformation. The technique integrates somatic regulation, emotional release, embodiment, and identity reconstruction to cater to both immediate and long-term psychological well-being.

The results underscore the significance of embodied modalities in mental health interventions, and the necessity for holistic models linking cognitive, emotional, and physiological domains of intervention. In addition, the infusion of movement into coaching frameworks promotes durability of results, rendering it very pertinent in terms of lifestyle change.

This study, moreover, extends the development of health psychology and somatic therapy by providing theoretical information and practical application. Dance represents a therapeutic modality, an avenue for resilience, a basic mechanism that may be used to build resilience on in the current day

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

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КОНФЛІКТ ІНТЕРЕСІВ: Автори заявляють про відсутність конфлікту інтересів.

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MODELING OF HEAT TRANSFER PROCESSES DURING THE FORMATION OF PROTECTIVE COATINGS

Summary. *This paper presents the fundamental principles of mathematical modeling of heat transfer during coating formation using thermal spraying. The main attention is paid to the thermal state of layered heterogeneous systems "coating as a whole – base".*

Key words: *layered heterogeneous systems, thermal spraying, "multilayer coating-sublayer-base", mathematical modeling, high-temperature zone, heat transfer*

Introduction. Problems of creating new and improving existing thermal spraying technologies necessitate an in-depth study of the thermal phenomena observed during the implementation of these technological processes [1–9]. This paper focuses on mathematical modeling of the thermal phenomena under study, since in this physical situation, where the specific nature of the processes under study encompasses both the localization of the high-temperature zone and high velocitys of temperature change, the relatively small sizes of the melt particles and the coating as a whole make it very difficult to obtain the required information using only full-scale experiments.

This paper examines thermal processes in layered, heterogeneous coating-substrate systems. Particular attention is paid to the thermal phenomena observed during the formation of the coating as a whole during high-velocity machining. Some average temperatures in the coating-substrate system are considered; elementary interactions between individual particles and the solid surface are not considered in the mathematical modeling.

The main publications related to the study of the thermal state of the "coating as a whole — base" system, depending on the conditions adopted in modeling for the coating itself, can be divided into the following three cases. The first was characterized by a monotonic increase in the coating thickness δ over time, the second by a discrete growth of δ, and the third by the assumption that the thermal resistance of the coating itself can be neglected. In the first case, the mathematical model of the heat conduction process is formulated in the approximation of L. S. Leibenson [4]. Accordingly, the spraying process is assumed to be quasi-stationary, the average mass flux density from the sprayer is considered constant over the surface of the base and the coating thickness will increase at a constant velocity V, the temperature profile in the coating is assumed to be linear and, accordingly, the heat flux supplied to the coating is assumed to be entirely spent on heating the base. Mathematical models with the specified assumptions are one-dimensional.

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In the second case, a three-dimensional non-stationary heat conduction problem is formulated for a multilayer plate. The following assumptions are fundamental. The heat supply source is assumed to move at a constant velocity *V*, corresponding to the motion of the plasma torch. It is assumed that in the heating spot itself, the heat flux density distribution obeys the Gaussian law. The increase in coating thickness after one plasma torch pass is not taken into account. The problem is formulated in a linear formulation, and all bounding surfaces of the multilayer system are assumed to be adiabatic, excluding the heat supply surface. In the third case, the thermal resistance of the coating was not taken into account in the mathematical modeling, because it is comparatively small.

The mathematical models for each of these three cases have shortcomings. In the first case, they are one-dimensional, significantly limiting the ability to describe the actual physical situation of spraying. Models for the second case are more general. In the third case, the model is a special case, since the thermal resistance of the sprayed layer is not taken into account. Therefore, the development of research based on mathematical models describing the second case is most important.

Based on the analysis of the models presented in the review for various cases, it can be concluded that particular attention should be paid to the development of research on an approach to analyzing the thermal state of layered, heterogeneous "coating as a whole — substrate" systems. The primary focus is on studying the most important principles of the heat transfer process under consideration, as applied to the spraying conditions of two classes of thermal spray coatings: metal-polymer coatings and composite coatings containing graphite.

In both situations, the quasi-stationary heat transfer process during the formation of multilayer coatings is investigated. A layered, heterogeneous system is present, consisting of a base 1 with a pre-applied sublayer 2 and a sprayed multilayer coating 3 (Fig. 1). The heat source moves along the upper surface of the system under study along the z-axis in the positive direction at a constant velocity *V* in accordance with the movement of the gas torch or plasma torch. Regarding the coating itself, the mathematical modeling assumes that the coating thickness increases with the application of each subsequent coating layer. Heat exchange between all bounding surfaces (except for the *XOZ* surface) and the surrounding medium occurs according to Newton's law, which is a boundary condition of the third kind. The heat transfer coefficients and the ambient temperature are assumed to be constant. Since the system under study has thermal and geometric symmetry with respect to the *YOZ* plane, only half of it is considered in the mathematical modeling.

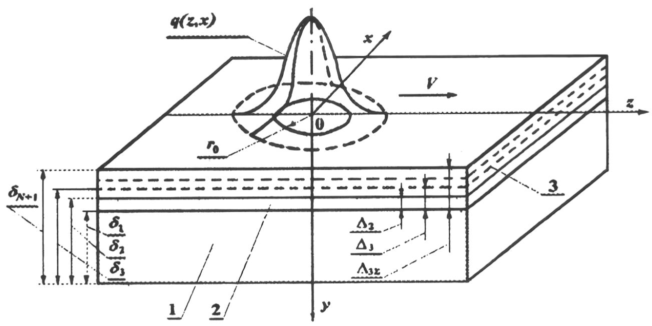

Fig. 1. To the formulation of the heat transfer problem for a layered inhomogeneous system: 1 — base; 2 — sublayer; 3 — multilayer coating

The mathematical formulation of a nonlinear quasi-stationary three-dimensional heat transfer problem for a layered-heterogeneous system "multilayer coating-sublayer-base" in a moving coordinate system, which is associated with an energy source, looks like this:

$$\frac{\partial}{\partial x}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial x}\right]+\frac{\partial}{\partial y}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial y}\right]+\frac{\partial}{\partial z}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}\right]-$$

$$-P_e\cdot C_V(y,\theta)\frac{\partial\theta}{\partial z}=0,$$

$$0<x<x_1,\ -\infty<z<+\infty,$$

$$0<y<y_1,\quad y_1(n)=\begin{cases}\delta_2 & npu\ n=0,\\ \delta_3 & npu\ n=1,\\ \ldots & \\ \delta_{N+2} & npu\ n=N,\end{cases}$$

$$\Lambda(y,\theta)\frac{\partial\theta}{\partial x}\bigg|_{x=0}=0$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial x}+Bi_{x_1}\theta\right]_{x=x_1}=0$$

$$\left[\Lambda_i(\theta)\frac{\partial\theta}{\partial y}+Bi_{y_0}\theta\right]_{y=0}=-\exp\left[-\left(x^2+z^2\right)\right],$$

$i=2$ при $n=0$; $i=3$ при $n=1,2,\ldots\ldots,N$,

$$\left[\Lambda_1(\theta)\frac{\partial\theta}{\partial y}+Bi_{y_1}\theta\right]_{y=y_1}=0,$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}-Bi_{z_0}\theta\right]_{z=-\infty}=0,$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}+Bi_{z_1}\theta\right]_{z=+\infty}=0,$$

$$\lambda(y,\theta)=\begin{cases}\Lambda_1\ \ npu\ \left(y_1-\delta_1\right)<y\le y_1\\ \Lambda_2\ \ npu\ \left(y_1-\delta_2\right)<y\le\left(y_1-\delta_1\right)\\ \Lambda_3\ \ npu\ 0\le y\le\left(y_1-\delta_2\right)\end{cases}$$

$$C_V(y,\theta)=\begin{cases}C_{V_1}\ \ npu\ \left(y_1-\delta_1\right)<y\le y_1\\ C_{V_2}\ \ npu\ \left(y_1-\delta_2\right)<y\le\left(y_1-\delta_1\right)\\ C_V\ \ npu\ 0\le y\le\left(y_1-\delta_2\right)\end{cases}$$

where $\theta=\left(t-t_c\right)\cdot\lambda_0/\left(q_{\max}\cdot r_0\right)$;

$P_e = V \cdot r_0/a_0$;
$Bi_{x1} = \alpha_{x1} \cdot r_0/\lambda_0$; $Bi_{y1} = \alpha_{y1} \cdot r_0/\lambda_0$; $Bi_{z0} = \alpha_{z0} \cdot r_0/\lambda_0$;
$Bi_{z1} = \alpha_{z1} \cdot r_0/\lambda_0$; $x = x_p/r_0$; $y = y_p/r_0$; $z = z_p/r_0$;
$\delta_1 = \delta_{p1}/r_0$; $\delta_2 = \delta_{p2}/r_0$; $\delta_3 = \delta_{p3}/r_0$; $\delta_{N+2} = \delta_{pN+2}/r_0$;
$\Lambda = \lambda/\lambda_0$; $C_V = c_v/c_{v0}$; $a_0 = \lambda_0/c_{v0}$;

n is the number of the sprayed coating layer;
N is the total number of sprayed coating layers;
δ_{p1} is the base thickness;
δ_{p2} is the total thickness of the base and the pre-applied sublayer;
δ_{p3} is the total thickness of the base, the pre-applied sublayer and one coating layer;
δ_{N+2} is the total thickness of the base, sublayer and N coating layers;
q_{max} is the maximum value of the heat transfer diagram;
t_c is the ambient temperature;
a_0 is the thermal diffusivity coefficient, α_{x1}, α_{x2}, α_{x3}, α_{x4} are the heat transfer coefficients on the corresponding surfaces;
r_0 is the heat spot radius;
λ_0 and c_v are fixed values of the thermal conductivity coefficient and specific heat capacity of the base material, respectively;
indices 1, 2 and 3 at the values of Λ and C_V relate the latter to the base, sublayer and coating, respectively.

To solve the problem, the integral method of complete polyargument systems was used [5; 6].

Composite clad powders containing solid lubricants are increasingly used to produce antifriction coatings using various thermal spraying methods. Composites with graphite as the primary particle, or core, are widely used in spraying. This graphite particle is coated with a metal shell, which protects the core from the harmful chemical effects of the environment. Heating the shell to the melting point ensures the core is welded to the base surface. Coatings made from composite powders of this composition are used in friction units operating without lubrication and under boundary friction conditions. Such coatings are used as bearing surfaces for plain bearings, in gas turbine engines for abradable stator coatings, in vane compressors, in ring pump seals, and in specialized military equipment. Therefore, the development and improvement of coating technology necessitates further research into the thermal phenomena observed in these situations. Of considerable interest are the data from mathematical modeling of heat transfer processes during the formation of coatings from clad composite powders containing graphite. These data represent the results of numerical studies examining the key factors influencing the thermal state of the objects under consideration, including spraying distance, the power of the supplied two-phase flow, the plasma torch rate, the cooling conditions of the free surfaces of the system, the preliminary application of sublayers, and other factors.

The main results of the analysis of the peculiarities of changes in the thermal state of the studied layered inhomogeneous system "coating-sublayer-base". The obtained data of the performed computational experiments correspond to the following values of the initial parameters of the system:

$x_1 = 2.56$; $\delta_1 = 0.34$;

sublayer thickness $\Delta_2 = 0.0085$ ($\Delta_2 = \delta_2 - \delta_1$);
thickness of a single coating layer $\Delta_3 = 0.00425$ ($\Delta_3 = \delta_3 - \delta_2$);
$Pe = 129.6$; $Bi_{x1} = Bi_{y1} = Bi_{zo} = Bi_{z1} = 5.96 \cdot 10^{-3}$;
from here on, steel 20 was considered as the base material, sublayer — Ni, coating — clad powder (graphite) — (Cu) with a volume content of components of 30% and 70%, respectively.

To better understand the influence of a pre-applied Ni layer and subsequent layers of composite powder on heat transfer, it is advisable to compare the obtained data with the results obtained for a separate steel substrate. The conducted studies have shown that the temperature fields in comparable objects are qualitatively similar, but can differ significantly quantitatively.

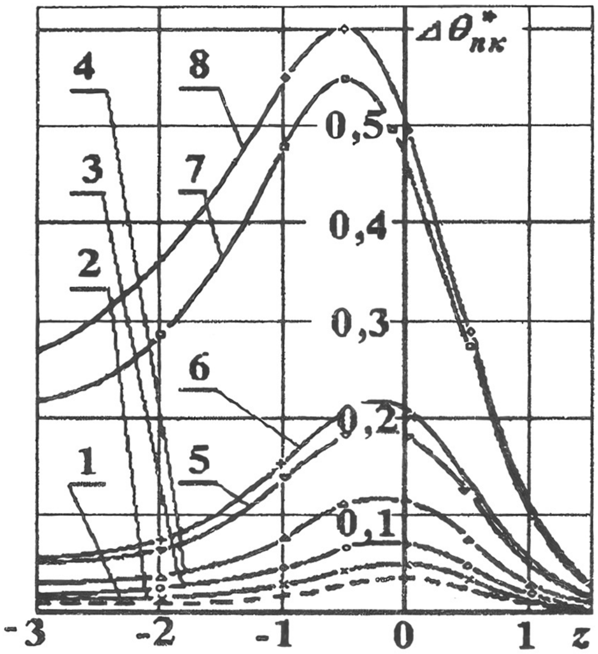

Fig. 2 Dependence $\Delta\theta^*_c = f(z)$ — for $x = 0$, $y = 0$ for systems: 1 — "steel base — Ni sublayer"; 2–7 — "coating-sublayer-base" with the number of coating layers of 1, 2, 4, 8, 9 and 60, respectively; 8 — separate base made of composite material (Cu)- (graphite)

The differences in the compared temperature fields show that the temperature levels of the coated part in the high-temperature zone are lower than the corresponding levels of a separate steel base, and the quantitative difference in the compared temperatures significantly depends on the number of coating layers N. The patterns of change in the value of $\Delta\theta^*_c$ ($\Delta\theta^*_c = \Delta\theta_c/\theta_{max}$,

$\Delta\theta_c = \theta_{st} - \theta_{csb}$, θ_{st} is the dimensionless temperature of a separate steel base, θ_{csb} is the temperature of the coating-sublayer-base system, θ_{max} is the maximum temperature of a separate steel base) are shown in Fig. 2. In the high-temperature zone, the effect of temperature reduction in the coating-sublayer-base system compared to a separate steel base is more rapid, the greater the coating thickness. On the heat supply surface *XOZ*, the largest differences $\Delta\theta^*_c$ of temperatures that are compared are 0.00492 for a coating thickness of 0.00425 (one coating layer) and 0.214 for a coating thickness of 0.03825 (nine coating layers), lines 2 and 6.

The thermal state of an individual steel base differs significantly from the thermal state of the multilayer system under consideration in the general case. Moreover, in cases where the coating thickness Δ_{3c} is small, the temperature discrepancies between the multilayer system and the individual steel base are relatively small. This is due to the fact that the base plays a major role in the heat transfer process under study. At sufficiently large coating thicknesses Δ_{3c}, its role in determining the system's temperature regime is significant, and accordingly, the temperature discrepancies between the individual base and the system increase.

Conclusions. The presented research results demonstrate the validity of using single-layer mathematical models for approximate estimates of the thermal state of a multilayer system for two limiting cases. The first case is for conditions where the coating thickness Δ_{3c} is relatively small, while the second case is for conditions where it is quite large. In the first case, only an isolated steel base was considered. The presence of the coating was ignored due to the coating's very low thermal resistance in the y-axis direction. In the second case, only the isolated coating was considered. In this case, the existence of the base was either completely ignored, or its thermophysical properties were used for the coating. At sufficiently large coating thicknesses, a regional influence of the base on heat transfer in the high-temperature zone of the multilayer coating was observed. This justifies the implementation of the aforementioned substitutions for the uniqueness conditions.

ДОДАТКОВА ІНФОРМАЦІЯ

ВНЕСОК АВТОРІВ: Усі автори зробили внесок порівну.
ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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КОНФЛІКТ ІНТЕРЕСІВ: Автори заявляють про відсутність конфлікту інтересів.

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PORTABLE ADAS CALIBRATION ZONE ASSESSMENT DEVICE: DESIGN, MEASUREMENT METHODOLOGY AND SERVICE APPLICATION

Summary. *Calibration accuracy for Advanced Driver Assistance Systems (ADAS) is a safety-critical process whose outcome is determined by aspects ranging not only from calibration equipment and technician proficiency levels, but also the physical properties of the workspace: the floor levelness, ambient illumination, and the absence of glare sources. Although the increasing number of ADAS calibrations carried out in service workshops and in mobile settings, there is no standardized portable instrument for the rapid pre-calibration audit of those environmental parameters. In this paper, the design, operating principle of the portable ADAS calibration zone assessment device, and its service application are discussed. The proposed instrument includes a high-precision inclinometer mounted on a three-point disc plate for floor slope measurement at nine spatially distributed reference points, a lux-meter mounted on a height-adjustable carriage for illumination measurement at the calibration target plane, and an optional narrow-field tube attachment for directed glare assessment. A microcontroller-based computing unit with an embedded display collects sensor input, compares the readings with OEM-defined thresholds, and provides a structured environment passport. It addresses a well-established gap between full calibration stations and manual ad-hoc checks; significantly decreases calibration failures attributable to environmental non-conformance; and works in fixed workshop and mobile (roadside) service scenarios. Reference performance thresholds, measurement workflow, and representative service implications are discussed.*

Key words: *ADAS calibration, floor levelness, illumination measurement, glare assessment, inclinometer, lux-meter, calibration zone audit, portable instrument, service workshop, environment passport.*

Introduction. Over the last year, Advanced Driver Assistance Systems (ADAS) have become standard equipment across a wide range of new passenger and light commercial vehicles, including forward-collision warning, automatic emergency braking (AEB), lane-keeping assistance, adaptive cruise control, and surround-view monitoring [7; 12].

The working performance of these systems relies on the right synchronization and calibration of cameras, radar transceivers, ultrasonic sensors, and LiDAR units for their alignment among the vehicle coordinate frame and among themselves. Miscalibration, even at sub-milliradian scale, can lead to systematic errors in object detection, range estimation, and lane boundary projection that can reduce the safety performance of these systems [4; 8].

However, the burgeoning fleet of ADAS-equipped vehicles generates a demand for calibration services across the aftermarket and dealership arena [1; 14]. Calibration is carried out in fixed service bays, but increasingly in mobile locations — roadside, at bodyshop partners, and at fleet depots.

In all deployment contexts, the OEM calibration protocol specifies environmental prerequisites to be met before the calibration sequence begins. These prerequisites consistently address three physical parameters: (1) floor levelness, represented as the max allowable slope in degrees or millimetres per metre of a vehicle footprint; (2) ambient illumination (minimum and maximum lux levels at the calibration target plane); and (3) absence of glare or intense localised light sources which can saturate camera sensors or displace target feature detection [9; 16].

In present workshop practice, ambient compliance is usually checked informally — and often by sight, or at a single moment, or not at all. This results in a well-documented set of calibration failures and unstable calibration results that are traceable not to equipment failure, but to environmental nonacceptance.

A 0.3° slope in one wheel position versus another is not noticeable to the eye but crosses the ±0.2° line stipulated by some OEMs when calibrating static cameras. Likewise, lighting that seems adequate on a subjective measure may fall below the 500 lux threshold needed for reliable target pattern detection, or suffer from a glare source in the sensor field of view that the technician cannot view from the technician's line of sight [6].

Current calibration stations, like the Autel IA700, offer inclinometers and optical compensation approaches that partially tackle floor non-conformity, but they are full calibration systems: not portable audit instruments. They only measure floor conditions at the instrument's own footprint, they do not map the vehicle footprint zone into a grid, and they do not include illumination measurement as a defined compliance parameter. Also, their size and logistical needs do not allow a pre-visit assessment tool that could be used in mobile service sites [16].

The current paper fills this void by outlining the design, measurement methodology, and service application of a portable ADAS calibration zone assessment device — a tripod-mounted sensor-integrated measuring device providing a mapping/characterisation of floor levelness, illumination at target height, and glare risk in a defined calibration zone and a formal compliance report output.

The device can be carried in the standard technician vehicle, configured in less than five minutes, and run independently from any specialized metrology knowledge. It is used in fixed and mobile service and produces repeated records of environmental condition — referred to as an environment passport — which can be used as evidence of calibration precondition compliance.

Background and Related Work

1. Environmental Prerequisites for ADAS Calibration

The sensitivity of ADAS sensors based on cameras to illumination is already well established. Li et al. (2023) which compared pedestrian detection performance to the standardised test environment showed quantifiable loss of sensitivity under low-light conditions where ambient illumination dropped below 300 lux, with AEB activation distance reduced by up to 18%.

Because sensor performance is light dependent, the IIHS AEB test protocols [7] require controlled lighting conditions. For a service calibration routine, the low-light requirement does not preclude the calibration process yet leads to calibration settings optimized for an artificially dim environment, which results in deterioration of real-world performance by using lower illumination levels of calibration settings.

The flat floor level affects the geometric properties of static camera calibration directly. Finally, the relative values of camera mounting angles, vehicle pitching at the calibration point and how angle of the calibration target in the camera field of sight are related: the slope of the floor of the car of θ° will generate an effective camera pitch error of θ° that is indistinguishable, from the standpoint of the calibration algorithm, from a physical camera miscalibration point of view.

Typical OEM calibration texts define ideal floor slope values of 0.1° — 0.5°, depending on sensor type and the accuracy of the calibration process [6; 16].

A third risk factor in the environmental range is glare from windows, overhead luminaires, as well as specular surfaces in the workshop. Wide-angle surround-view cameras (such as the ones used in the Intelligent Around View Monitor (I-AVM) systems of existing vehicles) are especially prone to this, because their wide field of view inevitably captures relatively more of the ambient environment.

A glare source at much higher luminance than target pattern saturates image regions, displaces the computed centroid of target features, and terminates calibration routines with a false error flag or, worse, an incorrect parameter set [2; 3].

2. Existing Instrumentation and its Limitations

The systematic calibration of multi-sensor ADAS systems with LiDAR-camera and radar–camera pairings has been widely investigated over the last few years [10; 15; 19; 20]. However, this work is primarily centred around the calibration algorithms themselves — targetless techniques or deep-learning-based ones or track-to-track associations — and not on the environmental conditions under which those algorithms perform accurately.

Inclinometers and floor-compensation algorithms are built into commercial calibration systems like the Autel IA700. The IA700 employs six HD cameras and a motorised crossbar to calibrate with in-the-moment floor compensation. Though, this system takes floor tilts in only at the instrument site, not on the vehicle's entire footprint. Illumination is not used as a compliance parameter.

Its size requires transportation in a large vehicle, precluding use as a pre-visit audit tool at mobile locations. Other commercial systems (Hella GUTMANN, Bosch DAS 3000) have similar limitations: they are calibration systems with incidental environmental sensing, and not environmental assessment instruments.

Lux-meters and bubble levels, available as separate tools, are completely ad hoc as an ADAS calibration audit methodology. One point measurements do not represent the vehicle footprint zone. There is a lack of a common nine-point grid protocol and a pre-defined threshold comparison method with no structured format of output.

Since no specific portable audit instrument has been developed, the process of environmental compliance verification before calibration has had no objective repeatable way for workshop operators to evaluate compliance.

3. Reference Platforms and Sensor Technologies

Rövid et al. (2025) present a reference platform for ADAS camera system evaluation that illustrates the significance of carefully managed and detailed test environments in producing reliable calibration results [16]. Their contribution supports the view that the measurement environment is itself a variable that must be quantified and controlled. Ding et al. (2024) propose a machine-vision-based approach to vehicle coordinate system reconstruction in end-of-line ADAS calibration, which necessitates a thorough understanding of vehicle position and floor geometry — a requirement that presupposes floor levelness assessment [6].

High-precision inclinometers for floor levelness measurement in the required range of 0–2° with resolution ±0.01° are commercially available, such as the Jewell DXI-100/200 series, which offers an electrical output signal proportional to tilt angle and can be integrated into a portable computing platform. Lux-meters with digital output interfaces — like the Seeed Studio S-Light-02 — offer illumination measurement in the range appropriate for ADAS calibration (100–10,000 lux) with sufficient accuracy to make threshold comparisons. The availability of these sensor components, combined with low-power microcontroller platforms, establishes the technical feasibility of the proposed device.

Device Design and Component Description

1. Overall Architecture

The portable ADAS calibration zone assessment device (hereinafter: the device) is a tripod mounted instrument consisting of five main functional elements: a vertical mast (1) with a height-adjustment mechanism; a support assembly (2) as the base; a tilt measurement unit containing an inclinometer sensor (3) mounted on a three-point disc plate (10) attached to the base of the mast; an illumination measurement unit containing a lux-meter sensor (4) mounted on a height-adjustable carriage (8) at the upper part of the mast; and a computing unit (6) with integrated display and power supply (5). For directed glare assessment, the illumination measurement unit can be supplemented with an optional tube attachment (7). These elements are functionally interconnected as schematically shown in Figure 1 and summarized in Table 1.

2. Mechanical Structure

Vertical mast (1) is made from high-strength aluminium alloy. A telescopic locking mechanism allows stepless height adjustment, permitting deployment across the full range of ADAS calibration target heights encountered in passenger vehicle service, between 0.5 m and 1.8 m from floor level. At the lower mast level, a pair of right-angle brackets mounted to a clamping collar supports the disc plate (10) perpendicularly to the mast axis. The disc plate (10) is circular, 14–16 cm in diameter. The bottom face has three point-contact feet (three bolts with spherical heads, locked with counter-nuts) spread out at equal angular intervals. This three-point geometry ensures deterministic contact with the floor surface, eliminating rocking errors that would otherwise affect inclinometer readings. The inclinometer sensor (3) rests on top of

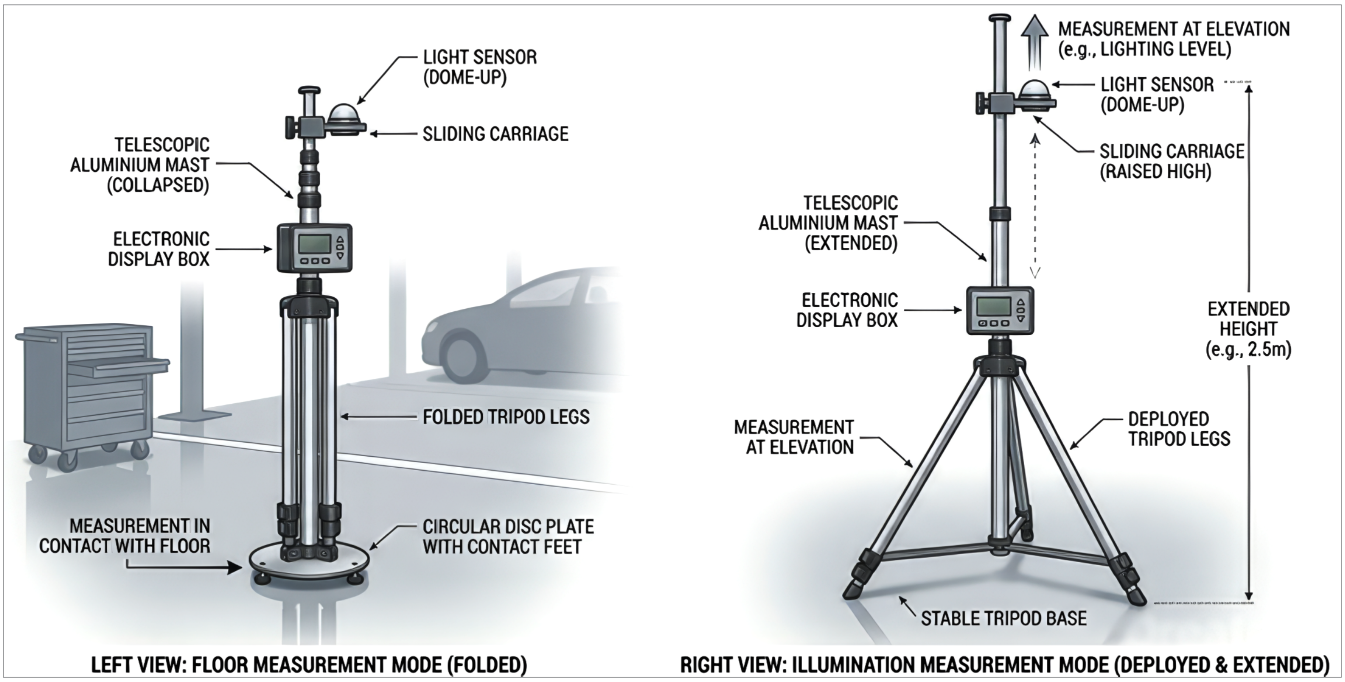

Fig. 1. Portable ADAS calibration zone assessment device: (a) floor levelness measurement mode with tripod legs folded and disc plate in contact with floor; (b) illumination measurement mode with tripod deployed and lux-meter carriage raised to target height

Table 1

Principal components of the portable ADAS calibration zone assessment device

Component	Designation	Primary Function
Vertical mast	(1)	Height-adjustable structural carrier for all measurement units; telescopic aluminium construction
Support assembly (tripod)	(2)	Three-leg base providing stable freestanding support; legs fold upward for disc-plate-only mode
Inclinometer sensor	(3)	Two-axis floor tilt measurement at nine grid reference points; mounted on disc plate (10)
Disc plate	(10)	14–16 cm diameter platform with three-point contact feet providing defined, repeatable contact geometry with the floor
Lux-meter sensor	(4)	Ambient and directed illumination measurement; mounted on height-adjustable carriage (8)
Height-adjustable carriage	(8)	Slides vertically along mast (1); locked at target height by clamp (9)
Tube attachment (optional)	(7)	Narrow-field-of-view attachment for directed glare measurement; snap-fit onto lux-meter housing
Computing unit	(6)	Microcontroller with embedded display; acquires sensor data, applies thresholds, displays results, stores records
Power supply	(5)	Rechargeable battery integrated with computing unit; powers sensors and display autonomously

the disc plate, fixed to the plate axis and centred on the plate axis.

When the device is in its illumination measurement mode, the tripod support assembly (2) offers three-leg freestanding stability. For monitoring floor levelness, the tripod legs are folded upward against the mast and secured with a strap, so that the mast is supported exclusively through the disc plate (10), allowing the inclinometer reading to represent the floor condition only at the measurement point, rather than that of the tripod leg positions.

3. Tilt Measurement Unit

The inclinometer sensor (3) delivers two-axis tilt measurement with ±0.01° resolution and ±10° range, which is considerably greater than the ±0.5° range relevant for ADAS calibration zone assessment. The sensor generates an electrical output signal that is proportional to the angle of tilt and is read by means of a digital interface from the computing unit (6). The sensor is supplied by the integrated power supply (5). The three-point contact geometry of the disc plate guarantees that the measured tilt is a faithful representation of the local floor plane at the measurement point. This is analogous to the manner in which a stylus of a coordinate measuring machine samples a surface at a defined contact geometry. The computing unit records the tilt readings at each of the nine reference points in the calibration zone grid and calculates the maximum tilt observed, the mean tilt and identifies the worst zone within the 3,000 × 2,000 mm vehicle footprint rectangle.

4. Illumination Measurement Unit

The lux-meter sensor (4) is installed on the height-adjustable carriage (8), which travels vertically along the mast (1) and is secured at the required height by clamp (9). The carriage position is set to the height of the calibration target centre for the respective vehicle and ADAS system under review. The sensor detects ambient illumination with an integrated white dome diffuser and gives a cosine-corrected output (representing illumination available at the surface area of interest). Illumination values are transmitted to the computing unit (6) via a digital interface and displayed in lux.

The optional tube attachment (7) is a snap-fit cylindrical collar with an internal diameter 1–2 mm greater than the external diameter of the lux-meter dome housing. Having fitted a tube, the effective field of view for the sensor is limited in size from near-hemispherical to around a 15–25° half-angle cone (depending on tube length), allowing direct measurement to a focused suspected glare source. The ratio of the directed (peak) to the ambient (background) measurement provides a quantitative glare risk index: the Peak/Ambient ratio is a significant reflection of a localised high-luminance source which adversely affects the camera calibration quality if markedly above 1.0.

5. Computing Unit

The computing unit (6) is a microcontroller-based module with an integrated LCD or OLED display mounted to the mast at a reading-convenient height of 150–190 cm. It includes: an analog-to-digital conversion interface for the inclinometer sensor; a digital bus interface for the lux-meter sensor; non-volatile memory for measurement record storage; a user interface consisting of control buttons and the embedded display; and, optionally, a wireless communication module (Bluetooth or Wi-Fi) for data transfer to a smartphone or tablet application. It displays real-time sensor readings, applies configurable pass/fail thresholds, and provides an audible or visual alert when a measurement exceeds a limit. After completing a nine-point floor survey and a target-height illumination measurement, the computing unit produces a structured summary of the results — the environment passport — that contains all measurement values, the applied thresholds, the pass/fail status for each parameter, the date and time, and an operator-entered zone identifier.

Materials and Methods

1. Reference Grid for Floor Levelness Assessment

The floor levelness test protocol is calculated by means of a 3 × 3 measurement grid of points in a rectangular area of 3,000 mm × 2,000 mm, which refers to the floor area that a regular passenger car fills during calibration. An operator then marks nine reference points (numbered 1 through 9) at the intersections of that grid onto the floor surface with chalk or removable tape (See Figure 2). The spacing corresponds to 1,000 mm in the longitudinal direction and 1,000 mm in the lateral direction, with the outermost points 500 mm from each edge of the rectangle.

At each reference point, the operator folds the tripod legs of the device upward and positions the disc plate (10) so that its centre coincides with the grid point, then waits 1–2 seconds until the inclinometer reading stabilises before pressing the Save button on the computing unit. The two-axis tilt vector recorded at each point is held by the computing unit. The computing unit calculates and displays: (a) the highest tilt magnitude observed across all nine points; (b) the mean tilt across all nine points; (c) the sub-zone in the grid that performed the worst; and (d) the pass/fail based on the threshold which is configured (default: 0.3° maximum tilt, configurable to OEM-specific values). Passive ambient illumination is recorded at every floor measurement point, thus creating a spatial illumination map of the zone as a by-product of the floor survey.

2. Target-Height Illumination Assessment

To assess illumination at the calibration target plane, the operator uses the device in tripod mode while keeping the tripod legs extended for stability. Carriage (8) is adjusted to the height of the calibration target centre for the vehicle model and calibration procedure — approximately 0.8 m to 1.4 m for windshield-camera calibration. The lux-meter sensor (4), without the tube attachment, is oriented horizontally toward the target position. The operator starts the measurement, waits 3–5 seconds for stabilisation, and records the result.

A minimum of three to five measurement locations within the target zone (left, centre, right, and optionally upper/lower) are recommended to determine the illumination uniformity. The computing unit estimates and presents the mean, minimum, and maximum illumination values at the measurement locations and the illumination uniformity ratio (minimum/maximum). Reference levels: minimum illumination ≥ 500 lux, maximum illumination ≤ 3,000 lux (to avoid sensor saturation), uniformity ratio ≥ 0.6. These values are consistent with

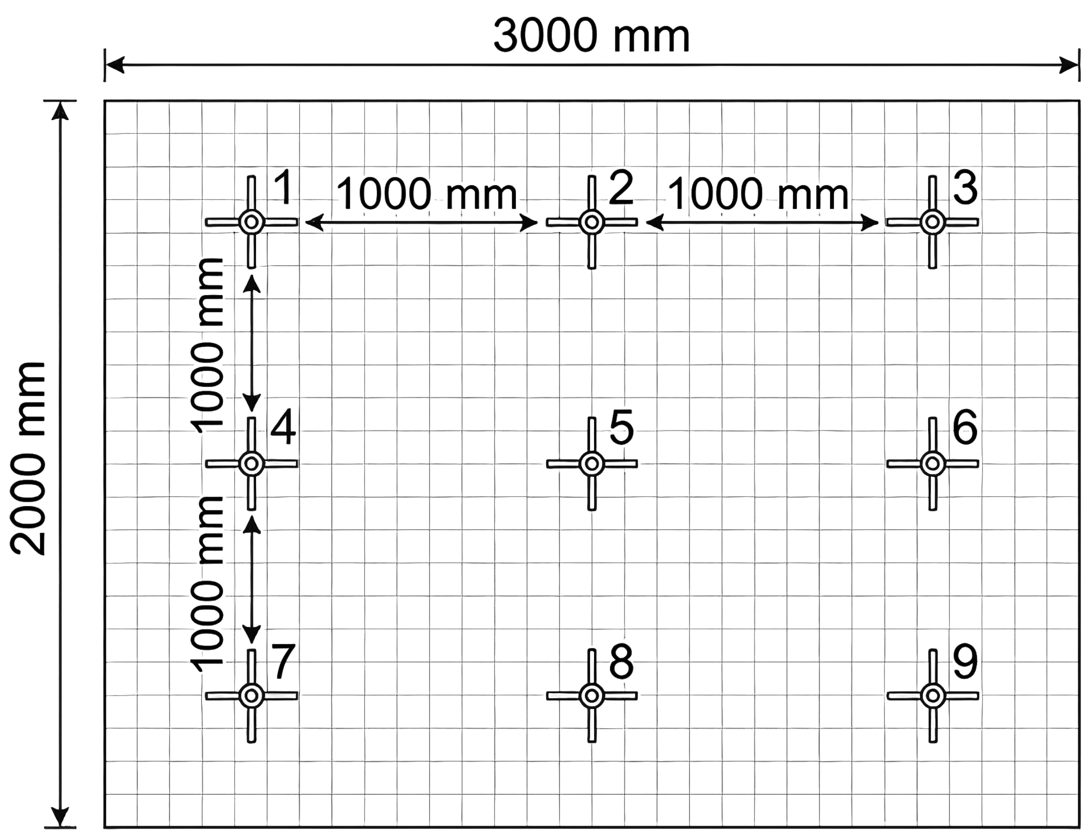

Fig. 2. Nine-point reference grid (3,000 mm × 2,000 mm) for floor levelness and ambient illumination survey

Note: numbers 1–9 indicate measurement sequence; crosses mark the three-point disc plate contact positions thresholds reported in OEM calibration files as well as IIHS and NHTSA testing instructions [7; 13].

3. Glare Assessment Protocol

In the event that the calibration procedure fails, or the response is unstable, and that the floor and illumination parameters are within specification, the glare from localised light sources is a cause. The glare assessment protocol uses the tube attachment (7) on the lux-meter sensor (4). The operator, then, points the sensor — tube attached — toward each possible source of glare in sequence: windows, overhead fluorescent or LED luminaires, glossy wall surfaces, and reflective equipment. For each direction of measurement, the peak directed measurement is recorded by the computing unit. The glare risk index is computed as:

Glare Risk Index = Peak directed measurement (lux) / Ambient background measurement (lux)

A Glare Risk Index substantially exceeding 1.0 — in practice, values above 5.0 are considered significant — indicates a source likely to impair camera calibration. The operator records the direction of the glare source and takes remedial action (closing blinds, repositioning a luminaire, placing a matte screen) before retrying the calibration.

The Environment Passport: Documentation and Service Application

1. Concept and Content

A key output of the device is the environment passport — a structured, timestamped record of the environmental conditions at the calibration location. The environment passport contains: operator and location identification; date and time of measurement; results of the nine-point floor survey (individual tilt readings, maximum, mean, worst zone, pass/fail); results of the target-height illumination survey (individual lux readings, mean, minimum, maximum, uniformity ratio, pass/fail); and, if conducted, glare assessment results (peak readings by direction, Glare Risk Index, pass/fail). The passport is stored in the non-volatile memory of the computing unit and can be printed, exported as a PDF via a connected smartphone application, or transmitted by email directly from the computing unit if the optional wireless module is fitted.

The environment passport serves multiple purposes in the service workflow. It provides the technician with an objective pre-calibration compliance check, replacing informal visual inspection. It provides the workshop owner with documentary evidence of calibration precondition compliance in the event of a customer dispute or insurance claim. It supports quality management systems in multi-bay workshops by enabling periodic environmental surveys of each bay and tracking changes over time (e.g., floor settlement, changes in lighting infrastructure). For mobile service operations, it demonstrates to the customer that the calibration was performed in a location that met the required environmental standards.

2. Workflow Integration

The suggested process for the incorporation of the device into ADAS calibration service process comprises four steps (See Figure 3):

Pre-calibration environmental survey: Prior to the vehicle placement, a nine-point floor survey is performed, and the result is logged by the operator. If the zone fails, the operator will find another area of the workshop or modify the boundaries and resurvey the area. This takes about 5–8 minutes.

Vehicle position and target location: The vehicle is parked in the surveyed zone and the calibration target is fixed at the OEM-specified distance and position. The operator proceeds to perform the target-height illumination measurement (2–3 minutes). In case the illumination is non-compliant, the operator may adjust lighting settings and re-measure.

Calibration execution: After checking compliance with environmental factors, the calibration procedure will be performed on the calibration system for the workshop (OEM CONSULT, AUTEL, or otherwise). The timestamp of the environment passport is contemporaneous with the timestamp of the calibration process.

Documentation and archiving: An environment passport is exported and archived with the calibration record (vehicle VIN, procedure reference, result). In the event

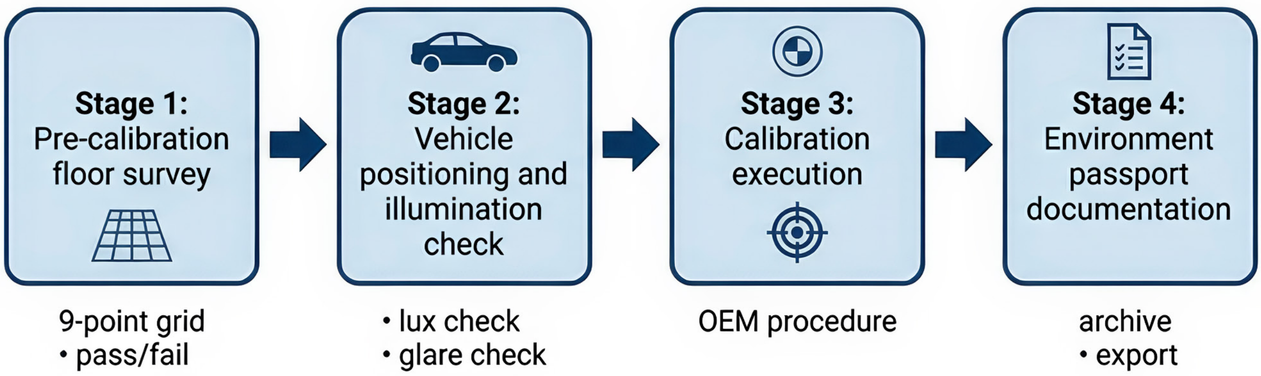

Fig. 3. Recommended four-stage workflow for integrating the portable ADAS calibration zone assessment device into the service process

of a calibration failure, the environmental parameters are recorded, which will aid in the analysis of root cause.

3. Mobile and Roadside Application

For the mobile ADAS calibrations, the environment passport offers particular worth. In the absence of an objective pre-calibration audit, mobile operators cannot show — to their own quality management system or the customer — that their calibration has taken place in a compliant environment. The proposed device, designed for single-operator transport and five-minute setup, makes this audit practical for every mobile job. The device, which is a folded tripod with mast, is compact enough to be transported in a standard hatchback or van. The device does not require mains power, operating autonomously on its internal rechargeable battery for a full working day.

Comparative Analysis

Table 2 summarises the functional characteristics of the proposed device in comparison with currently available alternatives: full ADAS calibration stations with inclinometer features, and the ad hoc combination of a spirit level and separate lux-meter.

Discussion. This proposed device addresses a well-defined instrumentation gap at one point in the ADAS service workflow in which it is needed: the pre-calibration environmental audit. And now the design explicitly limits its design to this operation.

It is not the type used as a calibration equipment, not performing calibration, rather it is a compliance verification tool that allows a go/no-go decision for the compatibility of the workspace before the calibration equipment is installed. This functional restriction is intentionally applied — because it does not try to compensate environmental non-conformance, which is the norm with some calibration stations, it guarantees that the calibration is done in a known-compliant environment, and not in one with partially misused calibration.

The nine-point grid for floor assessment can be seen as an optimization of physical efficiency and time to service. A nine-point survey over a 3 × 3 m area is suitable with 5 minutes from a single operator and provides spatial resolution to record floor slope gradients and local depressions that a single point measurement would fail to record.

The three-point contact geometry of the disc plate also eliminates a major source of measurement artefact — the rocking or bridging of a flat base plate over slightly convex or concave floor surface — that would otherwise cause systematic errors in the inclinometer reading.

The inclusion of glare assessment through the directed tube attachment increases the utility of the device to a class of calibration failures that can be difficult to diagnose without quantitative tools. The Peak/Ambient ratio metric is easy to calculate and interpret, and directing the measuring approach (pointing the tube-mounted sensing material to each potential glare source in turn) does not require some kind of optical expertise from the operator.

In comparison, the technical challenge of analyzing the histograms of the camera raw image for saturation evidence necessitates an approach that requires access and specialist knowledge at the calibration-system level.

A limitation of the current design is that measurements of floor levelness and illumination were made sequentially and in separate instrument combinations (disc-plate mode versus tripod mode). A potential application of this would be to complement the disc-plate measurement with a second inclinometer attached to the tripod legs to measure absolute floor tilt in tripod mode in a single deployed manner.

However, this sequential protocol adds only 2–3 minutes to the overall survey time and is considered acceptable for the target application. The environment passport concept is in line with the growing trend towards documented, traceable service processes in

Table 2

Comparative analysis: portable ADAS calibration zone assessment device versus existing approaches

Criterion	Full calibration station (e.g. Autel IA700)	Ad hoc spirit level + lux-meter
Floor survey area	Single-point (instrument location only)	Single-point or informal multi-point
Floor survey protocol	No standardised grid protocol	No standardised grid protocol
Illumination measurement	Not included as compliance parameter	Separate instrument; no threshold comparison
Glare assessment	Not included	Not possible
Structured output / report	Calibration record only; no environment audit report	None
Portability	Large system; requires large vehicle for transport	Portable but no unified instrument
Setup time	> 20 minutes	< 5 minutes but incomplete
Proposed device	Nine-point grid survey; full vehicle footprint coverage	Standardised protocol; automated threshold comparison; environment passport; < 8 min setup

the automotive aftermarket accelerated by growing complexities embedded in vehicle systems, as well as the potential risk of inaccurate alignment in ADAS calibration [11; 17].

With the deeper integration of ADAS systems with vehicle architectures and the advent of OTA-updatable systems like those found on CMF-EV platform vehicles, the demand for systematic, repeatable environmental audit processes will only continue to rise [5; 18].

Conclusion. In this paper, the design, measurement approach and treatment of a portable ADAS calibration zone appraisal system has been discussed. The key achievements are: A portable, single operator instrument that encompasses floor levelness (nine-point grid, three-point disc plate contact geometry), ambient and target-height illumination measurements (height-adjusted carriage), as well as directed glare screening (tube attachment), in a single tripod mount. A standardised nine-point measurement protocol for floor-levelness and spatial illumination (SM) mapping in the vehicle footprint zone and automatic pass/fail comparison against configurable OEM-aligned thresholds. Environment passport: a structured output document with timestamp that indicates environmental compliance before calibration, helpful for archiving quality management issues and customer facing documentation. Achieved applicability to fixed workshop as well as mobile service, setup time ≤ 8 min and can run autonomously on an integrated power supply.

The device will serve as a bridging solution between the documented disconnect between a full ADAS calibration station and informal ad hoc checking: a practical, low-cost, repeatable option to a family of calibration failures, that are based on errors that are environmental rather than fault-laden with the equipment or procedures themselves. Future works should develop a standardised threshold database indexed by OEM, sensor type, and calibration procedure and a wireless data transfer solution linking to workshop management applications.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.

КОНФЛІКТ ІНТЕРЕСІВ: Автори заявляють про відсутність конфлікту інтересів.

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MODEL FOR CONSISTENT AI INTERFACES BASED ON DESIGN-SYSTEM RULES

Summary. *The article proposes the Design-System AI Interface Consistency Model (DS-AICM), which maps task context, AI state, uncertainty, consequence and user control to design-system rules. Its novelty is explicit activation conditions, risk-proportional safeguards, artifact mapping and a governance feedback loop. A conceptual set expression, a matrix and three scenarios show internal coherence without software implementation or empirical effectiveness claims.*

Key words: *artificial intelligence, AI interface, design system, human-AI interaction, consistency, UX/UI design.*

Introduction. Artificial intelligence has become a visible interaction layer in digital products. Users no longer interact only with deterministic commands and predefined content: they formulate intentions, receive generated or ranked outputs, observe changing system states and decide whether an answer is sufficiently reliable for the next action. This shift changes the meaning of interface consistency. A visually uniform component library does not guarantee a consistent experience when one AI feature explains its limits, another hides uncertainty, and a third offers no way to correct or reverse an outcome.

Design systems codify reusable components, interaction principles and organizational knowledge. They support consistent implementation and cross-functional collaboration through shared standards and terminology [1, p. 2, 17; 2, p. 1]. AI-enabled interaction nevertheless introduces variability that cannot be addressed by typography, color, layout and component behavior alone. The same component may require different copy, controls and safeguards depending on whether the system generates a draft, recommends an option, predicts an outcome or supports a consequential decision.

The research problem is therefore to convert dispersed human-AI interaction recommendations into a compact rule-selection model that can operate inside design-system practice. The model must remain usable for Product Design and UX/UI teams while explicitly connecting context, AI state, uncertainty, consequence, explanation, recovery and user control. The present article addresses this problem conceptually; it does not present source code, a software prototype or an empirical performance model.

Analysis of recent research and publications. Research on design systems shows that they function as more than repositories of UI components. They also coordinate documentation and collaboration, while maintenance requires stable knowledge to evolve with concrete product needs [1, p. 17, 21–22; 2, p. 1]. Studies of interface consistency further indicate that consistency is relational: comparable tasks and contexts should preserve recognizable choices, whereas different contexts may justify different behavior [3, p. 1]. This distinction is essential for AI products because the acceptable degree of automation and required information can change with task consequence.

Human-AI interaction research supplies a substantial set of design requirements. Amershi S. et al. group 18 guidelines by interaction phase — initially, during interaction, when wrong and over time — and include capability framing, contextual information, correction and explanation [4, p. 3–4]. Yang Q. et al. identify uncertainty about AI capability and output complexity as distinctive sources of design difficulty [5, p. 1]. Liao Q. et al. show that explanation design should be driven by user- and context-dependent questions rather than model mechanics alone [6, p. 1, 3], while Eiband M. et al. translate transparency principles into a stage-based participatory process for product-specific decisions [7, p. 211–212].

Expectation management and control are equally important. Preparing users for imperfect AI can increase acceptance without implying that errors disappear [8, p. 1]. Onboarding research shows that people need information about capability, limitation, intended use and design objective before effective collaboration begins [9, p. 104:2–104:3]. Human-centered AI seeks high automation together with high human control [10, p. 495], and trust research frames the design goal as appropriate rather than maximal reliance [11, p. 50]. In decision support, explanations alone do not reliably eliminate overreliance or improve complementary team performance [12, p. 188:1–188:2; 13, p. 1–3]. Editable intermediate results and chained interactions can make complex AI behavior more inspectable and controllable [14, p. 1–2], while non-experts' prompt-design difficulties demonstrate the need for iterative support, error recognition and strategy formation [15, p. 1–3].

The literature therefore offers valuable principles, frameworks and empirical findings, but most contributions remain separate checklists or domain-specific results. Teams still need an operational answer to three questions: which rules activate in a given scenario, which design-system artifacts embody those rules, and how justified exceptions return to governance. DS-AICM addresses this gap by treating consistency as a conditional, traceable and maintainable rule-selection process.

Objectives of the article. The purpose of the article is to propose a conceptual model for ensuring consistency in AI-enabled interfaces by selecting and applying design-system rules according to task context, AI state, uncertainty, consequence, irreversibility and required user control. The scientific novelty lies in combining literature-derived human-AI requirements with explicit activation conditions, proportional safeguards, design-system artifacts, traceability and a governance feedback loop. The practical value is a reusable structure for design specification, hand-off and review. In this article, risk is used only as an umbrella term covering consequence, irreversibility, time pressure, uncertainty-related exposure and required domain expertise; consequence remains the principal matrix variable.

To achieve this purpose, the study addresses three analytical tasks. First, it identifies the dimensions of consistency required for AI-enabled interfaces and explains why a component-oriented design system alone is insufficient. Second, it determines how AI-specific requirements can be represented as conditional design-system rules with explicit activation criteria. Third, it proposes a conceptual model for selecting, applying and reviewing these rules across typical product scenarios.

Research methods. The study uses conceptual synthesis, comparative analysis, classification and scenario-based analytical assessment. The literature search and page-level source verification were conducted from 1 June to 5 July 2026 using targeted title, abstract and keyword combinations in accessible bibliographic, publisher and full-text records. For potential replication in Scopus, the search strategy can be expressed through the following TITLE-ABS-KEY query families: TITLE-ABS-KEY ("design system*" AND (governance OR consistency OR component*)); TITLE-ABS-KEY (("human-AI interaction" OR "AI interface*") AND (guideline* OR uncertainty OR explainability OR "user control")); and TITLE-ABS-KEY (("AI-assisted decision-making" OR "generative AI") AND (reliance OR recovery OR onboarding OR transparency)). The strategy was iterative and designed for conceptual coverage rather than exhaustive systematic review; no PRISMA-style hit count is claimed.

Inclusion criteria were: peer-reviewed publication in English; direct relevance to design systems, interface consistency or observable human-AI interaction requirements; sufficient methodological or conceptual detail to derive a rule, activation condition or governance implication; and availability of verifiable bibliographic metadata and full text for page-level citation. Purely algorithmic explainability studies without an interface implication, non-peer-reviewed practitioner blogs, duplicate versions and papers used only for general AI background were excluded. The final analytical corpus contains 15 publications. Publisher and DOI records were used as the bibliographic source of truth. The corpus is therefore described as peer-reviewed literature rather than a Scopus-only sample.

The analysis followed five steps. First, recurring problems and requirements were extracted from the selected papers. Second, overlapping requirements were grouped into consistency dimensions and rule families. Third, existing approaches were compared against six criteria that expose the proposed model's incremental contribution. Fourth, the activation logic was formalized through a set expression and a consequence-uncertainty matrix. Fifth, three scenarios were used for non-empirical analytical verification. Two checks were applied: coverage, meaning that each proposed rule family was either linked to a literature-derived requirement or explicitly identified as an author-developed operational extension; and differentiation, meaning that scenarios with different consequence and uncertainty levels produced different mandatory rule sets. These checks demonstrate internal coherence, not external effectiveness.

Results

1. Theoretical foundations of AI interface consistency. For this study, an AI interface is an interaction layer through which a person specifies a goal, receives or supervises an AI-produced result and can influence subsequent system behavior. Consistency is defined as a stable relationship among user intent, the current AI state, output properties, interface feedback and available controls. The definition deliberately shifts attention from identical appearance to predictable meaning and action.

Seven complementary dimensions are distinguished. Visual-structural consistency covers components, hierarchy, spacing and placement. Interaction-state consistency covers loading, generation, completion, interruption, error and recovery. Semantic consistency concerns stable terminology for AI actions and outputs. Epistemic consistency concerns the communication of uncertainty and limitation. Explanatory consistency concerns reasons, evidence and provenance. Agency consistency concerns editing, confirmation, cancellation, undo and escalation. Governance and accessibility consistency concerns documented ownership, exceptions, traceability and inclusive use.

The dimensions are interdependent. A "Regenerate" control is not consistent merely because it looks the same: its label, consequence, state transition and recovery behavior must also be predictable. Likewise, a confidence indicator may create inconsistency when related features use incompatible scales or fail to explain what the value means. Each reusable AI pattern should therefore specify four linked layers — component, content, behavior and control — while uncertainty and consequence determine which additional layers become mandatory. The rules presented in Table 1 are synthesized by the author from the reviewed literature and extended to the operational requirements of design-system governance and accessibility; they are not verbatim reproductions of individual publications.

A separate comparison is necessary because scientific novelty cannot be established by listing useful principles alone. Table 2 presents the author's comparative synthesis of existing approaches and the proposed DS-AICM. The criteria are analytical dimensions selected in this study: evidence from prior work supports the first two approach columns, while the DS-AICM column reports the contribution proposed here.

2. Design-system rules for AI interfaces. Within DS-AICM, the author defines a rule not as a general instruction such as "be transparent", but as a conditional statement connecting an observable design situation with a required interface response. A usable record contains at least five fields: activation condition, required pattern, prohibited pattern, rationale and evidence or ownership. For example, when an AI result can materially influence a consequential decision, the proposed model requires the interface to expose the relevant basis of the recommendation, enable human review and prohibit silent automatic execution.

Capability framing and state visibility. Within DS-AICM, capability framing and state visibility are represented as conditional rule records. The reviewed literature supports disclosure of capability, limitation and context before use [4, p. 3; 9, p. 104:2–104:3]. The proposed model extends this basis by requiring a product-specific state vocabulary — queued, processing, partial, completed, interrupted and failed — and by defining the controls available in each state.

Uncertainty, explanation and provenance. The proposed model does not require a numerical confidence value in every interface. It requires an uncertainty representation that is understandable and actionable in the given context. The author proposes

Table 1

Dimensions of AI interface consistency and corresponding design-system rules

Dimension	Design objective	Representative rules and artifacts
Visual-structural	Preserve recognizable hierarchy and component use.	Shared tokens, layouts and AI-status components; generated content is distinguished without creating a separate visual language.
Interaction-state	Make progress, change and failure predictable.	Named states for idle, queued, generating, partial result, completed, interrupted, failed and corrected; documented transitions and permitted actions.
Semantic and content	Keep terminology and instructions stable.	Consistent names for AI functions, outputs and controls; product-specific capability statements, prompt guidance and action-oriented messages.
Epistemic	Communicate uncertainty and limitations proportionally.	Limitations, confidence or verification needs appear when they affect action; false precision is avoided; facts, suggestions and hypotheses are distinguished.
Explanatory and provenance	Support understanding of relevant reasons and sources.	"Why this?", evidence, data origin or transformation history are provided according to task consequence through progressive disclosure.
Agency and recovery	Maintain meaningful user control.	Edit, retry, stop, undo, compare, reject and escalation controls are defined where applicable; consequential execution requires confirmation.
Governance and accessibility	Keep rules maintainable, auditable and inclusive.	Rule ownership, exception rationale, review dates and accessibility behavior for dynamic content, status announcements and keyboard interaction are documented.

Source: developed by the author through conceptual synthesis based on [1, p. 2, 17, 21–22; 3, p. 1; 4, p. 3–4; 6, p. 1, 3; 10, p. 495; 11, p. 50, 73–75; 14, p. 1–2] and extended to the operational requirements of design-system governance and accessibility

Table 2

Existing approaches versus DS-AICM

Criterion	Conventional design systems	Human-AI guidelines and frameworks	Proposed DS-AICM contribution
Activation conditions	Usually implicit in component documentation or product convention.	Guidelines identify desirable behavior, but selection is often left to practitioner judgment.	The proposed model gives each rule an observable trigger tied to context, AI state, consequence, uncertainty or personalization.
Risk proportionality	Not normally central to component selection.	HCAI and trust frameworks establish the importance of control and calibrated reliance.	Within DS-AICM, safeguards increase with consequence, uncertainty and irreversibility instead of relying on one uniform disclaimer.
Design-system artifacts	Components, tokens, patterns, documentation and code.	Principles, checklists, studies and domain examples.	The proposed model maps activated requirements to components, content, behavior, controls, state definitions and ownership fields.
Governance loop	Ownership and maintenance may exist, but AI-specific exceptions are not necessarily structured.	Most approaches focus on design guidance or evaluation rather than repository evolution.	DS-AICM records context, owner, evidence and review date for exceptions; recurrent exceptions may become governed patterns.
Recovery rules	Generic error and undo patterns may be available.	Correction, dismissal and control are recommended, but not always linked to state and consequence.	When activated, DS-AICM specifies stop, retry, edit, undo, compare, reject or escalation behavior.
Traceability	Traceability is often limited to component usage and implementation.	The rationale for a selected guideline may remain external to the design specification.	The proposed model traces each safeguard from scenario condition to rule, design-system artifact, implementation behavior and review decision.

Source: author's comparative synthesis; descriptions of conventional design systems and human-AI approaches are based on [1, p. 2, 17, 21–22; 2, p. 1; 4, p. 3–4; 6, p. 1, 3; 10, p. 495; 11, p. 50, 73–75; 14, p. 1–2], while the DS-AICM column presents the contribution proposed in this study

that a low-consequence creative suggestion may need concise limitation text and an easy retry, whereas decision support may require calibrated uncertainty, evidence, provenance and an explicit verification step. Within DS-AICM, explanation depth is proposed to increase with task consequence and novelty, while technical detail is disclosed progressively. This rule is derived through conceptual synthesis: prior work supports question- and context-dependent explanations, expectation management and appropriate reliance, while also showing that explanations alone can encourage or fail to prevent inappropriate reliance [6, p. 1, 3; 8, p. 1; 11, p. 50, 73–75; 12, p. 188:1–188:2; 13, p. 1–3].

Agency, recovery and governance. Within DS-AICM, the author proposes that meaningful control include editing inputs, interrupting a long operation, rejecting an output, restoring a prior state, requesting alternatives and escalating to a human or authoritative process. Feedback controls must state whether they alter only the current result, contribute to product improvement or personalize future behavior. The governance fields — owner, exception rationale, evidence and review date — are operational extensions introduced by the model, informed by design-system evolution and human-AI correction and control research [1, p. 21–22; 4, p. 3; 14, p. 1–2; 15, p. 1–3].

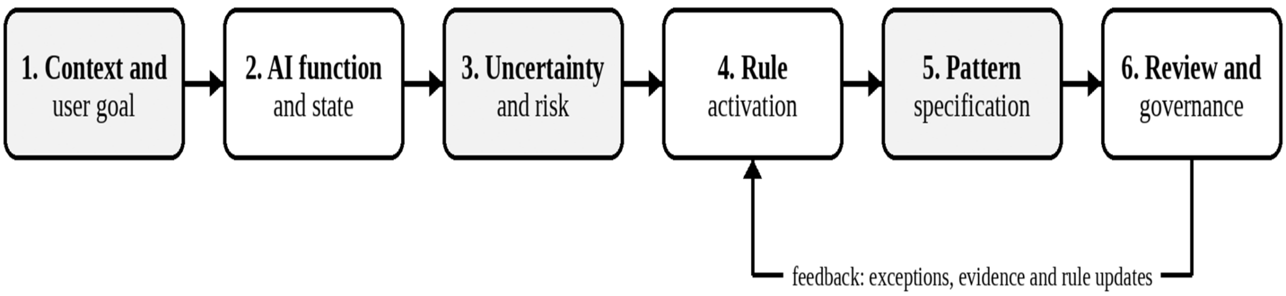

Fig. 1. Design-System AI Interface Consistency Model (DS-AICM)
Source: developed by the author through conceptual synthesis based on [1, p. 21–22; 4, p. 3–4; 14, p. 1–2]

3. Proposed Design-System AI Interface Consistency Model. The proposed Design-System AI Interface Consistency Model (DS-AICM) consists of six linked stages and a governance feedback loop. It begins with the user's situation rather than the existing component inventory, then narrows the design problem until an auditable set of rules and artifacts can be specified. Figure 1 presents the overall sequence.

Stage 1. Context framing. The model records the user role, task, expected outcome, conditions of use, decision consequence and acceptable delay.

Stage 2. AI function and state mapping. The feature is classified as generation, transformation, recommendation, classification, prediction or decision support. The relevant normal, interrupted and failure states are then identified. Together, the first two stages prevent a pattern from being selected solely because an existing component is available.

Stage 3. Assessment of uncertainty, consequence and irreversibility. The model assesses output uncertainty, the potential consequence of error, reversibility, time pressure and the need for domain expertise.

Stage 4. Rule activation. Always-on requirements are combined with additional safeguards triggered by the conditions identified at the previous stage. For conceptual use, low, medium and high ordinal levels are sufficient; the model does not imply a statistically calibrated risk score.

Stage 5. Pattern specification. The activated rule set is translated into design-system artifacts: components, content, behavior and controls. These artifacts include state definitions, interface copy, explanation depth, confirmation, recovery and provenance requirements.

Stage 6. Review and governance. The proposed solution is checked for cross-product consistency, accessibility and safety. A justified deviation is documented together with its context and owner, while recurring deviations return to the repository as candidates for a new governed pattern. This creates the governance feedback loop.

The activation logic can be expressed as a conceptual set union:

$$R_{\text{act}}(x) = R_{\text{base}} \cup R_{\text{risk}}(c,v) \cup$$
$$\cup R_{\text{uncertainty}}(u) \cup R_{\text{personalization}}(p).$$

Here, x denotes the design scenario; c is consequence; v is irreversibility; u is output or capability uncertainty; and p denotes personalization or feedback that changes future behavior. The expression is a conceptual design-decision representation rather than an executable software algorithm. Every scenario receives the base set, while additional rule families become mandatory when their activation conditions are present.

The matrix is proposed in this study and is not reproduced from an existing framework. Within DS-AICM, the author assumes a conservative upper-right condition and a lightweight lower-left condition. This prevents two common design errors: applying high-friction safeguards to every creative feature, and treating a generic disclaimer as sufficient for a high-consequence decision. When conditions conflict, the rule associated with the greater consequence or lower reversibility prevails. Personalization activates disclosure and consent requirements independently of the matrix because it changes future system behavior.

Discussion. The findings correspond to the three analytical tasks defined at the beginning of the study. First, the analysis shows that AI-interface consistency includes visual, behavioral, semantic, epistemic, explanatory, agency and governance dimensions. A component-oriented system alone is insufficient because the meaning and required safeguard of a component depend on the AI state and the consequence of use. Second, the study represents each requirement as a conditional rule with an activation trigger and linked design-system artifacts. Third, the proposed six-stage structure, conceptual activation set, consequence-uncertainty matrix and scenario walkthroughs provide a structured way to select, apply and review those rules in typical product situations.

The comparison in Table 2 clarifies the novelty claim. DS-AICM does not claim originality for human control, explainability or uncertainty communication. It integrates those established concerns with design-system governance through explicit activation

Table 3

Consequence-uncertainty matrix for rule activation

Consequence	Uncertainty	Required level	Proposed mandatory rule set
Low	Low	Base	AI-role disclosure; stable naming; state visibility; accessibility; ordinary edit or cancel behavior.
Low	High	Base + uncertainty	Base rules plus limitation text, verification cue, retry or alternative, and explicit recovery from poor output.
High	Low	Base + consequence	Base rules plus provenance, review, confirmation, auditability and prohibition of silent automatic execution.
High	High	Full safeguards	All rule families: uncertainty, explanation, provenance, confirmation, human review, recovery, escalation and audit history.

Source: developed by the author through conceptual synthesis based on [4, p. 3–4; 10, p. 495; 11, p. 50, 73–75; 12, p. 188:1–188:3; 13, p. 1–3]

Table 4

Scenario-based application of DS-AICM

Scenario and conditions	Rule mapping proposed in DS-AICM	Conceptual consistency outcome
Generative writing assistant. Low consequence; medium uncertainty; reversible draft.	Base rules plus uncertainty and recovery: show generation state and limitations; mark generated content; provide edit, stop, regenerate, compare and undo; keep labels stable across entry points.	The output is understood as a draft. Users can revise it and encounter the same recovery behavior throughout the product.
Recommendation module. Medium consequence; preference-dependent output; multiple valid alternatives.	Explain the main recommendation factors; provide "Why this?", alternatives and preference controls; disclose relevant data use; allow rejection and correction.	Recommendations remain adjustable support rather than a single objective answer, and users retain control over criteria.
High-consequence decision-support dashboard. High uncertainty; expert review required.	Activate full safeguards: evidence and provenance, calibrated uncertainty, mandatory review and confirmation, no silent execution, audit history, recovery and escalation.	The interface supports appropriate reliance, preserves accountability and applies equivalent safeguards to comparable decisions.

Source: scenarios and rule mappings developed by the author; underlying requirements synthesized from [4, p. 3–4; 8, p. 1; 9, p. 104:2–104:3; 10, p. 495; 11, p. 50, 73–75; 12, p. 188:1–188:3; 13, p. 1–3; 14, p. 1–2; 15, p. 1–3]

conditions, risk-proportional rule selection, scenario-to-rule-to-artifact mapping, implementation traceability and a governance feedback loop. A designer can justify why a confirmation or recovery control appears, while an engineer can identify the AI state, artifact and behavior to implement.

Risk proportionality is the second contribution. As defined above, risk is an umbrella category, while consequence remains the principal matrix variable. The model neither classifies every AI feature as high risk nor reduces responsible design to a universal disclaimer. Requirements increase when uncertainty, consequence or irreversibility increases. At the same time, the governance feedback loop preserves context-sensitive design. Design systems must evolve with concrete product needs [1, p. 21–22]; DS-AICM supports that evolution by recording justified exceptions and returning recurrent patterns to the governed rule set.

The scenario analysis is an internal analytical check only. It shows that the model differentiates low- and high-consequence use cases, but it does not prove improved usability, safety or development efficiency. External validation would require expert review, application to a real product and user or audit data. This limitation is preferable to presenting uncollected expert opinions or simulated performance as empirical evidence.

Conclusions and prospects for further research. The article proposes DS-AICM as a conceptual model for ensuring consistency in AI-enabled interfaces through design-system rules. Consistency is defined as a stable relationship among user intent, AI state, output properties, feedback and user control. The model organizes the problem into seven dimensions and six linked stages: context framing, AI-function and state mapping, assessment of uncertainty, consequence and irreversibility, rule activation, pattern specification, and review with a governance feedback loop.

The scientific contribution is the conditional connection of human-AI interaction knowledge with operational design-system artifacts. The comparison table identifies the incremental value over existing approaches; the conceptual set expression and decision matrix formalize rule activation; and the scenarios illustrate proportionate requirements for a writing assistant, a recommendation module and a high-consequence dashboard. The practical result is a concise method that Product Design and UX/UI teams can use before implementation.

The study remains conceptual. It has not been implemented as software and has not been evaluated in a user study or external expert panel. The literature selection was targeted rather than systematic, and the scenarios do not cover every AI modality or domain. Further research should include structured assessment by three to five UX/UI and engineering experts, checklist evaluation of existing AI interfaces, application to a real product, usability testing, refinement of activation thresholds and measurable compliance criteria for design-system audits.

ДОДАТКОВА ІНФОРМАЦІЯ

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ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.
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МІТІГАЦІЯ ЯК ЕЛЕМЕНТ КЛІМАТИЧНОЇ БЕЗПЕКИ В УКРАЇНІ

MITIGATION AS ELEMENT OF CLIMATE SECURITY IN UKRAINE

Анотація. *У роботі розглянуті основні засади кліматичної політики України у сфері мітігації, визначений внесок України у глобальну кліматичну безпеки а контексті мітігації, проаналізовано інструменти монетизації CO2 у сфері мітігації, підкреслено роль мітігації і синергетичних заходів в кліматичній безпеці, кількісно оцінений масштаб мітігації і внесок у кліматичну безпеку і для групи комбінованих заходів мітігації і адаптації. Зроблено акцент на розкоординованості кліматичної політики у сфері кліматичної безпеки, відсутність самого поняття «кліматична безпека» у кліматичному плануванні і інтегрованого підходу на рівні держави до мітігації як його елементу.*
Ключові слова: *зміна клімату, мітігація, скорочення викидів, парникові гази, монетизація* $CO_{2.}$

Summary. *The paper considers the main principles of Ukraine's climate policy in the field of mitigation, identifies Ukraine's contribution to global climate security in the context of mitigation, analyzes the tools for monetization of CO2 in the field of mitigation, emphasizes the role of mitigation and synergistic measures in climate security, quantifies the scale of mitigation and contribution to climate security, and for groups of combined mitigation and adaptation measures. Emphasis is on the lack of coordination of climate policy in the field of climate security, the absence of the very concept of "climate security" in climate planning and an integrated approach at the state level to mitigation as its element.*
Key words: *climate change, mitigation, emission reduction, greenhouse gases, monetization of CO2.*

Вступ. Для України, яка постраждала від повномасштабної війни, питання кліматичної безпеки все більше набувають виміру не тільки окремих її компонентів, таких як мітігація, але і національної та економічної безпеки. Кліматична безпека як поняття поки що не розглядалася як комплексна міждисциплінарна парадигма із чіткою стратегією розвитку та інтеграцією всіх компонентів, скоріше характерна окрема активність без узгодженості на рівні держави. Елементи мітігації, як компоненту кліматичної безпеки (скорочення викидів CO_2, моніторинг викидів, проекти в рамках Кіотського протоколу, розвиток відновлюваної енергетики) впроваджувалися скоріше на рівні окремих секторів чи підприємств без прив'язки і інтеграції до кліматичної безпеки в тому числі через відсутність центру координації політик.

Попри повномасштабну війну, Україна залишається одним із ключових гравців глобальної кліматичної архітектури. Викиди парникових газів України у 2023–2025 роках є на рівні близько 200–220 млн. т CO_2-еквівалента (0,41% глобальних) [1]. Останній Національно визначений внесок України (NDC 2 від жовтня 2025 р.) [2] містить ціль не перевищення викидів CO_2 на рівні 65% від рівня 1990 р., і далі кліматична нейтральність до 2050–2060 років. У період Кіотського протоколу 2008–2012 рр. (і далі до 2014 р.) Україна була світовим лідером за кількістю проектів та абсолютною кількістю скорочень викидів за механізмом Спільного Впровадження (Стаття 6 Кіотського протоколу) — більше 600 зареєстрованих проектів, в середньому 120 млн. т CO_2/рік скорочень викидів CO_2 (верифікованих проєктів) [3]. Також Україна (через взаємодію між урядами) активно брала участь в реалізації Статті 17 — реалізуючи Схему прямих екологічних (зелених) інвестицій, що дала можливість скоротити близько 50 млн. т CO_2 і залучити до 250 млн. Євро інвестицій.

Наразі Україна є Стороною Паризької угоди (з 2015 р.), яка містить прямі механізми скорочення викидів CO_2 (Стаття 6), а також уряд впроваджує на національному рівні механізм торгівлі квотами по Статті 6 Паризької угоди. Так у червні 2026 року затверджена Постанова КМУ Про реалізацію експериментального проекту щодо виконання окремих положень статті 6 Паризької угоди [4]. У 2024–2025 рр. були підписані Меморандуми із Швейцарією (2022) і Японією (2024) в рамках статті 6.2 Паризької угоди, перші проекти і скорочення викидів CO_2 очікуються у 2026–2027 рр.

Починаючи з 2021 р. частково впроваджені внутрішні інструменти скорочення викидів, такі як внутрішня система торгівлі викидами (в частині вимірювання, звітність та верифікація), податок на CO_2. У 2026 р. розпочався перший перехідний етап реалізації механізму прикордонного вуглецевого коригування (Carbon Border Adjustment Mechanism CBAM). Також наявні непрямі інструменти декарбонізації і кліматичного фінансування: схема зелених облігацій, енергосервісні компанії, співфінансування зелених проектів через різні урядові програми і фонди, пільгове кредитування, цільове фінансування через фонд декарбонізації, тощо. Скорочення викидів від цих механізмів оцінюються у діапазоні 20–50 млн. т CO_2/рік з 2022 р. і дотепер. В Україні доступні різноманітні добровільні системи торгівлі викидами (Добровільний вуглецевий ринок (Voluntary Carbon Market), Gold Standard), є одиничні приклади проектів (агросектор і лісове господарство), що сприяє поступовій декарбонізації і підвищенню кліматичної безпеки.

Таким чином, «кумулятивний внесок» у глобальну кліматичну безпеку за період 2008–2026 (Кіотський протокол і всі інші механізми) з точки зору абсолютних скорочень викидів можна оцінити як 600–800 млн. т CO_2-екв.

Мітігація (Mitigation), або прямі скорочення викидів CO_2

Мітігація (пом'якшення) — це комплекс заходів, спрямованих на зменшення обсягів викидів парникових газів (ПГ) та збільшення їх поглинання. Для України це означає перехід до низьковуглецевої енергетики, підвищення енергоефективності, розвиток відновлюваних джерел енергії (ВДЕ) та впровадження циркулярної економіки. Закон про основні засади державної кліматичної політики [5] фіксує ціль України — досягнення кліматичної нейтральності до 2050 року. Проміжна ціль передбачає скорочення викидів парникових газів на 65% до 2030 р. порівняно з рівнем 1990 року. Досягнення цих показників вимагає впровадження комплексних заходів у наступних сферах:

- Модернізації промисловості (зокрема енергетики, металургійної, хімічної, виробництво цементу, добрив) із заміщенням викопного палива на електрифікацію та зелений водень.
- Розвитку розподіленої генерації та відновлюваної енергетики.
- Збільшення площ лісів та захисних насаджень для природного поглинання CO_2-екв.

Скорочення викидів є елементом кліматичної безпеки, який може бути кількісно оцінено через скорочення CO_2, симетрично до кліматичного ризику, стійкості або адаптаційної здатності. Чим менше викидів CO_2, тим нижче кліматичні ризики, а значить вище кліматична безпека. Мітігація визначена і синхронізована з національно визначеним внеском (ЕСКО) України, національними планами (Національний план з економіки клімату (НПЕК-2030), Енергостратегія-2050, Дорожня карта ВДЕ до 2030, Планом відновлення України, тощо) та цілями Європейського союзу (ЄС) з декарбонізації.. П'ята швидка оцінка завданої шкоди та потреб (RDNA5) [6] вказує збитки, пов'язані із секторами, що генерують викиди CO_2 на рівні 150 млрд. дол. (потреби на відновлення — 90,6 млрд. дол. (з них 70,8 млрд. — тільки на електроенергетику)). За даними групи експертів Initiative on Greenhouse Gas Accounting of War (Climate Focus, Екодія та ін.), додаткові викиди виключно від військових дій в Україні в період лютий 2022 — лютий 2025 сягнули 175 млн. т CO_2, а загальні пов'язані збитки — до 57 млрд. дол. США [7].

Основні інструменти мітігації, що вже використовуються в Україні:

1) CBAM ЄС (з 2026): моніторинг, верифікація та звітність для 6 секторів (сталь, цемент, добрива/аміачні продукти, алюміній, електроенергія, водень). Очікувані втрати без дій — 1–2 млрд. євро/рік;

2) Стаття 6 Паризької угоди: проектні механізми та ITMO (обмін квотами — Швейцарія, Японія,

Climate Market Club). Забезпечує пряме фінансування і зниження кліматичних ризиків через обмін квотами між проектами або урядами. Очікуване додаткове фінансування — 0.5–1 млрд. Євро/рік;

3) Податок на CO_2. Внутрішній інструмент стимулювання декарбонізації. При рівні податку 30 Євро/т CO_2 (в 50 раз вище, ніж зараз, але співставно із цінами на скорочення викидів в CBAM і Європейською системою торгівлі викидами парникових газів (ЄСТВ)) та реформі адміністрування і розподілу очікуване додаткове фінансування — 3–5 млрд. Євро/рік;

4) Внутрішня система торгівлі викидами, лінкована з ЄСТВ. При доопрацюванні законодавчої бази очікуване фінансування — 0.5–1 млрд. Євро/рік;

5) Інші механізми (добровільні системи торгівлі, схема зелених облігацій, ЕСКО, співфінансування зелених проектів, пільгове кредитування, цільове фінансування через фонд декарбонізації та інші). Очікуване фінансування — 0.2–0.5 млрд. Євро, в основному дрібномасштабні проєкти для населення і домогосподарств.

Роль ESG-звітності в мітігації

ESG-звітність (Environmental, Social, Governance — набір стандартів діяльності компанії для оцінки її сталого розвитку) є інструментом прозорості звітності для залучення кліматичного фінансування. Фінансові інституції, такі як Європейський банк реконструкції і розвитку (EBRD), Світовий банк (WB), Міжнародна фінансова корпорація (IFC) запроваджують оцінку проєктів за ESG-критеріями. Цей стандарт звітності містить розділи аналізу кліматичних ризиків (кількісна та якісна оцінка), що напряму пов'язано із впливом того чи іншого бізнесу на кліматичну безпеку («внесок» у кліматичну безпеку). Таким чином для кліматичної безпеки впровадження стандартів звітності ESG є базовим принципом кількісного визначення поточного стану кліматичної стійкості об'єктів та бізнесів, та для подальшого отримання фінансування на відновлення і реконструкцію, а також зниження кліматичних ризиків і впровадження заходів зі скорочення викидів CO_2.

Справедливий перехід (Just Transition) як елемент мітігації. Україна зобов'язалася повністю відмовитися від вугілля в електрогенерації до 2035 року (підтверджено в НПЕК-2030, Енергетичній Стратегії до 2050, Державній цільовій програмі справедливого переходу вугільних регіонів до 2030 року — постанова КМУ № 711 від 2025 [8]). Програма охоплює 10 вугільних регіонів (близько 2,2 млн. жителів) і передбачає поступове закриття державних шахт, перепідготовку працівників, створення нових робочих місць у секторі ВДЕ, відбудову інфраструктури на основі критеріїв стійкості, рекультивації шахт і ґрунту, диверсифікації, розвиток еквівалентного виробництва енергії на основі ВДЕ, енергоефективності, зниження вуглецевого сліду, соціальної підтримки громад. Справедливий перехід підвищує здатність системи опиратися кліматичним ризикам і має прямий ефект скорочень викидів CO_2.

Кількісна оцінка масштабу компонентів мітігації і загальну оцінку ризиків і впливів на кліматичну безпеку показані у табл. 1.

Найбільш важливими компонентами є прямі скорочення та механізми монетизації CO_2, які мають також і найбільші мультиплікаційні ефекти для економіки (комерційно окупні проекти).

Концепція синергії мітігації і адаптації

В теперішній час Україна має необхідність реалізації кліматичної політики в умовах повоєнної відбудови та євроінтеграції, необхідно розглядати заходи мітігації в комплексі з іншими компонентами кліматичної безпеки. Це створює унікальну ситуація, коли замість відбудови зруйнованих індустріальних об'єктів за старими технологіями, держава може інвестувати у «зелені» інновації та циркулярну економіку і одночасно отримати ефекти для різних компонентів кліматичної безпеки.

В цьому контексті існує аспект синергії адаптації та мітігації. Існують так звані комбіновані заходи, які одночасно зменшують викиди (мітігація)

Таблиця 1

Оцінка масштабу інвестицій і втрат на мітігацію за ключовими компонентам та вплив на кліматичну безпеку

№	Компонент кліматичної безпеки	Інвестиції до 2050 р., млрд. Євро	Втрати від бездіяльності до 2050 р., млрд. Євро	Мультиплікаційни ефекти для економіки до 2050 р., млрд. Євро**	Вплив на кліматичну безпеку
1	Мітігація, скорочення викидів ПГ, в т.ч.	10…25	20…40	25…50	Високий
1.1	Прямі скорочення викидів	10…15	15…20	10…15	Високий
1.2	Механізми монетизації CO_2	3…5	10…15	25…30	Високий
1.3	ESG звітність, моніторинг, звітність, верифікація	2…5	3… 5	5…10	Середній
1.4	Just transition	5…10	5…10	5…10	Середній

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Таблиця 2

Порівняльний аналіз основних груп комбінованих заходів мітігації та адаптації в Україні

Технологія / Захід	Якісна синергія (Мітігаційний (М) + Адаптаційний ефекти (А))	Кількісні індикатори, Потенціал для України	Ризики та обмеження (зокрема iLUC (Indirect Land Use Change — (непрямі зміни у землекористуванні))
Виробництво енергії з біомаси, біометану, біогазу	М: Заміщення викопного палива, утилізація відходів агропромислового конкурсу, виробництво зеленого водню (поглинання CO_2) А: Органічний дигестат відновлює гумус ґрунту, підвищуючи його вологоутримуючу здатність під час посухи, зменшується ефект від екстремальних явищ при потраплянні відходів в води/ґрунт.	Потенціал: Біомаса: до 20 Мтне/рік Біогаз/біометан: 20–25 млрд. нм3/рік. Скорочення викидів: 1.3…2.5 т CO_2-екв./тне (заміщену)	Висока потреба в інвестиціях, системи ПСО і субсидій, невиконання критеріїв стійкості
Агроекологічні практики (No-Till, Strip-Till, крапельне зрошення, точне землеробство, виведення стійких сортів, тощо)	М: Депонування вуглецю в ґрунті, зменшення витрат дизпалива, зменшення енергоспоживання на інфраструктурі А: Запобігання вітровій та водній ерозії, збереження ґрунтової вологи в умовах дефіциту опадів	Збільшення вмісту органічного вуглецю в ґрунті на 0.1–0.3% щорічно. Економія палива: 20–50% (20–40 літрів/га). Скорочення викидів 0.5…1 т CO_2-екв./тне (заміщеного палива)	Початкове зниження врожайності у перші роки, проблеми кваліфікації персоналу, проблеми з критеріями стійкості, великі інвестиції, необхідність закупівлі спецтехніки, вибудовування складної системи моніторингу,
Енергетичні культури, проєкти запобігання iLUC	М: Забезпечення сталого постачання біопалива з мінімальним вуглецевим слідом. А: Вирощування на деградованих/малородючих землях, стабілізація зсувів, відновлення біорізноманіття.	Потенціал площ в Україні: до 2–3 млн. га маргінальних земель. Поглинання: 10–20 т CO_2-екв./га/рік (міскантус, енергетична верба, тополя).	Необхідність суворого сертифікаційного контролю (ISCC).
Мала та мікрогідроенергетика (русловi ГЕС)	М: Генерація чистої відновлюваної електроенергії з низьким вуглецевим слідом. А: Локальне регулювання паводків, створення резервуарів прісної води для посушливих періодів.	Скорочення 0.4–0.6 т CO_2-екв./МВт·год Забезпечення автономності громад. Підвищення стійкості до паводків	Ризик порушення річкових екосистем, замулення русел; висока залежність від сезонного обміління річок.

та підвищують стійкість екосистем чи інфраструктури (адаптація).

Нижче в таблиці 2 наведено оцінку з якісними та кількісними показниками для умов України, щодо синергетичного ефекту основних груп заходів мітігації і адаптації.

Групи заходів, звісно, не обмежуються представленими, але така оціночна матриця може бути розроблена для всіх компонентів кліматичної безпеки в комплексі, що може надалі бути використано для кількісних оцінок в процесі розробки Концепції кліматичної безпеки України.

Висновки і рекомендації

1) Скоординувати державну політику у сфері кліматичної безпеки через створення єдиного координаційного органу, Офісу кліматичної безпеки, з чітко визначеними повноваженнями.

2) Розробити Концепцію кліматичної безпеки як окремий інтегрований документ, що пов'яже енергетичне, кліматичне та військове планування, врахувати синергетичні ефекти від заходів мітігації та адаптації.

3) Доповнити стратегічні документи України, такі як НПЕК-2030, Енергетична стратегія-2050, Національна безпекова стратегія, План відновлення України, та інші пов'язані новим окремим розділом «Кліматична безпека». Інтегрувати поняття «Кліматична безпека» у ЗУ «Про основні засади державної кліматичної політики».

4) Передбачити координацію заходів і пріоритетне фінансування тих, що мають ефект і для адаптації і для мітігації в процесі справедливого переходу

5) Обов'язкова ESG-звітність для бізнесу як ключовий елемент отримання фінансування від міжнародних фондів і донорів і Фонду кліматичної безпеки.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.
КОНФЛІКТ ІНТЕРЕСІВ: Автори заявляють про відсутність конфлікту інтересів.

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ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ВПЛИВУ НА ТЕПЛОВИЙ СТАН БАГАТОШАРОВОЇ СИСТЕМИ УМОВ ЇЇ ОХОЛОДЖЕННЯ

STUDY OF THE REGULARITIES OF COOLING CONDITIONS INFLUENCE ON THE THERMAL STATE OF A MULTILAYER SYSTEM

Анотація. *Дану роботу присвячено аналізу закономірностей впливу струменевого охолодження на температурний режим багатошарової системи «покриття-підшар-основа».*
Ключові слова: *температура, охолодження, система «покриття-підшар-основа».*

Summary. *This work is devoted to the analysis of the regularities of influence of jet cooling on the temperature regime of the multilayer "coating-sublayer-base" system.*
Key words: *temperature, cooling, multilayer "coating-sublayer-base" system.*

При реалізації плазмово-дугового способу нанесення покриттів достатньо широке застосування знаходить струменеве охолодження оброблюваних деталей. Дане охолодження запобігає перегріву виробу та окисленню власне покриття. Крім того воно служить для усунення небезпеки коробления в умовах достатньо невеликих розмірів напилюваних деталей і достатньо значних товщин напилюваних покриттів (більш $0{,}5\cdot10^{-3}\ldots1\cdot10^{-3}$). Як охолоджуючі агенти а даній роботі використовуються різні гази (стиснутий газ, аргон, азот, вуглецевий газ) та вода [1–8].

Дана робота присвячена налізу закономірностей впливу струменевого охолодження на температурний режим досліджуваної багатошарової системи. Розглядались ситуації, що відповідають різним умовам охолодження на верхній та нижній обмежуючих поверхнях досліджуваного об'єкту. Досліджуються умови, які відповідають відсутності та наявності спеціального охолодження системи. В останньому випадку розгляду підлягали такі варіанти охолодження: 1 — спеціальне охолодження повітрям або водою вільної поверхні покриття; 2 — охолодження водою тільки вільної поверхні основи; 3 — спільне охолодження водою вільних поверхонь покриття та основи.

На рисунках 1, 2 та 3 наведено характерні дані отриманих чисельних рішень за наступних значень вихідних параметрів: $x_1 = 2{,}56$; безрозмірна товщина підшару $\Delta_2 = 0{,}0085$; товщина одиночного шару покриття $\Delta_3 = 0{,}00425$; Pe = 129,6. Інші вихідні дані наведено в таблиці 1.

Згідно з отриманими даними струменево повітряне охолодження в умовах, що розглядаються малоефективне. А водяне ж охолодження дозволяє в цілому суттєво зменшити температурні рівні покриття, як показано на рис. 1. Тут $\theta^* = \theta / \theta_{від}^{max}$, де $\theta_{від}^{max}$ — максимальна безрозмірна температура при відсутності спеціального охолодження системи. Відмінності температур, які відповідають відсутності і наявності спеціального охолодження поверхні покриття повітрям, не перевищують 0,0172, зниженню температури за рахунок водяного охолодження досягає 0,145. Як видно, вплив охолодження локалізується в зоні прилеглій до поверхні теплопідводу. По мірі віддалення від поверхні теплопідводу розбіжність порівнюваних температур зменшується, так що на нижній поверхні системи вони виявляються незначними. В ситуації, що аналізується спостерігається прояв ефекту регіонального впливу граничних умов третього роду на поверхні теплопідводу.

Зупинимось на розгляді закономірностей впливу умов охолодження на вільній поверхні основи. Особлива увага приділяється порівняльному аналізу даних, що відповідають різним товщинам основи δ_1. На рис. 2а) наведено результати, що відносяться до ситуації, коли товщина основи $\delta_1 = 0{,}34$ на рис. 2

Таблиця 1

Варіанти розрахунків

№ варіанту	Характеристика умов охолодження	Bi_{y_0}, 10–3	Bi_{y_1}, 10–3	Товщина основи Δ_1
1	Відсутність спеціального охолодження	5,95	5,96	0,34
2	Спеціальне охолодження повітрям вільної поверхні покриття	149	5,96	0,4
3	Охолодження водою вільної поверхні покриття	1490	5,96	0,34
4	Спеціальне охолодження повітрям вільної поверхні покриття	5,96	149	0,34
5	Охолодження водою вільної поверхні покриття	5,96	1490	0,34
6	Сумісне охолодження водою вільної поверхні покриття та основи	1490	1490	0,34
7	Відсутність спеціального охолодження	5,96	5,96	0,34
8	Охолодження водою вільної поверхні основи	5,96	1490	0,34
9	Сумісне охолодження водою вільної поверхні покриття та основи	1490	1490	0,34

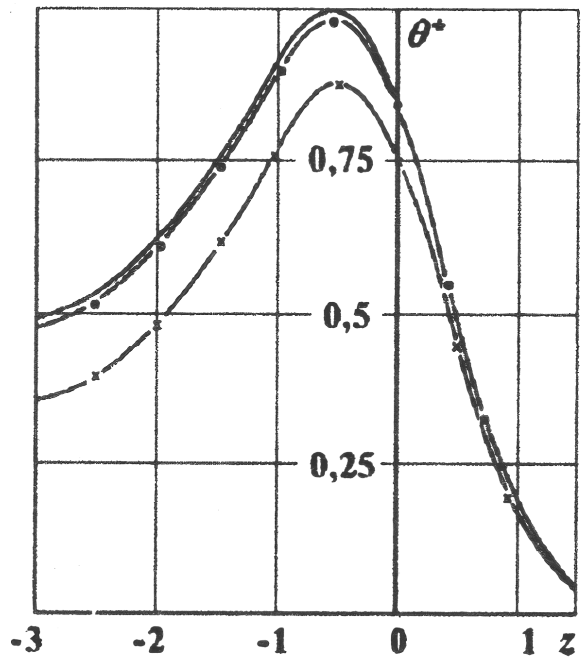
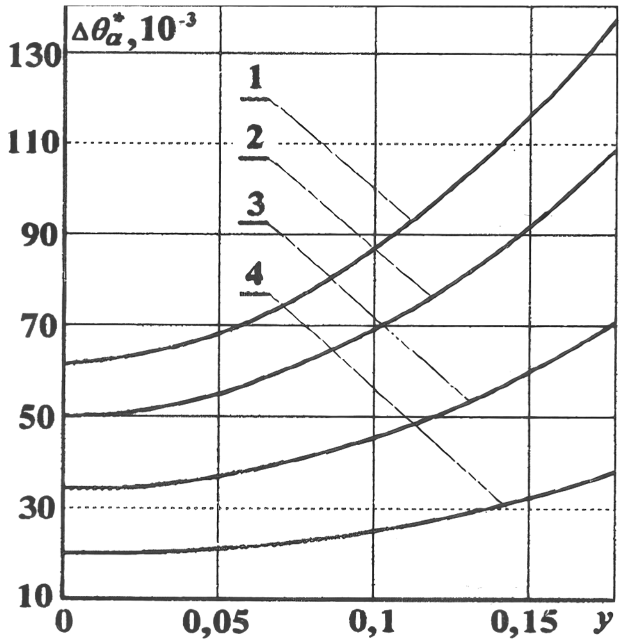


Рис. 1. Розподіл безрозмірної температури θ^* вздовж осі z в шарово-неоднорідній системі «одношарове покриття-підшар-основа» для різних умов охолодження вільної поверхні покриття: 1 — відсутність спеціального охолодження, $Bi_{y_0} = 5{,}96\cdot10^{-3}$; 2 — спеціальне охолодження повітрям $Bi_{y_0} = 0{,}149$; 3 — спеціальне охолодження водою, $Bi_{y_0} = 1{,}49$

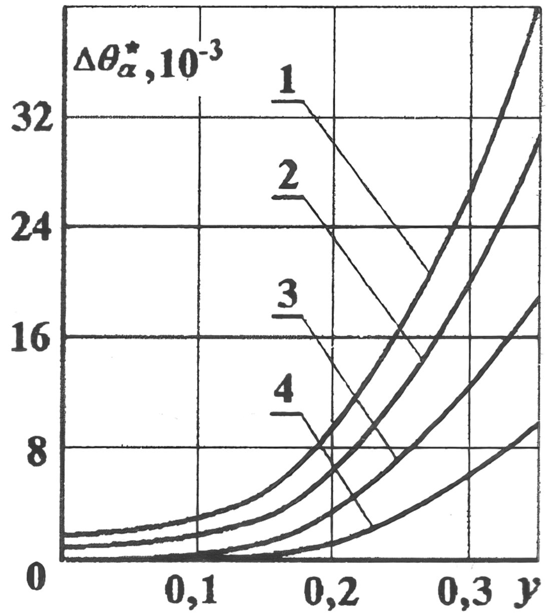
б) — $\delta_1 = 0{,}17$. Як видно із зіставлення рис. 2а) та б) чим більша товщина основи δ_1, тим менші при інших рівних умовах відхилення температур $\Delta\theta_\alpha^*$. Тут $\Delta\theta_\alpha^* = \Delta\theta_\alpha \,/\, \Delta\theta_{від}^*$, де $\Delta\theta = \theta_{від} - \theta$, де $\theta_{від}$, θ — відповідно температури системи при відсутності та наявності спеціального охолодження. Ефект зниження температури пов'язаний з водяним охолодженням основи виявляється більш суттєвим при малих значеннях δ_1. Так в точці з координатами $x = 0$, $z = -3{,}075$, розташованій на нижній поверхні системи, вказане зниження температури $\Delta\theta_\alpha^*$ складає 0,0382 при $\delta_1 = 0{,}34$ і досягає 0,137 при $\delta_1 = 0{,}17$. В випадку достатньо великої товщини δ_1 вплив умов охолодження основи локалізується поблизу її нижньої поверхні, а при малих товщинах δ_1 вплив водяного охолодження основи помітно позначається по всій її товщині.

Із проведеного аналізу слідує, що в умовах газотермічного напилення водяне охолодження вільної поверхні основи виявляється достатньо ефективним в плані забезпечення необхідного температурного режиму власне покриття лише при відносно невеликих товщинах основи.

Перейдемо до розгляду особливостей впливу на тепловий стан системи спільного охолодження водою її верхньої та нижньої поверхні. Для з'ясування специфіки цього впливу доцільним є зіставлення отриманих даних з відповідними результатами, які відповідають охолодженню лише вільної поверхні основи. Згідно з отриманими результатами, зниження температури обумовлене спільним охолодженням, виявляється значно більшим за величиною



а)



б)

Рис. 2. Залежність $\Delta\theta_\alpha^* = f(y)$ в системі «одношарове покриття-підшар-основа» для $z = -3{,}075$ за умов спеціального охолодження водою ($Bi_{y_0} = 1{,}49$) вільної поверхні основи: 1 – $x = 0$; 2 – $x = 0{,}53$; 3 – $x = 0{,}85$; 4 – $x = 1{,}12$; а) при $\Delta_1 = 0{,}34$; б) при $\Delta_1 = 0{,}17$

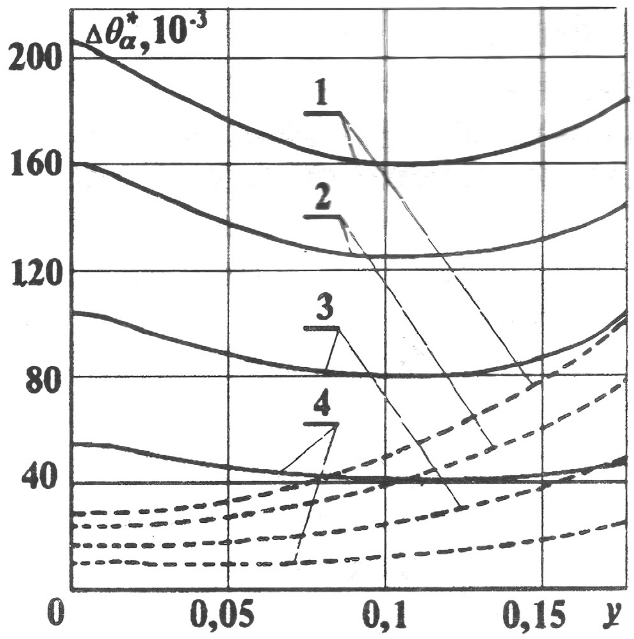


Рис. 3. Залежність $\Delta\theta_\alpha^* = f(y)$ в системі «одношарове покриття-підшар-основа» при Δ_1 = 0,17 для z = –2,05: 1 – x = 0; 2 – x = 0,53; 3 – x = 0,85; 4 – x = 1,12; пунктирна (штрихова) лінія — охолодження водою тільки вільної поверхні основи Bi_{y_0} = 1,49; суцільна лінія — сумісне охолодження водою вільної поверхні покриття і основи, $Bi_{y_0} = Bi_{y_1}$ = 1,49

ніж у випадку охолодження тільки вільної поверхні основи. Наприклад, в точці з координатами x = 0, z = –3,075, яка знаходить на верхній поверхні системи, величина $\Delta\theta_\alpha^*$ = 0,246 в умовах спільного охолодження і $\Delta\theta_\alpha^*$ = 0,137 при охолодженні лише нижньої поверхні основи.

Представляє також інтерес також те, що при односторонньому та двосторонньому охолодженні характер впливу умов охолодження по висоті системи є принципово різним. А саме, у випадку одностороннього охолодження максимальне зниження температури $\Delta\theta_\alpha^*$ реалізується на поверхні, що охолоджується, з віддаленням від неї величина $\Delta\theta_\alpha^*$ зменшується. Тобто має місце монотонна зміна величини $\Delta\theta_\alpha^*$ вздовж координати y (див пунктирні лінії на рис. 3). В умовах двостороннього охолодження залежність $\Delta\theta_\alpha^* = f(y)$ має екстремальний характер. При цьому найменші значення відмінностей температур $\Delta\theta_\alpha^*$ спостерігаються в центральній по товщині частини системи (суцільні лінії на рисунку 3). Очевидно, описана картина поведінки величини $\Delta\theta_\alpha^*$ безпосередньо пов'язана з тенденціями, які зумовлені ефектами регіонального впливу граничних умов третього роду на вільних поверхнях покриття та основи.

ДОДАТКОВА ІНФОРМАЦІЯ

ВНЕСОК АВТОРІВ: Усі автори зробили внесок порівну.
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АНАЛІТИЧНЕ ПОРІВНЯННЯ СТРАТЕГІЙ ЛІНИВОГО ТА НЕТЕРПЛЯЧОГО ВІДНОВЛЕННЯ У РОЗПОДІЛЕНИХ СХОВИЩАХ

ANALYTICAL COMPARISON OF LAZY AND EAGER REPAIR IN DISTRIBUTED STORAGE

Анотація. *Розподілені сховища з надлишковим кодуванням потребують стратегії відновлення блоків після відмов вузлів. Нетерпляче відновлення (ER) запускається негайно, ліниве (LR) відкладає ремонт до критичного порогу, задаючи компроміс між надійністю та витратами пропускної здатності. Запропоновано марківську модель обох стратегій; виведено вирази для ймовірності втрати даних і витрат на відновлення та замкнену умову переходу λ*, що визначає межу доцільності лінивого відновлення.*

Ключові слова: *розподілені сховища, надлишкове кодування, ліниве відновлення, нетерпляче відновлення, ланцюги Маркова, ймовірність втрати даних, витрати на відновлення.*

Summary. *Distributed storage systems with erasure coding require a strategy for repairing blocks after node failures. Eager repair (ER) starts immediately; lazy repair (LR) defers repair until a critical threshold, trading a wider vulnerability window for bandwidth savings. We propose a Markov model that formalizes both strategies and derive expressions for the data loss probability, repair costs, and a closed-form transition condition λ* that determines when lazy repair is appropriate.*

Key words: *distributed storage, erasure coding, lazy repair, eager repair, Markov chains, data loss probability, repair bandwidth.*

Вступ. Сучасні децентралізовані сховища — Filecoin, Codex, Walrus — використовують надлишкове кодування (erasure coding) для захисту від відмов вузлів [1]. У схемі (n, k) об'єкт розбивається на n блоків, і для його відновлення достатньо будь-яких $k < n$ з них. При відмові вузла система втрачає блок, зменшуючи запас надлишковості. Якщо до наступного відновлення відбудеться ще $n - k$ відмов, дані втрачаються безповоротно.

Ключове проектне рішення — *коли* запускати відновлення. Стратегія ER усуває дефіцит негайно після кожної відмови, підтримуючи повну надлишковість, але генерує постійний ремонтний трафік. Стратегія LR відкладає відновлення до моменту, коли кількість наявних блоків досягає критичного порогу δ або минає часовий ліміт D, знижуючи витрати пропускної здатності ціною ширшого вікна вразливості.

Системи Walrus і Codex декларують використання LR [2], проте не надають аналітичного обґрунтування умов його доцільності. Існуючі теоретичні роботи аналізують надійність розподілених сховищ через ланцюги Маркова [3], але не порівнюють LR та ER у єдиній формальній рамці.

Внески цієї роботи: Єдина марківська модель для ER та LR із загальними параметрами λ, D, n, k. — Аналітичний вираз для P_loss та порівняльний аналіз B_repair для обох стратегій. — Замкнена умова переходу λ*, що визначає межу доцільності LR.

Аналітична модель

Модель системи

Розглядаємо один об'єкт, закодований у схемі (n, k): n блоків, мінімум k для декодування. Стан системи $s \in \{k, k+1, \dots, n\}$ — кількість наявних блоків. Відмови блоків незалежні; кожен блок відмовляє зі швидкістю λ. Відновлення одного блоку займає час, розподілений експоненційно з середнім t_r (мережева передача + запис), $\mu = 1/t\_r$.

Стан втрати: $s = k - 1$ — поглинаючий стан, з якого відновлення неможливе.

Нетерпляче відновлення (ER)

При ER відновлення починається негайно після кожної відмови. Система поводиться як ланцюг народження-загибелі зі станами $\{k, \dots, n\}$:

- **Перехід s → s — 1** (відмова): швидкість $\alpha\_s = s \cdot \lambda$
- **Перехід s → s + 1** (відновлення, $s < n$): швидкість $\mu\_ER = 1 / t\_r$

Ймовірність втрати визначається як першопрохідна ймовірність досягнення стану k - 1 до повернення до стану n [3]. При μ_ER >> λ втрата вимагає $n - k$ послідовних відмов до першого завершення ремонту. Ймовірність відмови до ремонту у стані s становить $s{\cdot}\lambda / (s{\cdot}\lambda + \mu\_ER) \approx s{\cdot}\lambda / \mu\_ER$. Перемноживши по всіх станах від n до $k + 1$, отримуємо формулу (1):

$$P_{loss}^{ER} \approx \prod_{s=k+1}^{n} \frac{s\cdot\lambda}{\mu_{ER}} = \frac{n!}{k!}\cdot\left(\frac{\lambda}{\mu_{ER}}\right)^{n-k} \qquad (1)$$

Очікувані витрати на відновлення: B_repair^ER ≈ $n{\cdot}\lambda{\cdot}$B_block за одиницю часу, де B_block — розмір одного блоку. При μ_ER >> λ система переважно перебуває у стані n, тому частота ремонтів приблизно дорівнює $n{\cdot}\lambda$.

Ліниве відновлення (LR)

При LR відновлення не запускається, поки $s > \delta = k + 1$. Коли s досягає δ, система чекає D одиниць часу перед початком відновлення. Відповідно, вікно вразливості між входом у стан δ і завершенням відновлення становить $D + t\_r$.

У стані $s = k + 1$ система перебуває перед єдиним кроком до втрати. Ймовірність втрати обчислюється як ймовірність того, що наступна відмова відбудеться раніше, ніж завершиться відновлення, відповідно до формули (2):

$$P_{loss}^{LR} = \frac{(k+1)\cdot\lambda}{(k+1)\cdot\lambda+\mu_{LR}} \qquad (2)$$

де μ_LR = 1 / (D + t_r). Підставляючи, отримуємо формулу (3):

$$P_{loss}^{LR} = \frac{(k+1)\cdot\lambda\cdot(D+t_r)}{1+(k+1)\cdot\lambda\cdot(D+t_r)} \qquad (3)$$

При LR ремонт відбувається лише при досягненні порогу δ. Нехай ν_LR — частота досягнення δ з початкового стану n. Оскільки у LR ремонту немає вище δ, система дрейфує вниз виключно через відмови; час першого проходження від стану n до k + 1 складається з $n - k - 1$ незалежних фаз, і ν_LR ≈ λ / Σ_{s=k+2}^{n} (1/s). Звідси отримуємо формулу (4):

$$B_{repair}^{LR} \approx \nu_{LR}\cdot(n-k)\cdot B_{block},\ \ \nu_{LR} \ll n\lambda \quad \text{при } \lambda \ll \mu_{ER} \qquad (4)$$

Умова переходу λ*

Визначимо λ* як значення λ, за якого обидві стратегії забезпечують однакову P_loss. При малих λ, де (k + 1)·λ·(D + t_r) << 1, права частина лінійна, як показано у формулі (5):

$$P_{loss}^{LR} \approx (k+1)\cdot\lambda\cdot(D+t_r) \qquad (5)$$

Прирівнюючи до P_loss^ER і ділячи на λ*, отримуємо формулу (6):

$$\frac{n!}{k!}\cdot\frac{\left(\lambda^*\right)^{n-k-1}}{\mu_{ER}^{n-k}} = (k+1)\cdot(D+t_r) \qquad (6)$$

Розв'язок для $n - k \geq 2$ подано у формулі (7):

$$\boxed{\lambda^* \approx \left[\frac{(k+1)!\cdot(D+t_r)\cdot\mu_{ER}^{n-k}}{n!}\right]^{\frac{1}{n-k-1}}} \qquad (7)$$

Згідно з формулою (7), для $n - k \geq 2$ існує єдина точка перетину λ* (ліва частина зростає як λ^(n–k–1), права є константою відносно λ). Для $n - k = 1$ ліниве та нетерпляче відновлення мають різні P_loss при будь-якому λ > 0, і LR завжди гірше за ER на величину, пропорційну D.

Практичний наслідок: λ* спадає зі збільшенням D — чим довша затримка LR, тим вужчий діапазон λ, за якого LR є безпечним. При D → 0 λ* → ∞ (LR завжди безпечне). При D >> 1/((k+1) λ) ймовірність втрати при LR прямує до 1.

Висновки. Ми запропонували єдину марківську модель для порівняння стратегій лінивого та нетерплячого відновлення у розподілених сховищах. Ключовий результат — замкнений аналітичний вираз для порогу λ*, що дозволяє проектувальникам системи обирати стратегію без симуляції: при* $\lambda < \lambda$ ліниве відновлення забезпечує еквівалентну надійність при значно менших витратах пропускної здатності; при $\lambda > \lambda^*$ нетерпляче відновлення є необхідним.

Обмеження. Модель передбачає незалежні відмови вузлів, пуасонівський процес відмов та експоненційно розподілений час відновлення. Корельовані відмови (збій стійки, відмова дата-центру) виходять за межі цієї роботи.

Майбутня робота: валідація моделі на реальних трасах відмов (Filecoin, Storj) [4] та розробка адаптивної стратегії, що динамічно перемикається між LR та ER на основі поточної оцінки λ.

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Література

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