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ЕКОНОМІЧНІ НАУКИ

STRUCTURING MULTICHANNEL DEMAND GENERATION SYSTEMS IN THE GLOBAL EMPLOYMENT SERVICES MARKET

Summary. *This conceptual article examines how demand is generated, segmented, and converted in the global employment services market – a market whose institutional heterogeneity, territorial fragmentation, and acute legal and personnel risks make the interorganizational customer journey unusually long and multi-actor. Drawing on customer-journey and buying-center research, switching-cost theory, the internationalization literature, and transaction cost economics, the article develops an integrative account of multichannel demand generation as a single commercial system whose effectiveness depends on the internal coherence of segmentation, messaging, content, channels, and commercial routing. Its contribution is threefold. First, it proposes that demand in cross-border employment services be segmented along three interacting axes – the client's prior experience with international hiring, the mode of market entry, and the composition of the buying circle – rather than by generic firmographic variables. Second, it identifies an affective dimension of demand specific to this market: the perceived overload of technical buyers confronting a high-stakes, largely non-technical entry decision. Third, it advances a structural argument that horizontally optimized providers underperform in high-specificity segments such as technology, where specialized provision holds the advantage. These claims are stated as five explicit propositions available for empirical testing, and the argument concludes with a staged implementation model – diagnose, design, pilot, scale – for practitioners. The article will be useful to business development leaders, go-to-market strategists, and commercial teams in international employment services.*

Key words: *global employment services market, demand generation, B2B customer journey, buying center, demand segmentation, cross-border employment services, employer of record, go-to-market strategy.*

Introduction. In the global employment services market, demand generation has become a core coordinating function, because the market it operates in is fragmented across jurisdictions and institutionally diverse. As cross-border hiring expands, digital labor platforms proliferate, and compliance requirements intensify, clients increasingly need an intermediary that can connect a personnel need to legal, payroll, and organizational infrastructure at speed. In this environment demand rarely arises on its own. It must be cultivated through the sequential explication of service value, the reduction of perceived risk, and the continual confirmation of supplier reliability. Consequently, the importance of digitalization and intermediate institutions for the labor market has been noted [15; 16], and studies on interorganizational customer journeys have shown that for companies the key to competitiveness is to master the entire service contact chain as a system [14].

The behavior of the corporate buyer has also become considerably more complex in recent years [28]. The decision to purchase an employment service is formed incrementally and includes several levels of coordination within the client company. Typically, the discussion involves the HR function, the finance unit, the legal department, procurement, and operational managers. The path to a deal therefore runs through many touchpoints, spread over time and differing in function: some frame the problem, some help compare solutions, and some exist to overcome internal objections and build consensus among the stakeholders involved. A concept of the interorganizational customer journey as a complex, relational, and multistage construct of procurement processes, decision centers, and interfirm relationships is emerging in the literature [11]. Moreover, recent studies find that the alignment of customer experience occurs simultaneously at the individual, team, and organizational levels [9], which

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further multiplies the points a demand system must coordinate [26]. For precisely this reason, demand in the employment services market cannot be regarded as a reaction of a single individual to a single marketing message.

This suggests that single-channel marketing is a poor fit for environments in which the client traverses a long evaluative trajectory, where different channels and stages are invoked at various times, and where different information is processed depending on organizational role. Research suggests that customer journey management improves firm outcomes when the company preserves the integrity of customer relationships, structures the sequence of interactions, and aligns digital and in-person forms of interaction [14; 26]. The customer-journey construct itself, as consolidated by Lemon and Verhoef [24], conceives the journey as a sequence of prepurchase, purchase, and postpurchase stages composed of touchpoints that differ in ownership — brand-owned, partner-owned, customer-owned, and social/external — only some of which the firm directly controls. Becker and Jaakkola [1] likewise distinguish firm-controllable from non-controllable stimuli and argue that experience management consists in steering the customer toward intended responses across them. Coherence matters precisely for this reason: the firm cannot dictate every touchpoint, only orchestrate consistency across those it owns and respond deliberately to those it does not. In the employment services market, this is especially important because trust develops slowly, and an unsuitable supplier choice can carry meaningful implications for staffing continuity, compliance, and cost. Therefore, any further consideration of a multichannel demand generation system must proceed from the premise that a channel constitutes part of a broader architecture of persuasion, navigation, and coordination of interests within the client company.

Although the global employment services market has grown in economic significance, scholarly attention to it remains unevenly distributed. Cross-border employment services — employer-of-record models, outstaffing, and international staffing — have been analyzed mainly in terms of their legal, regulatory, and tax implications [19]. While academic scholarship on the operational aspects is emerging, it still remains limited. Yet, systematic research from a business-to-business (B2B) perspective remains scarce for these services. This scarcity is exacerbated by the fact that the more general B2B literature on customer journeys and buying centers [14; 28; 11; 22] does not consider its specific interorganizational demand management processes due to the institutional heterogeneity, territorial fragmentation, and specific legal and personnel risks involved. A gap therefore remains: how demand is generated, segmented, and converted in cross-border employment services has not been articulated as a coherent commercial system.

This article addresses that gap by proposing a multi-axis model of demand segmentation for cross-border employment services. Its contribution is threefold. First, it holds that demand in this market cannot be adequately segmented by generic variables such as need, scale, or organizational maturity, and structures it instead along three interacting axes: the client's prior experience with international hiring (first-time versus incumbent-switching), the chosen mode of market entry (a small beachhead versus full-scale establishment), and the composition of the buying center, which in technology shifts toward technical leadership acting as economic buyer. Second, extending an underexplored thread in organizational-buying research that recognizes the role of emotion alongside rational evaluation, it identifies an affective dimension specific to this market: the perceived overload of technical buyers facing an inherently non-technical, high-complexity entry decision, which operates as an independent determinant of demand. Third, it advances a structural argument that horizontally optimized providers — efficient for generalized cross-border hiring — underperform in high-specificity segments such as technology, where role-specific conditions become the decisive criterion, thereby defining where a specialized demand system must concentrate. Existing research on professional service operations [25] does not address the demand-segmentation architecture required to sustain role-specific specialization at scale. This structural argument is advanced as a testable proposition (developed as P5 below) rather than an established result, and it is explicitly bounded: where role-specificity is low, horizontally optimized providers retain the advantage on coverage, speed, and cost.

Methodology. This article is conceptual in nature. Following Jaakkola's [17] account of conceptual research designs, it combines two of the four templates she identifies: theory synthesis, which integrates findings dispersed across separate literatures into a more coherent whole, and typology, which organizes a phenomenon into distinct, theoretically grounded types. Sources were selected from peer-reviewed literature published primarily between 2016 and 2026, supplemented by foundational theoretical works [e.g., 32; 18], with purposive sampling prioritizing fit to the cross-border employment context and organizational buying research rather than systematic-review coverage. Experience and entry mode are treated as the two independent conditioning dimensions, chosen to isolate the conditions that govern buying-center composition and decision pathways, with these dimensions interacting to define segments within which demand properties remain stable. The analysis concentrates explicitly on the technology segment of cross-border employment services, where the mismatch between technical decision-weight and non-technical service attributes creates distinctive demand conditions not present in generalized labour provision. The aim is not

to test hypotheses on primary data but to construct an integrative account of demand generation in the global employment services market and to specify how demand in this market can be segmented. Consistent with the requirements of conceptual work, the theories drawn upon and their role in the analysis are made explicit below.

The analysis draws on several bodies of literature that function as its domain theories. B2B customer-journey and buying-center research [24; 1; 28; 11; 14; 26; 23; 4] supplies the model of multi-actor, multi-stage interorganizational demand and the mechanics of influence within the buying center. Pre-purchase interaction and trust formation in HR services [22] supplies the mechanism of value formation before contract, and the organizational-buying literature on emotion in ostensibly rational decisions [20] supplies the affective component of the argument. The segmentation and structural claims additionally draw on switching-cost theory [6; 3], the internationalization literature on market selection, entry mode, and staged commitment [18; 27; 2; 13], and transaction cost economics [32; 12]. Evidence on the structure and scale of the market is drawn from the International Labour Organization [15; 16] and from recent labour-market analysis of growth in complementary-human-skills demand relative to substitutable-skills decline [30]. Sources were selected purposively for their fit to the cross-border employment context rather than through systematic-review sampling, consistent with a synthesis-and-typology design whose goal is conceptual integration rather than exhaustive coverage. The analysis is additionally informed by the author's experience leading commercial functions in the global staffing and employment services sector, used as an interpretive lens on the synthesized literature rather than as a source of primary data. Because the author holds a commercial role at a specialized provider, this position is disclosed explicitly; the structural claims about specialized versus generalized provision are grounded in the cited literature rather than in proprietary experience.

The synthesis proceeds by comparing how these literatures treat segmentation, messaging, content, channels, and commercial routing, and by integrating them around the organizing claim that demand becomes a stable flow of deals only when these elements are internally coherent. Where the argument advances claims that the existing literature does not yet establish — the three-axis segmentation, the role of the technical leader, the affective dimension in this specific market, and the structural limits of horizontally optimized provision — these are stated as explicit propositions (P1–P5 below), in the manner of a conceptual model paper [17], so that they are available for subsequent empirical testing. Because the study is conceptual, it does not provide primary empirical validation of these propositions; that limitation and the resulting research agenda are addressed below.

Results and Discussion

The Market and Its Buying Dynamics

Following the introduction, the subject of analysis must be delineated more precisely, as the global employment services market comprises a set of heterogeneous intermediary and operational solutions that connect employers with labor resources, payroll infrastructure, and legal support. This market includes temporary and permanent staffing services, the engagement of workers through an external employer, international payroll administration, management of contingent workers, the outsourcing of recruitment functions to a specialized provider, support for international mobility, and services related to compliance with labor requirements across different jurisdictions. Such a market composition has emerged under the influence of digitalization and the expansion of cross-border employment. The International Labour Organization associates this shift with the growth of digital labor platforms and with the deepening of intermediary forms of labor organization in the global economy, which renders the employment services market both more capacious and more heterogeneous [15]. This means that demand formation must be structured so that a single company can simultaneously require recruitment, payroll, personnel administration, and legal protection. This institutional and territorial specificity is not merely an operational complication; it shapes how demand itself must be segmented and addressed — a commercial consequence that generalized, horizontally optimized provision tends to overlook.

A particularly salient manifestation of this complexity can be observed in the technology industry, where firms frequently combine rapid international expansion with volatile hiring plans, scarce specialist talent, and geographically distributed teams. These attributes of employment services usage we can denote as compressed decision times, sudden market engagement, and constant labor-force adaptation. Hence, the clients' demands are a compressed mix of hiring urgency, role specificities, cross-border payroll, precise contractor classifications, and last but not least continuity of execution in great growth spurts. For these reasons, the technology industry is the market sector most relevant to the study of multichannel demand generation, as the most important attributes of the service provider are speed, compliance reliability, operational scalability and ability to deploy a workforce in several jurisdictions simultaneously. Recent evidence drawn from tens of millions of job postings across several economies shows that demand for skills complementary to AI has grown substantially, even as AI substitutes for routine task execution [30]. This complementarity-rather than direct AI adoption alone-intensifies the need for employers to source diverse and specialized talent, placing additional coordination demands on external service partners navigating multiple skill categories, jurisdictions, and rapid hiring cycles.

The complexity of this market stems largely from the service's very structure. The client purchases not an isolated operation, but a bundle of processes, obligations, and guarantees that affect hiring, payments, taxes, employment status, cross-border data transfers, and the risks of labor disputes. The pre-contractual stage acquires a distinctly trust-based character. Research in the field of HR services for organizations shows that value in the early stages is formed through interaction, the joint clarification of expectations, and the gradual reduction of uncertainty [22]. This occurs because the potential client evaluates the supplier through the prism of competence, predictability, and the ability to account for the client's context. Within the logic of employment services, this is especially consequential because an error in supplier selection has repercussions for workers, budgets, and legal compliance. Therefore, demand here arises through the sequential accumulation of trust and cognitive certainty. The path to purchase becomes saturated with returns to previously addressed issues and repeated verification of arguments.

The customer journey in this market also has a cognitive and affective dimension that predominantly rational models tend to underweight. Establishing a presence in a new market — selecting jurisdictions, securing premises, ensuring compliance, and arranging payroll and equipment — is an inherently complex and largely non-technical undertaking. When the economic buyer is a technical leader, this complexity frequently produces a state of perceived overload and uncertainty [29], since the decision extends well beyond their domain of fluency. In this context, perceived risk and cognitive burden operate as independent determinants of demand alongside price and capability. The stakes are amplified by the asymmetry between what the provider prices and what the client commits: from the buyer's side, the decision is weighed not as a monthly service fee but as the full cost of the expansion — salaries carried many months ahead, operational time, and the exposure of a failed entry — so the magnitude against which risk is assessed is the commitment, not the rate. Research on organizational buying has shown that ostensibly rational purchase decisions are in fact shaped by emotion as well as fact, and that receptivity to emotion-based messaging is greater among higher-status, executive-level buyers [20] — precisely the position the technical leader frequently occupies. This thread nonetheless remains underexplored in the employment services context. A demand system that addresses only rational selection criteria, while neglecting the buyer's need for assurance that the full operational perimeter will be handled end to end, will underperform precisely with the stakeholder who most often holds budget authority.

Additional complexity arises from the regional fragmentation of demand. The norms regulating worker status, permissible forms of outsourcing HR functions, the calculation of mandatory payments, the storage of personal data, and the regime governing the use of contractors differ substantially between countries and even within particular integration spaces. As a result, the client's request is almost always tied to a specific territory and to a specific model of business expansion. At the same time, the purchasing decision is formed within a multilevel circle of participants. More recently, literature around interorganizational customer journeys describes it as an iterative trajectory within and between the relationships of multiple organizations, anchored to multiple centers of use and coordination. The same customer journey is perceived in different ways by the actors involved [28]; for example, the time and quality of employee onboarding is important to the HR function while price transparency and discipline in payroll are critical for the finance function. The legal department also considers the legal foundations of the employment model to be important. For procurement, supplier manageability and the comparability of terms are essential. For operational management, executional stability and launch timelines are decisive.

In technology-oriented segments, the composition of this buying circle differs from the general B2B pattern in a consequential way. Alongside HR, finance, legal, procurement, and operational management, the technical leadership function — the CTO, the VP or Director of Engineering, and senior engineering managers — frequently acts as the economic buyer or as a decisive technical gatekeeper, determining required headcount, the seniority and skill profile of engineers, and whether a given block of work is externalized at all. Its evaluation criteria are distinct: where finance assesses payroll discipline and legal assesses the regime of responsibility, technical leadership assesses the demonstrable engineering quality of candidates, the provider's understanding of distributed engineering workflows, and the risk that augmentation with external engineers erodes executional continuity and architectural coherence. In this segment, therefore, the buying circle is not merely broader; its center of gravity shifts toward technical leadership, and a demand system addressing only HR, procurement, and legal will systematically miss the participant who often holds both budget authority and veto.

The Multichannel System and Demand Segmentation

In this market, the multichannel demand system is a coordinated structure in which every channel answers to one commercial logic and works as part of a single persuasion trajectory. Its defining property is coherence. It sets common priorities across segments, territories, and service lines; it assigns each channel a function according to where the client stands on the path to a deal. It provides continuous feedback based on data on company behavior, depth of engagement,

and movement through the sales funnel. It personalizes content for different segments and roles within the client organization. It evaluates outcomes through contribution to the flow of qualified deals, since it is precisely this indicator that reflects the system's real commercial value. Research on interorganizational customer journey management indicates that effectiveness increases when a company is capable of coordinating touchpoints as a unified managerial capability, while the digitalization of the journey intensifies the significance of such coordination due to the growth in the number of channels, roles, and transitions between them [14; 26]. The employment services market cycle is shown in Figure 1.

After defining the nature of the global employment services market and describing the multichannel demand generation system as a coordinated commercial construct, it is logical to proceed to its strategic foundation. Such a system begins with a clear understanding of which companies possess the highest probability of moving from interest to deal. This concerns identifying the target customer profile and dividing the market into segments along three interacting axes — the client's prior experience with international hiring, the chosen mode of market entry, and the composition of the buying circle — developed in detail below. Here, it is especially important to consider how a company expands its workforce, how it distributes functions between internal teams and external suppliers, which risks it considers critical, and at what point in its growth it encounters constraints. Segmentation in this logic becomes a means of identifying manageable zones of demand within which it is possible to predict motives for contact, the depth of doubt, and the probable length of coordination.

These three axes can be stated explicitly. The first is the client's prior experience with international hiring. A first-time cross-border buyer that has never hired abroad, or never through an intermediary, is governed primarily by uncertainty and perceived risk; the pre-contractual trust dynamic operates at maximum intensity, and demand work must carry a heavy educational load. An experienced buyer already working with outsourcing or outstaffing providers, or with established international hiring platforms, faces a different barrier-not whether to hire abroad, but switching

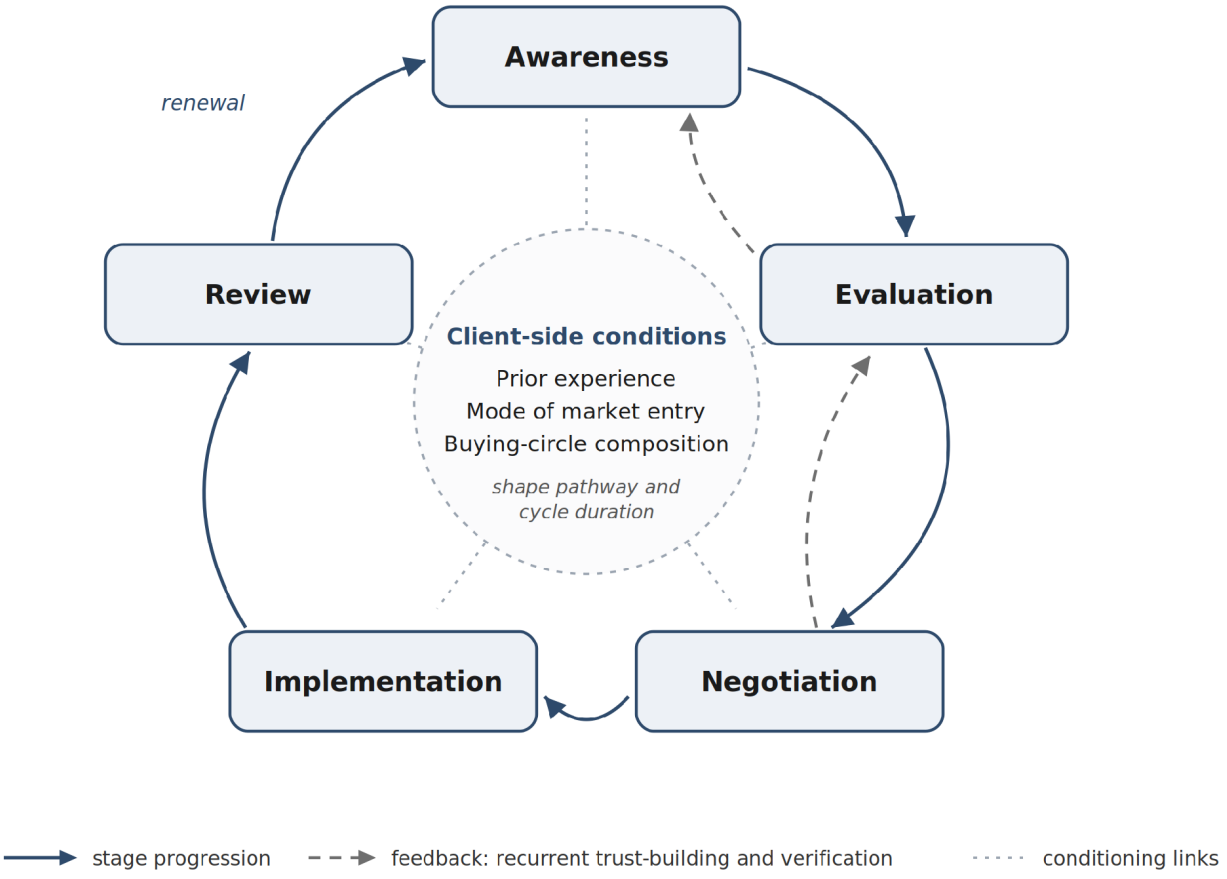


Fig. 1. The employment services market cycle. Clients progress through awareness, evaluation, negotiation, implementation, and review toward renewal, with feedback loops capturing recurrent trust-building and verification. Prior experience, mode of market entry, and buying-circle composition shape which pathway a client follows and how long the cycle runs

cost and demonstrable advantage over an incumbent solution-so the commercial question becomes comparative rather than educational. The second axis is the mode of market entry, understood here as the scale and staging of the commitment rather than its legal form. One client commits to full-scale entry from the outset, hiring twenty to fifty people (for illustration) and establishing a local office, while another begins with a small beachhead of a few engineers as a low-risk test and scales only after the initial cohort proves viable; these differ in decision velocity, risk tolerance, and the argument that moves them. The third axis is the composition of the buying circle, which in technology shifts toward technical leadership, as developed above.

These axes interact rather than operate in isolation. The experience regime predicts not only the barrier but the maturity and composition of the client's own decision process: first-time buyers frequently have not yet recognized that technical leadership must own seniority and skill decisions and may initiate the process through HR or procurement alone, whereas experienced buyers typically arrive with that function already central. Read together, the three axes yield a workable typology — a first-time, beachhead client requires maximum education and minimum risk, while an incumbent-switching, full-scale client compares options and moves quickly — that translates an abstract market into a small set of recognizable commercial situations. These four buyer types, together with each type's dominant barrier and demand response, are mapped in Figure 2, in which the diagonal indicates the shift in the buying circle's center of gravity from HR or procurement toward technical leadership.

The diagonal marks the buying circle's shift from HR- or procurement-initiated toward technical-leadership-centered decisions.

The journey through these decisions is itself ordered. A client typically settles first where to expand; then how to operate there — a choice with two related but distinct components: the form of establishment, ranging from contracting through an intermediary to setting up a wholly owned entity, and the scale and staging of the commitment, from a small initial cohort to a full local operation (for illustration); and only then with whom to contract, so that provider choice is a late and dependent stage rather than the organizing one.

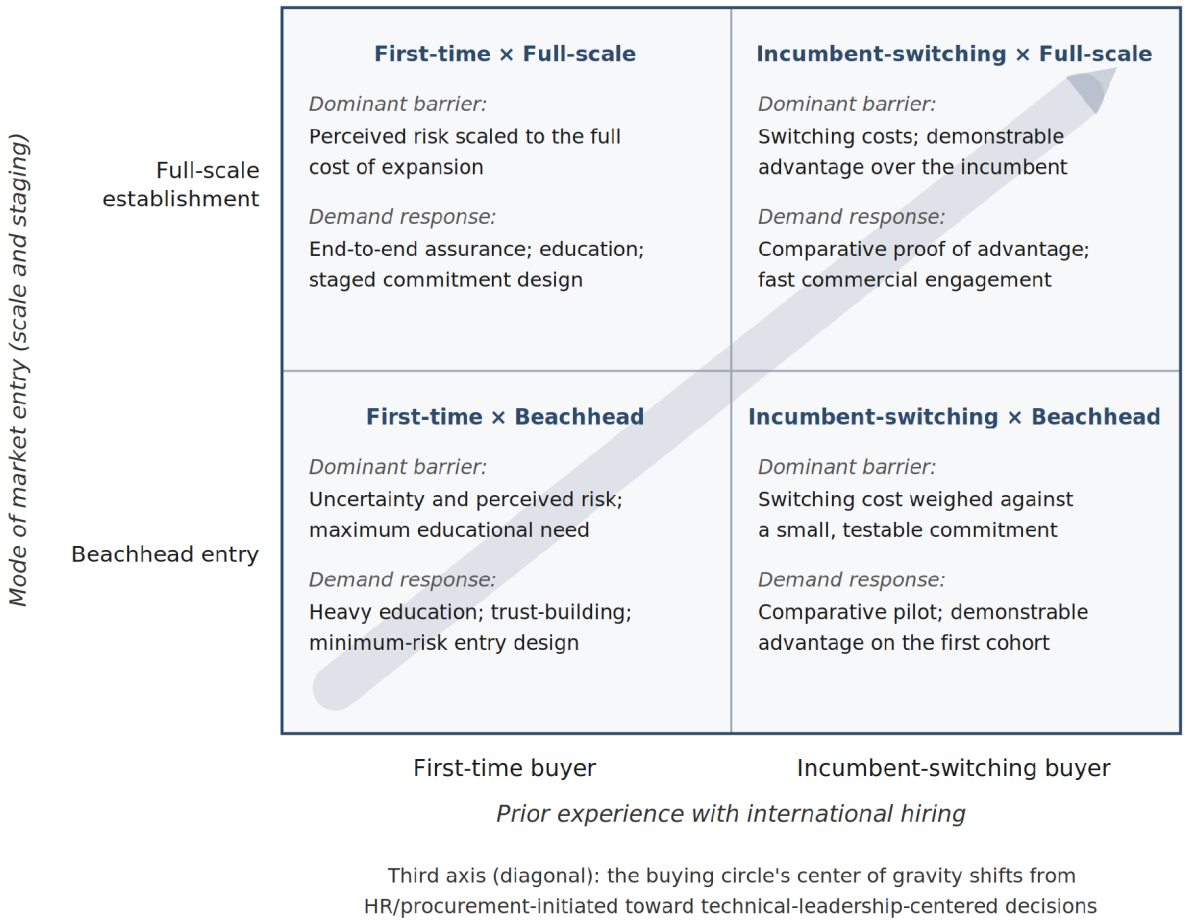


Fig. 2. A typology of demand in cross-border employment services. Two axes — the client's prior experience with international hiring (first-time versus incumbent-switching) and the mode of market entry (beachhead versus full-scale establishment) — define four buyer types, each with a distinct dominant barrier and demand response

This ordering mirrors the classical structure of the internationalization decision, organized around market selection and entry mode [13]: the form of establishment is a position on a control continuum that firms move along as circumstances change [27; 2], while commitment typically escalates in increments as experiential knowledge accumulates [18] — the pattern the beachhead entry reproduces. In cross-border employment, own entity, employer of record, and outstaffing are the contemporary positions on that continuum, and even clients that ultimately establish their own entity commonly rely on intermediated hiring and recruitment support during the transition, so the provider is relevant across the continuum rather than at its low-control end alone. Because provider selection depends on the country and mode choices that precede it, demand work on the early stages must address those questions rather than the provider's own merits, and the provider that helps shape the mode decision captures a more consequential point of leverage than the vendor comparison that follows it. The sequence is tightest where the entry is unfamiliar and high-stakes, and it compresses or reorders for experienced buyers who arrive with country and mode already settled.

The structure of supply differentiates demand further. Horizontally optimized providers are built for generalized cross-border hiring, and this is a genuine strength: it delivers breadth of jurisdictional coverage, speed, and operational simplicity for undifferentiated demand. The same optimization, however, leaves a structural gap in segments with high role-specificity, of which technology is the clearest case. Engineering roles are subject to specialized tax and incentive regimes in a number of jurisdictions, to classification nuances particular to technical work, and to talent competition markedly more intense than for many other professional categories. For a technology client, the provider's value therefore depends not only on compliant cross-border employment but on fluency in the specific conditions of engineering hiring — consistent with evidence that technical purchase complexity shifts buying-center evaluation toward expert criteria [7]. This helps explain the demand dynamic described above: an experienced client operating on a horizontal platform may switch not because the platform fails at generalized employment, but because role-specific depth becomes the decisive criterion — a consideration on which the technical leader in the buying circle is typically the participant who recognizes that gap first. (The author holds a commercial role at a specialized provider; however, horizontal platforms retain competitive advantage where clients prioritize standardization, cost efficiency, and multi-jurisdictional scale over role-specific expertise).

The next level of strategic work is associated with selecting target geographies and industry directions, since demand for employment services arises in a context of pronounced territorial and economic differences. Some markets create high demand for rapid employee onboarding in new countries. Others intensify the need for payroll support and personnel administration. Still others bring to the fore questions of employment regime, contractor status, and local labor compliance. For this reason, geography and industry specialization must be considered jointly. It is at this stage that the circumstances triggering purchasing behavior on the client side are determined, as well as which difficulties the client seeks to eliminate first and which pain points possess the greatest force. For one group of companies, the decisive basis becomes the acceleration of entry into a new market. For another group, the central motive is reducing operational overload. For a third, the greatest significance lies in reducing legal vulnerability. At the same time, priorities must be established among the service lines themselves, since different offering lines have different sales velocities, different depths of client engagement, and different capacities to open access to subsequent deals.

On this basis, reproducible demand work scenarios are developed, each built around a specific market situation. Such a scenario unites the target segment, the concrete reason for contact, a set of meanings, the route of contacts, and the expected commercial objective. Within one scenario, a company may work with organizations expanding their presence across several countries. Within another, it may interact with employers seeking to streamline payroll and personnel administration. Within each scenario, it is determined in advance which arguments will be primary, which signals will indicate increasing interest, and which set of channels will gradually translate attention into a deal discussion.

In technology-oriented market segments, the practical structuring of such scenarios increasingly depends on AI-powered go-to-market strategies. These strategies expand the firm's capacity to identify high-potential accounts, detect early expansion signals, and adapt commercial communication to the probable needs of different stakeholder groups. In the context of employment services, AI can support the interpretation of vacancy patterns, hiring velocity, geographic expansion signals, role seniority, skills demand, and recurring changes in workforce structure. This makes it possible to distinguish between firms that are merely visible in the market and firms that are approaching a concrete employment decision. For technology companies, this analytical layer is valuable chiefly for timing and relevance, since interest often becomes visible through publicly observable business activity before a formal purchasing request is issued. The provider can therefore structure outreach and content around observable indicators such as multi-country hiring activity, growth in AI-related roles, increased reliance on distributed engineering teams, or shifts from contractor-heavy models to more formal employment infrastructures.

Message Architecture, Channels, and Content

Once the strategic foundation has been defined, the architecture of the value proposition becomes crucial, as vague formulations rapidly lose persuasive force in the employment services market. Universal promises oversimplify the client's complex reality and poorly reflect the distinctions between the situations in which companies seek solutions. Therefore, the message must be structured on several levels. At the first level, an overarching meaning is set. It explains why the task of managing international employment, payroll, and personnel administration has become especially acute. At the second level, the specific segment's logic is disclosed. Here it is shown exactly how the general problem manifests itself in a particular type of company, what constraints such companies encounter, and what consequences inaction entails. At the third level, the supplier's offering is formulated. It must clearly demonstrate the solution method, the expected outcome, and the organizational advantages of the chosen model. Such a composition helps preserve the intellectual coherence of the entire system and avoid divergence between the advertising message, educational content, and the commercial team's argumentation.

Particular attention must be paid to how the message is perceived by different participants in the buying circle. In employment services, the same formulation does not elicit the same response across the buying circle. Each of these participants considers the supplier through its own system of criteria and internal obligations. Therefore, the message must preserve a common semantic core while simultaneously adapting to different forms of professional attention. At the same time, the system must preserve equilibrium between overall brand integrity and local relevance.

The role of channels in such a system is determined by their function in the overall trajectory of demand generation. Search promotion through paid placement enables targeting already crystallized interests when the client is explicitly seeking a solution. Promotion in social networks strengthens awareness, restores the attention of previously engaged audiences, and sustains brand presence in the professional information field. Search engine optimization and organic search results create a long-term flow of interested companies that begin their journey by studying the problem and gradually move toward supplier selection. Content marketing performs a deeper function. It builds trust, educates the market, and helps the client conceptualize its situation as a manageable solution. Webinars and digital events create a space for deeper contact and enable identification of the degree of readiness for a substantive conversation. Email sequences sustain attention during long coordination cycles and return the client to the discussion when interest wanes. Outbound communication by the commercial team acquires the greatest force when it is embedded within the overall system of signals and responds to already manifested activity. Partnership and ecosystem channels expand access to the audience and strengthen trust by aligning with actors who already have recognized standing in adjacent fields. Taken together, these channels form a coherent system for advancing the client toward a deal, in which each touchpoint reinforces the previous one and prepares the next. These channels map onto the touchpoint categories identified in the customer-experience literature: paid search, organic search, content, email, and webinars are brand-owned touchpoints; partnership and ecosystem channels are partner-owned; and peer references and professional-community signals are external or social touchpoints beyond the provider's direct control [24]. The provider's task is therefore not to own the journey but to maintain coherence across owned touchpoints while shaping the partner-owned and responding to the social [1]. The global employment services market strategy is illustrated in Figure 3.

As the multichannel demand generation system grows more complex, the content system assumes particular importance, since it is precisely this system that binds the strategic design, the value proposition, and the work of channels into a unified logic of client movement. In the market under consideration, content serves as demand infrastructure. It helps the company recognize its own problem, identify a suitable solution, evaluate the supplier, and coordinate internally. Therefore, the content system must be constructed as an ordered set of materials with different cognitive and commercial loads. One part of the materials reveals the problem itself and renders it visible to the client. Another explains the differences between possible classes of solutions. A third shows how the supplier's specific offer removes the identified difficulties. A fourth reinforces trust through facts, cases, implementation results, and operational reliability. A fifth helps the commercial side conduct the deal within the client's organization when coordination among several participants is required. In such an arrangement, content ceases to be an auxiliary appendage to promotion and becomes a mechanism for the sequential formation of commercial readiness.

A fully developed content system requires precise anchoring of each piece to the stage of the client's movement, the characteristics of the segment, the regional context, and the expected next action. The same text or analytical material cannot work equally effectively during the initial interest phase, during supplier comparison, and when the transition to substantive contact is being discussed. For this reason, content must be embedded in the trajectory of promotion and must take into account in advance which action is considered desirable at each segment of the path. For the early stage, an invitation to deeper exploration of the topic is appropriate. For a more mature stage, an offer of calculation, consultation, or process demonstration is suitable. For a client who has already manifested

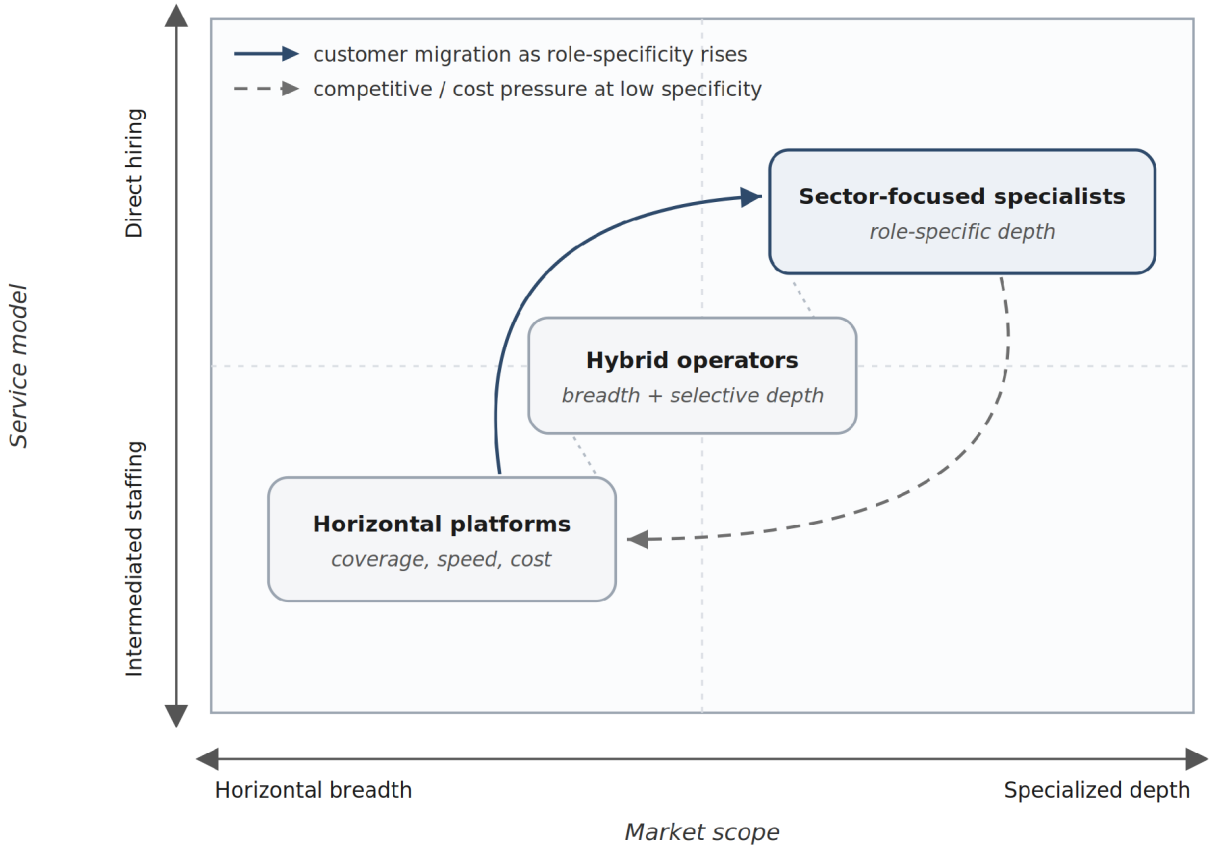


Fig. 3. Global employment services market strategy. Providers are positioned by market scope (horizontal breadth versus specialized depth) and service model (direct hiring versus intermediated staffing), distinguishing horizontal platforms, sector-focused specialists, and hybrid operators. Arrows trace customer migration as role-specificity rises and the competitive pressure that bears on low-specificity positions

sustained interest, materials are needed to support the internal defense of the choice across the financial, legal, and operational sides. Localized content plays a particularly important role, since the employment services market depends on territorial differences in legal regime, personnel practice, and organizational expectations. Material constructed without regard to a specific country rapidly loses persuasive force when the client requires clarity on local hiring, payroll, and compliance conditions.

Maturity Signals, Routing, and Analytics

However, even a highly developed content system does not in itself create a commercial result. Engagement indicates the degree of interest, but does not disclose readiness to move into a deal. Reading materials, participating in events, browsing pages, and repeat visits acquire meaning only when they are assembled into a recognizable structure of intent. Therefore, in a multichannel system, evaluation is required both at the individual contact level and at the organizational level. In one case, the intensity and quality of the actions of a specific company representative are analyzed. In the other, the aggregate activity of several participants within a single client is tracked. Such an approach makes it possible to see when interest ceases to be accidental and becomes an emerging purchasing movement. Additional significance is attached to signals that trigger the system's responsive action: repeated visits to pages describing the solution, review of materials relating to several countries, return to the terms of cooperation, and participation of several employees from the same company in the same content journey. All of this may serve as grounds for including the commercial team. Precise routing is required here. Some contacts require further nurturing through content. Others must be transferred to personal support. Still others require a delayed return to active work. Alignment among the marketing function, the outbound team, and sellers is the central condition for manageable conversion, because each side must understand the degree of client maturity and the appropriate next step in the same way.

In technology-intensive client environments, this alignment intersects with the client's own use of AI in hiring and workforce management, as many firms now automate vacancy drafting, applicant sourcing, CV analysis, shortlisting, and candidate matching. This

adoption reshapes what buyers seek from external providers: as generic sourcing and screening tasks are internalized and automated, the buyer's value function shifts away from coverage and cost toward compliance, contextual judgment, and role-specific depth — the capabilities least susceptible to automation [30]. The demand generation system should therefore articulate provider support precisely where AI cannot substitute for human expertise, while remaining analytically balanced about bias, opacity, and data governance in algorithmically mediated hiring [31; 21]; framed this way, client AI-adoption reinforces rather than erodes the structural advantage of specialized provision in high-specificity segments (P5).

Evaluation of the effectiveness of such a system likewise requires more complex analytics than merely calculating cost per inquiry or the number of formally qualified contacts. These indicators reflect only the surface of the process and explain poorly why some channels and materials lead to qualified deals while others only produce the appearance of activity. Analytics must encompass the breadth of presence in target segments, the depth of engagement, transitions between stages, the influence on the formation of commercial opportunities, and the ultimate contribution to revenue. Of particular importance is accounting for the cumulative impact of multiple touchpoints, since a decision in the employment services market is rarely made under the influence of a single contact. The client may first encounter content through search, then return through a repeated touchpoint in the digital environment, thereafter study analytical material, attend an event, and only then enter into direct dialogue. For this reason, measurement must be conducted at the organizational level, and the contribution of channels should be evaluated through their participation in creating and accelerating the flow of deals. Only such an analytical framework enables discerning the true productivity of the demand generation system and determining which elements genuinely move the client toward a commercial decision.

The Operational Model and Staged Implementation

A multichannel demand system performs only as well as the operational model that binds strategy, content, channels, and execution into a stable framework. The team works on two levels. The center sets direction — the segmentation principles, the value-proposition architecture, the measurement rules, and the shared design of demand scenarios — while local units adapt these to particular countries, industries, and client contexts. This is especially important for the market under consideration, since a unified semantic core must be preserved amid marked differences in the legal environment, business practice, and decision-making modalities. The function responsible for the market packaging of the product translates service characteristics into clear value scenarios for different segments. The regional marketing function correlates these scenarios with the local business environment and specific demand sources.

The revenue operations function maintains data integrity, signal routing, client handoff quality, and result comparability. The commercial function transforms identified and prepared interest into a negotiation process and a deal. Such a structure requires a stable rhythm of joint work, in which planning, hypothesis testing, and feedback analysis occur regularly and rest on a unified understanding of which scenarios actually move the market. It is for this reason that execution must be built around repeatable demand work scenarios, each of which represents a complete commercial construct with a clear objective, a logic of contacts, and an expected result.

The practical implementation of such a model begins with a careful analysis of the current state of the demand generation system, as shown in Figure 4.

At this stage, it is important to identify which segments and geographies already deliver qualified commercial results, where demand breaks down along the path to the deal, which channels generate only superficial activity, and at which points content loses coherence with the client's real questions. After this, it becomes possible to design a holistic architecture in which priority segments, service lines, the route of client movement, the logic of messages, the roles of channels, the rules for assessing the maturity of interest, and the mechanisms of interaction between the marketing and commercial sides are redefined. The next step is to launch a limited number of pilot scenarios in those market zones where there is a clear reason for contact, sufficient demand concentration, and an opportunity to gather feedback rapidly. Such a sequence allows avoiding excessive complication at the outset and affords the opportunity to test the system's viability under manageable conditions. The client's mode of entry mirrors the logic by which the provider's own demand system must be deployed: the beachhead client, scaling only after a proven test, parallels the staged pilot-then-scale architecture proposed here.

Further development requires cautious scaling, in which expansion into new regions and additional service directions occurs only after the initial scenarios have demonstrated a stable capacity to create qualified commercial opportunities. Scaling, in this case, is associated with the transfer of principles that have proven effective, rather than the mechanical reproduction of individual actions. Each new market and each new service line requires repeated adjustments to content, channels, routing, and client-readiness criteria, since the system maintains its general logic only through fine-tuned adaptation to the new context. Verification and optimization must proceed continuously. It is necessary to constantly compare expectations, actual client behavior, and deal outcomes. It is necessary to

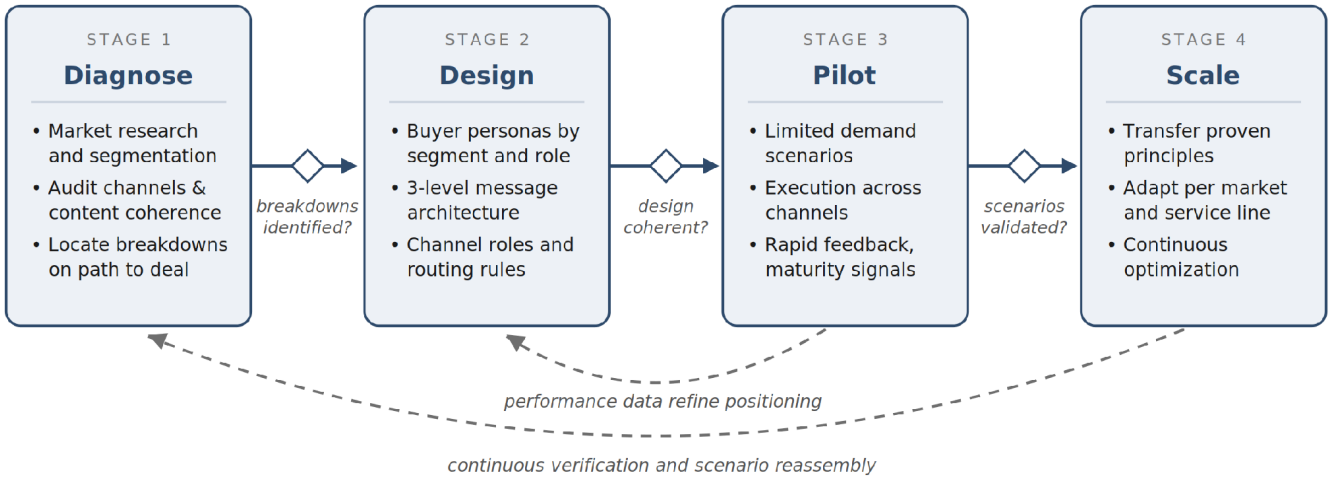


Fig. 4. Implementing a demand generation system. A staged pipeline runs from diagnose through design and pilot to scale, each stage carrying its own activities and a decision gate. Feedback loops return performance data from later stages to refine earlier positioning, so upstream strategic work informs downstream tactical deployment

refine maturity signals, eliminate superfluous touchpoints, strengthen effective connections, and reassemble scenarios that have lost persuasive force. In this resides the practical meaning of implementation. A multichannel demand generation system becomes stable only when it develops as a manageable, learning, and internally coherent commercial environment.

Synthesis and Propositions. The foregoing analysis can be condensed into five propositions that make the article's conceptual contribution explicit and available for empirical testing.

P1. In the global employment services market, demand converts into a stable flow of deals as a function of the internal coherence of segmentation, messaging, content, channels, and commercial routing, rather than of any single channel. Because the journey spans touchpoints that differ in ownership and firm-controllability [24; 1], coherence operates by reducing the conflicting signals that a multi-actor buying center must reconcile. Operationalizing coherence as a measurable construct-for instance, message-consistency scoring across touchpoints or channel-role clarity scoring-tightens falsifiability and enables empirical assessment. The marginal value of coherence rises with the length of the journey and the number of participating actors and touchpoint owners, and is correspondingly low for short, single-actor purchases.

P2. Demand in cross-border employment services is more accurately segmented by three interacting axes — the client's prior experience with international hiring, the mode of market entry, and the composition of the buying circle — than by generic firmographic variables such as size or maturity. Each axis maps to a distinct, theoretically identified barrier that firmographics do not capture: the experience axis determines whether the dominant barrier is the perceived risk of a first, incumbent-free purchase or the procedural, financial, and relational switching costs of displacing an incumbent [6; 3] in the B2B staffing context); the entry-mode axis reflects the incremental escalation of commitment characteristic of internationalization [18] and the switching dynamics of changing an established operation mode [27]; and the buying-circle axis fixes whose criteria govern (P3). The three axes should outperform firmographics on operationally falsifiable outcomes such as conversion rate and cycle length. The experience axis discriminates only where a meaningful incumbent category exists, such as established hiring platforms; absent any incumbent, it collapses toward the perceived-risk pole.

P3. In technology-oriented segments, the technical leadership function frequently captures both the gatekeeper and the economic-buyer or decider roles, applying evaluation criteria distinct from those of HR, finance, legal, and procurement. The buying-center influence is on the side of the actor who has decision-critical information [23]. Purchase-importance and complexity determine which information cues lead to a purchase [4]. These findings also apply to B2B gatekeepers and technical buyers [7]. If the externalization requires technical expertise, the technical evaluation will dominate the information flow, and the technical leader will control the information, having the budget authority. Hence, organizational contexts extend from the buying-center-to-ecosystem [11]. The effect holds to the degree the work is technically specialized; as the service commoditizes, evaluative competence diffuses and procurement and finance regain influence.

P4. Perceived risk and cognitive burden act as determinants of demand alongside price and capability, and this effect is amplified by the seniority of the buyer. When a high-stakes decision lies outside the buyer's domain of competence — a largely non-technical market-entry decision confronting a technical buyer — purchase complexity and importance raise perceived risk and processing load [5], increasing reliance on

assurance and affect; the stakes are amplified by a gap between what the provider prices and what the buyer commits: the buyer is not weighing a monthly service fee but the full cost of the expansion — salaries carried for six to twelve months, operational time, and the risk of a failed entry — so the decision is evaluated against a large multi-month commitment rather than the per-seat rate, and it is this magnitude, not the price of the service, that drives perceived risk and the need for assurance. Critically, this reliance on assurance is stronger, not weaker, among senior and executive buyers [20], and elevated cognitive load intensifies this dynamic [29], particularly among those who most often hold budget authority. The effect is strongest when the decision is simultaneously outside the buyer's expertise and high in stakes, and attenuates for routine repurchase or for buyers who are themselves expert in the entry tasks.

P5. Horizontally optimized providers, efficient for generalized cross-border hiring, underperform in segments with high role-specificity such as technology, where specialized provision holds a structural advantage. By transaction-cost logic, standardized, market-like provision is efficient at low asset specificity but is poorly matched as specificity rises and fit comes to require specialized knowledge and governance [32; 12], for service make-or-buy. Role-specificity is a form of human-asset specificity [10] — specialized tax and incentive regimes, classification nuance, and unusually intense talent competition — that extends the transaction-cost framework into the employment-services context: standardized provision cannot price or service such specificity as well, shifting the buyer's value function from coverage and cost toward role-specific depth. The specialized provider's advantage rises with role-specificity and disappears at low specificity, where horizontal platforms dominate on coverage, speed, and cost; consistent with the broader transaction-cost debate, the relevant contrast here is specialized versus generalized provision rather than integration versus market.

These propositions are conceptual and are offered as a basis for subsequent empirical work, as outlined below.

Limitations and Future Research. This study is conceptual, and its propositions have not been subjected to primary empirical testing; the framework should be read as a basis for investigation rather than as a validated result. Its scope is deliberately weighted toward the technology segment, which exhibits the role-specificity that motivates the argument most sharply, and the three-axis typology and the structural claim about horizontally optimized provision may require adjustment in segments with different specificity profiles, such as manufacturing, healthcare, or logistics. Several constructs are also candidates for measurement that this article does not supply — operationalizing the experience and entry-mode axes from observable hiring signals, or measuring the perceived overload of technical buyers and its effect on supplier selection. Future research could test the propositions through buyer-side surveys and decision studies in cross-border hiring, through analysis of vacancy and expansion data to validate the segmentation axes, and through comparative work across industries to establish the boundary conditions of the structural argument. Such work would also allow the affective dimension identified here [20] to be quantified in the specific context of employment services.

Conclusion. This analysis has argued that demand generation in the global employment services market is best understood as a single system of commercial coordination, in which segmentation, the value proposition, content, channels, and routing operate under one logic of advancing the client toward a deal. What makes the market distinctive is the combination of institutional heterogeneity, territorial fragmentation, a multilevel buying circle, and acute client sensitivity to legal, personnel, and financial risk. Under such conditions, stable demand is formed through the sequential reduction of uncertainty, the accumulation of trust, and the synchronization of contacts at the client organization level. This insight carries a direct implication: the multichannel model acquires explanatory and applied significance only when all elements of the system are internally coherent.

In particular, this article contributes a multi-axis segmentation of demand — by the client's experience with international hiring, the mode of market entry, and the composition of the buying circle — together with an affective dimension specific to technical buyers and a structural account of why horizontally optimized providers underperform in high-specificity segments such as technology.

Demand generation should therefore be built as a reproducible structure: a clear target-customer profile, geography and industry considered together, prioritized service lines, and scenarios tied to specific market situations. The message architecture must work on several levels at once, holding a common semantic core while adapting to how HR, finance, legal, procurement, and operations each read the same offer differently. Particular emphasis is placed on the fact that content must perform an infrastructural function in demand generation, helping the client recognize the problem, comprehend classes of solutions, compare suppliers, and prepare internal coordination. In this way, the article proposes that content, maturity analytics, and commercial coordination be regarded as interdependent components of a single commercial system.

The study's practical contribution is a staged implementation model: diagnose the current state of the demand system, design a coherent architecture, launch a limited set of pilot scenarios, and scale only those that prove able to generate qualified commercial opportunities. Growth in this market requires not the mechanical expansion of activity, but the managed

adaptation of scenarios to new countries, segments, and service lines. This leads to the article's key recommendation. An effective multichannel system in the sphere of global employment services must develop as a learning commercial environment with a unified strategic core, regular feedback, and continuous optimization of the interconnections among content, channels, and the actions of the commercial team.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.

DECLARATION OF CONFLICTING INTERESTS. The author holds a senior commercial role at a specialized provider of international employment services — a category of firm whose competitive position is discussed in the article's structural argument (Proposition 5, on specialized versus horizontally optimized provision). This interest is disclosed so that readers may weigh it. The conceptual claims advanced here are grounded in the cited literature rather than in proprietary data or the commercial interest of any individual firm, and the author's practitioner experience is used only as an interpretive lens on the synthesized sources, as stated in the Methodology. The structural claims are framed as testable propositions rather than validated findings.

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LEGAL AND FINANCIAL SECURITY OF THE CONSTRUCTION BUSINESS AS A CONDITION FOR PRESERVING ASSETS DURING THE WAR AND ECONOMIC INSTABILITY

Summary. *This article examines the conditions under which a small and medium-sized construction enterprise can preserve its assets and sustain business continuity during prolonged armed conflict and macroeconomic instability. Drawing on the empirical case of a Kyiv-based construction and real estate company that maintained profitability throughout the full-scale war in Ukraine (2022 to present), the study synthesizes evidence from international academic literature, OECD economic surveys, World Bank damage assessments, and professional legal analyses. The methodology combines systematic literature review, case study analysis, and comparative institutional analysis. Key findings show that the integration of four mutually reinforcing security dimensions, namely legal structure optimization, proactive tax compliance, financial discipline oriented toward real estate reinvestment, and war risk insurance, substantially improves organizational resilience. The article proposes an original author's framework, the Legal and Financial Security System (LFSS), and a risk matrix tailored to construction businesses in conflict-affected environments. The results confirm the initial hypothesis that disciplined legal and financial governance enables asset retention and sustained revenue generation even under conditions of extreme external stress. Findings are relevant to construction business owners, legal practitioners, investors, and policymakers engaged in post-conflict recovery and reconstruction planning.*

Key words: *construction business, legal security, financial security, asset protection, wartime economy, business resilience, real estate investment, risk management, Ukraine reconstruction, economic instability.*

Introduction. The global construction sector has historically functioned as one of the most capital-intensive and legally complex industries, where the interplay between contractual obligations, physical assets, and regulatory environments creates unique vulnerabilities during periods of macroeconomic stress. Under conditions of armed conflict and sustained economic instability, these vulnerabilities are significantly amplified, and the capacity of a construction business to preserve its asset base while maintaining operational continuity becomes the central measure of organizational viability.

Ukraine provides the most acute contemporary case for studying this phenomenon. Following Russia's full-scale invasion in February 2022, Ukraine's GDP contracted by 28.8% that year, recovering to +5.3% in 2023 and +3.5% in 2024, yet remaining constrained by ongoing hostilities, energy infrastructure damage, and severe labour shortages [1]. By the end of 2024, the World Bank estimated cumulative direct damage to Ukrainian infrastructure at $176 billion, with total reconstruction and recovery needs reaching $524 billion over the subsequent decade, approximately 2.8 times the country's nominal GDP for 2024 [2]. The construction and real estate sector experienced a particularly pronounced contraction, with production volumes declining by an estimated 40% in 2022, while simultaneously becoming one of the key drivers of partial recovery in 2023 through infrastructure repair and reconstruction projects [3].

Despite this challenging context, a subset of construction firms demonstrated measurable resilience, maintaining revenue streams and preserving portfolio value. Research on small and medium-sized enterprise (SME) resilience under crisis conditions consistently identifies financial discipline, diversified asset structures, and robust legal governance as critical success factors [4; 5]. However, the specific combination of legal and financial mechanisms that enable construction businesses to navigate wartime conditions in particular has received limited systematic academic attention. Existing literature addresses either general SME crisis resilience [6; 7] or macroeconomic dimensions of conflict-affected economies [1; 3], but rarely integrates these perspectives into a practitioner-oriented, sector-specific framework.

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The scientific gap addressed by this study concerns the absence of an integrated legal-financial security model specifically calibrated to the operational conditions of construction businesses during periods of armed conflict and macroeconomic instability, tested against verifiable empirical evidence.

The goal of this research is to identify, systematize, and empirically validate the legal and financial mechanisms that enable construction businesses to retain assets and sustain profitability during wartime conditions, and to formulate an actionable framework applicable to practitioners in conflict-affected and economically volatile environments.

The scientific novelty of this study lies in the synthesis of an original author's Legal and Financial Security System (LFSS) framework that integrates four interdependent dimensions of organizational protection, validated against a longitudinal practitioner case spanning 20 years of operation including three years of full-scale war.

The primary **hypothesis** is that disciplined legal structuring combined with proactive tax compliance and real estate-focused reinvestment enables a construction company to retain the majority of its asset value and maintain positive cash flow even under conditions of active armed conflict, provided these mechanisms are implemented systematically and proactively rather than reactively.

The scope of this study is limited to small and medium-sized construction enterprises operating in urban markets within conflict-affected economies. Findings are not intended to be directly generalized to large publicly listed corporations or to purely residential developers without commercial real estate operations. The study draws predominantly on Ukrainian and international evidence; direct applicability to other conflict zones would require adaptation to local legal frameworks. These limitations do not compromise the core analytical and methodological contribution of the work, which retains broad relevance for practitioners and scholars in construction management, business law, and post-conflict recovery economics.

The practical value of this work extends beyond the Ukrainian context. As construction entrepreneurs and professionals from economically disrupted regions increasingly migrate to and establish businesses in the United States, their experience in operating under legal and financial duress represents a transferable body of knowledge. The disciplined asset-protection strategies documented here align with principles that support small business development, urban real estate investment, and economic diversification in the US market, particularly in communities where immigrant entrepreneurship plays a significant role in local economic growth.

Materials and Methods. This study employs a multi-method research design combining systematic literature review, case study analysis, and comparative institutional analysis. The choice of methodology reflects the nature of the research problem, which requires both theoretical grounding in existing academic frameworks and empirical validation against real-world evidence from a specific organizational context.

The systematic literature review was conducted across Scopus-indexed journals, OECD and World Bank publications, and professional legal analyses. The initial search employed keyword combinations including "construction business financial security," "SME resilience wartime," "asset protection conflict economy," "legal risk construction," and "real estate investment crisis." Sources were evaluated for relevance, credibility, and recency, with a focus on peer-reviewed articles and authoritative institutional reports.

The source base was classified into three categories. The first category comprises peer-reviewed academic publications from journals indexed in Scopus and Web of Science, including studies on SME financial resilience [4; 5; 6], corporate governance under economic uncertainty [8], financial risk management in wartime [9], and financial discipline in crisis contexts [7,; 10]. The second category includes authoritative institutional reports from organizations such as the OECD [1; 11], the World Bank [2], the United Nations Development Programme [3], and the International Finance Corporation [12], providing macroeconomic and sector-specific statistical data. The third category comprises professional legal analyses and industry reviews from qualified legal practitioners and industry bodies [13; 14; 15], which provide regulatory and applied context for the legal security dimensions examined.

The case study component draws on a longitudinal practitioner case: a Kyiv-based construction and real estate SME founded in 2007 that operated continuously through multiple economic crises, including the post-2014 geopolitical instability, the COVID-19 pandemic, and the full-scale war commencing in February 2022. The company accumulated a real estate portfolio of approximately 2,500 square meters of commercial property in Kyiv through a disciplined strategy of reinvesting construction revenues into properties on which the company had performed construction work. At a conservative market valuation of $500 per square meter, the portfolio represents an asset base of approximately $1.25 million in real estate holdings. Prior to the full-scale invasion, the business generated an annual return of approximately 10% on assets, of which 8% was systematically reinvested and 2% constituted the owner's personal compensation. This model of financial discipline, sustained over nearly 20 years, provides a uniquely robust empirical basis for the analysis of long-term asset protection strategies under sustained adverse conditions.

The comparative institutional analysis examines the legal and regulatory frameworks governing construction business protection in conflict-affected economies, drawing on the updated Ukrainian Law

"On Insurance" (effective January 1, 2024), bilateral investment treaty (BIT) provisions, and international investment protection mechanisms including ICSID arbitration and MIGA programs [13]. This dimension contextualizes the case evidence within the broader international legal environment relevant to businesses operating in conflict zones.

Data triangulation across these three methodological components ensures that analytical conclusions are grounded in both theoretical frameworks and verifiable empirical evidence, reducing the risk of over-reliance on any single data source.

Results and Discussion. The scale of economic disruption caused by Russia's full-scale invasion of Ukraine provides essential context for evaluating business survival strategies. Ukraine's GDP growth trajectory illustrates the severity and subsequent partial recovery of the economic environment in which the case study company operated.

Figure 1 presents the annual GDP growth rate of Ukraine from 2019 to 2024, based on verified data from the OECD Economic Survey of Ukraine 2025 [1] and the World Bank [2]. The catastrophic 28.8% contraction in 2022 represents the single largest annual economic decline recorded in Europe in the post-Soviet period, followed by a recovery that remains partial and fragile due to continued hostilities.

The construction sector's trajectory within this macro context is particularly instructive. The UNDP assessment of Ukrainian micro and small businesses confirmed that production capacity utilization fell from approximately 72% of pre-war levels to 45.7% in the 2022–2023 period [3]. Only 9.5% of surveyed companies reported no financial losses as a result of the war, while the majority experienced disruptions to supply chains, access to labor, and client bases. These conditions created a structural divide between firms that had established proactive legal and financial protections and those that had not.

Ukraine's reconstruction and recovery needs, estimated at $524 billion through 2035 by the World Bank Group, Government of Ukraine, European Commission, and United Nations joint assessment [2], represent both the scale of destruction and the future opportunity for construction businesses. Housing alone accounts for almost $84 billion of these needs, with transport, energy, commerce, and agriculture sectors representing additional massive demand for construction services. For businesses that preserved their operational capacity and asset base through the initial shock, this reconstruction pipeline represents a structural growth opportunity of multi-decade duration.

The distribution of these reconstruction needs across sectors is illustrated in Figure 3. Before turning to the risk analysis and the proposed framework, Table 1 below presents a systematic classification of the primary risk categories facing construction businesses in conflict-affected economies, along with their typical exposure levels and recommended mitigation mechanisms.

The risk landscape facing construction businesses during armed conflict is multidimensional and

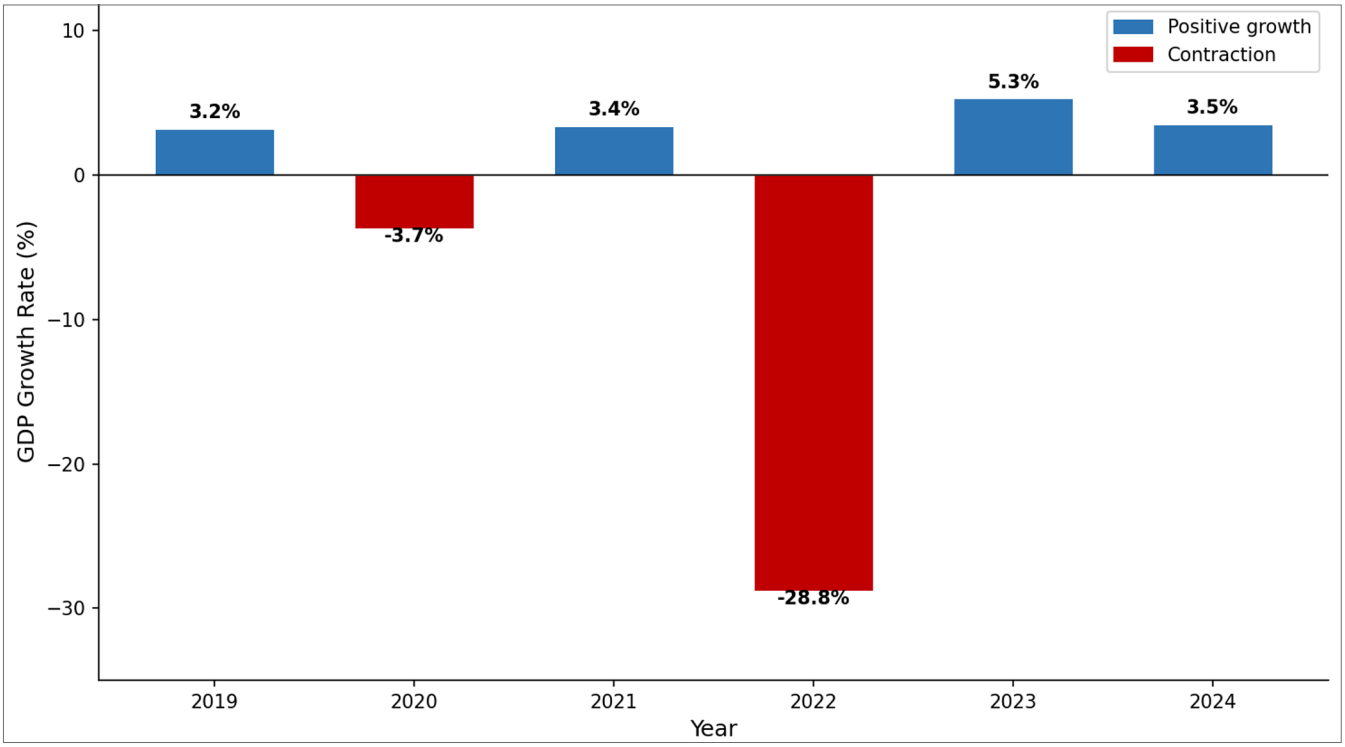


Fig. 1. Ukraine GDP Annual Growth Rate
Source: compiled by the author based on [1; 2]

Table 1

Risk Classification for Construction Businesses in Conflict-Affected Economies

Risk Category	Description	Construction Business Exposure	Mitigation Mechanism
Military / Physical Destruction	Direct damage to assets from hostilities	High: facilities, equipment, real estate	War risk insurance (MIGA, DFC), distributed assets
Regulatory / Legal Instability	Frequent changes in tax, property, and contract law	Medium-High: contracts may become void	Legal due diligence, force majeure clauses, BIT protection
Currency Depreciation	Rapid hryvnia devaluation eroding asset value	High: reduces real value of cash holdings	Real estate as inflation hedge, USD-denominated revenues
Counterparty Default	Clients/tenants unable to pay during crisis	Medium: rental income disruption	Diversified tenant base, advance payment clauses
Forced Asset Nationalization	State appropriation under martial law provisions	Low-Medium: state registers assets	SPV structure, bilateral investment treaties

Source: compiled by the author based on [9; 13; 14; 15]

interrelated. A systematic classification of these risks helps practitioners prioritize protective actions and allocate limited resources to the highest-impact mitigation mechanisms. Table 1 presents the author's categorization of primary risk types, informed by the analyzed literature and case study evidence.

The central analytical contribution of this study is the Legal and Financial Security System (LFSS) framework, developed on the basis of the theoretical literature, the case study evidence, and comparative institutional analysis. The LFSS conceptualizes the security of a construction business not as a set of isolated legal or financial tools, but as an integrated system in which four interdependent dimensions reinforce each other's effectiveness.

The first dimension, corporate structure optimization, involves the deliberate design of the legal entity structure to minimize liability exposure and isolate assets from operational risks. This may include the use of special purpose vehicles (SPVs) for specific projects, holding company arrangements for the real estate portfolio, and the separation of construction operations from property management activities. Research on corporate governance under economic policy uncertainty confirms that firms with clearer governance structures and defined liability boundaries demonstrate stronger financial performance during crisis periods [8]. In the Ukrainian context, investment protection under bilateral investment treaties provides an additional layer of security for businesses with international ownership structures [13].

The second dimension, tax policy and compliance management, is frequently underestimated as a security mechanism. Transparent, audit-ready accounting that maintains full compliance with applicable tax obligations eliminates a critical category of legal and financial risk. During periods of heightened regulatory scrutiny and martial law, businesses with clear tax records face substantially reduced risk of asset freezes, forced audits, or state interference. Academic analysis of corporate tax behavior during crisis periods confirms that firms reducing aggressive avoidance practices in response to heightened regulatory attention tend to preserve better relationships with state institutions and face fewer operational disruptions [16].

The third dimension, asset protection through real estate holdings, reflects a fundamental characteristic of real property as an inflation-resistant store of value. Unlike cash holdings, which are subject to currency depreciation and banking system risks, or equipment, which depreciates and may be destroyed or requisitioned, commercial real estate in well-selected urban locations maintains or appreciates in value over multi-decade investment horizons, even surviving periods of significant disruption. The case company's strategy of systematically reinvesting construction revenues into properties it had built provides a particularly robust illustration: the company developed deep knowledge of the quality and structure of the assets it acquired, and the act of reinvesting in those assets aligned the company's incentives with long-term value creation rather than short-term profit extraction.

The fourth dimension, war risk insurance and legal hedging, became increasingly structured in Ukraine following the full-scale invasion. The new Law "On Insurance" (effective January 2024) aligned Ukrainian insurance regulation with EU directives, enabling more sophisticated hybrid coverage approaches that combine local property insurance with international political risk insurance instruments from providers such as the Multilateral Investment Guarantee Agency (MIGA) and the U.S. International Development Finance Corporation (DFC) [14]. For construction businesses with foreign capital participation, ICSID arbitration and BIT provisions provide additional legal backstops against unlawful expropriation or denial of justice [13].

Figure 2 below illustrates the structural relationships among these four dimensions and their expected outcomes, as developed by the author.

The LFSS framework differs from generic crisis management models in its sector specificity and its

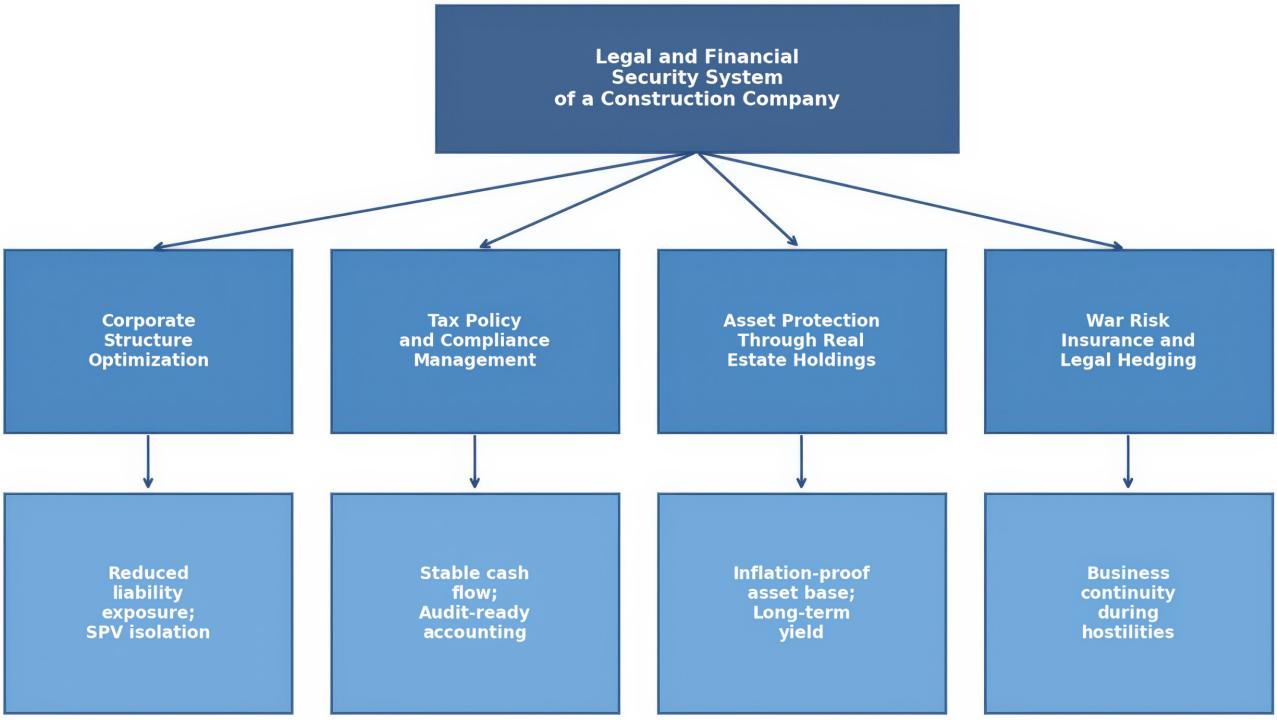


Fig. 2. Author's Model: Legal and Financial Security Framework for Construction Businesses in Conflict-Affected Economies

Source: author's development based on [4; 8; 9; 13; 14]

integration of legal and financial dimensions within a single operational architecture. Whereas most SME resilience frameworks focus predominantly on operational flexibility and access to external finance [5; 6; 7], the LFSS places the legal governance of assets at the center of the security model, recognizing that a construction company's primary vulnerability is not operational but patrimonial: the risk of losing accumulated physical assets that represent the product of decades of reinvestment.

The longitudinal case study of the Kyiv-based construction and real estate company provides concrete empirical grounding for the LFSS framework. Founded in 2007 under the direct management of its founder, the company operated for 17 years prior to the full-scale invasion and continued operations through the war period. The founder served as both operational director and strategic decision-maker, personally controlling all significant legal, financial, and technical decisions, a governance model consistent with research showing that owner-managed SMEs in emerging economies demonstrate higher adaptive capacity during crises than firms with dispersed management structures [4].

The company's financial discipline model is quantifiable: a consistent reinvestment rate of 80% of net returns, an owner compensation rate of 20% of returns (2% of total asset value at a 10% annual yield), and a deliberate strategy of minimal debt. This approach is consistent with findings from financial resilience research demonstrating that SMEs with balanced capital structures, characterized by low leverage and diversified revenue sources, demonstrate superior resilience profiles during crisis periods [9]. In the Ukrainian context, SMEs in western regions with conservative financial profiles showed resilience indicators (KT) of 0.89 versus 0.81 for central regions and significantly lower for eastern conflict-exposed regions in the same period [9].

The Ukraine M&A market data for 2023 reported by KPMG provides broader sectoral context: despite the war, real estate and construction remained among the four most active sectors for transactions, with approximately 10 transactions recorded in the sector in 2023 alone, indicating continued market functionality even under extreme conditions [15]. Foreign direct investment in Ukraine's economy reached $3.4 billion in agriculture alone in 2023, signaling that sophisticated investors maintained confidence in well-structured asset holdings [3].

Figure 3 below illustrates the distribution of Ukraine's identified reconstruction needs by sector through 2035, providing context for the structural demand environment that resilient construction businesses are positioned to address.

The reconstruction needs data visualized in Figure 3 are particularly significant for construction businesses that preserved their organizational capacity through the conflict period. The housing sector alone requires almost $84 billion in investment, with transport ($78 billion), energy ($68 billion), and commerce and industry ($64 billion) representing additional demand streams. Companies that enter the reconstruction

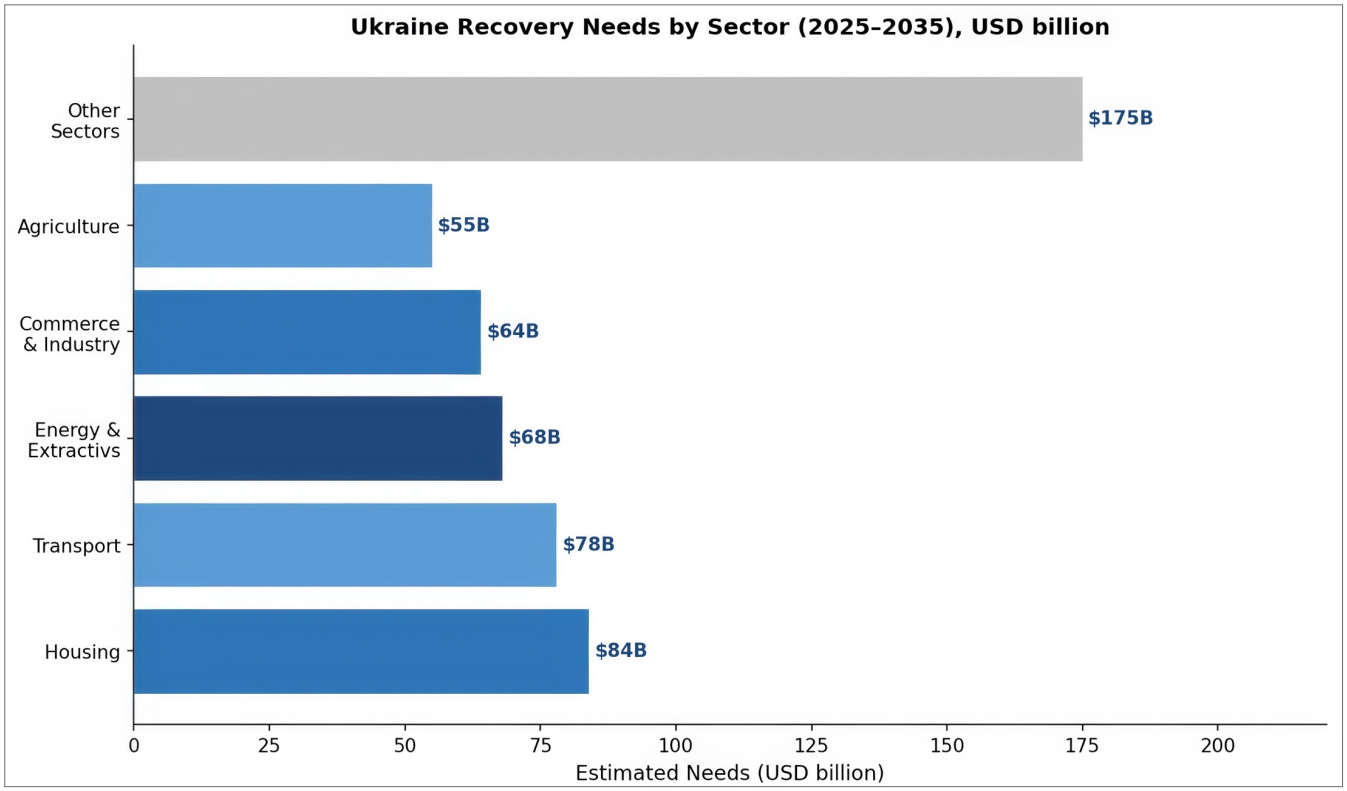


Fig. 3. Ukraine Recovery and Reconstruction Needs by Sector, 2025–2035 (USD billion)

Source: compiled by the author based on [2]

period with intact legal structures, clear property rights, operational teams, and established reputations are structurally positioned to capture a portion of this demand, whereas firms that lost assets or legal standing during the conflict period face substantially higher barriers to participation.

Table 2 below presents the author's synthesis of the LFSS dimensions with their associated tools, outcome indicators, and applicable legal and regulatory frameworks, drawing on the case study and analyzed literature.

The empirical and theoretical analysis converges on a core insight: the legal and financial vulnerability of construction businesses during wartime does not emerge uniformly across all risk categories. Different types of risks carry different combinations of probability and impact, and an effective security strategy must prioritize protective actions accordingly. The author's risk matrix, presented in Figure 4, organizes the principal risk categories facing construction businesses in conflict-affected environments across two dimensions: probability of occurrence and potential business impact.

The risk matrix presented in Figure 4 was developed by the author based on the synthesis of risk categories identified in the systematic literature review [4; 9; 13; 14] and the empirical evidence from the case study. It provides a practical decision tool for

Table 2

Legal and Financial Security System (LFSS): Dimensions, Tools, and Outcomes

Security Dimension	Key Tools Applied	Outcome Indicators	Applicable Framework
Legal Structure	SPV formation, holding company structure, BIT clauses	Reduced liability; asset ring-fencing	Corporate law, international investment law
Tax Compliance	Transparent accounting, tax planning, audit readiness	Zero tax penalties; stable cash flow	National Tax Code; OECD guidelines
Financial Discipline	Low debt ratio, reinvestment of 80%+ profit, cost control	Portfolio growth 10% p.a. net of inflation	SME financial resilience framework
Asset Protection	Real estate holdings, title insurance, cadastral registration	Asset base $1.0M+ held through 3+ years of war	Property law, insurance law
Risk Insurance	War risk, property, liability insurance; MIGA programs	Business continuity; loss recovery	New Insurance Law Ukraine (2024); MIGA

Source: author's development based on [1; 4; 8; 9; 13; 14]

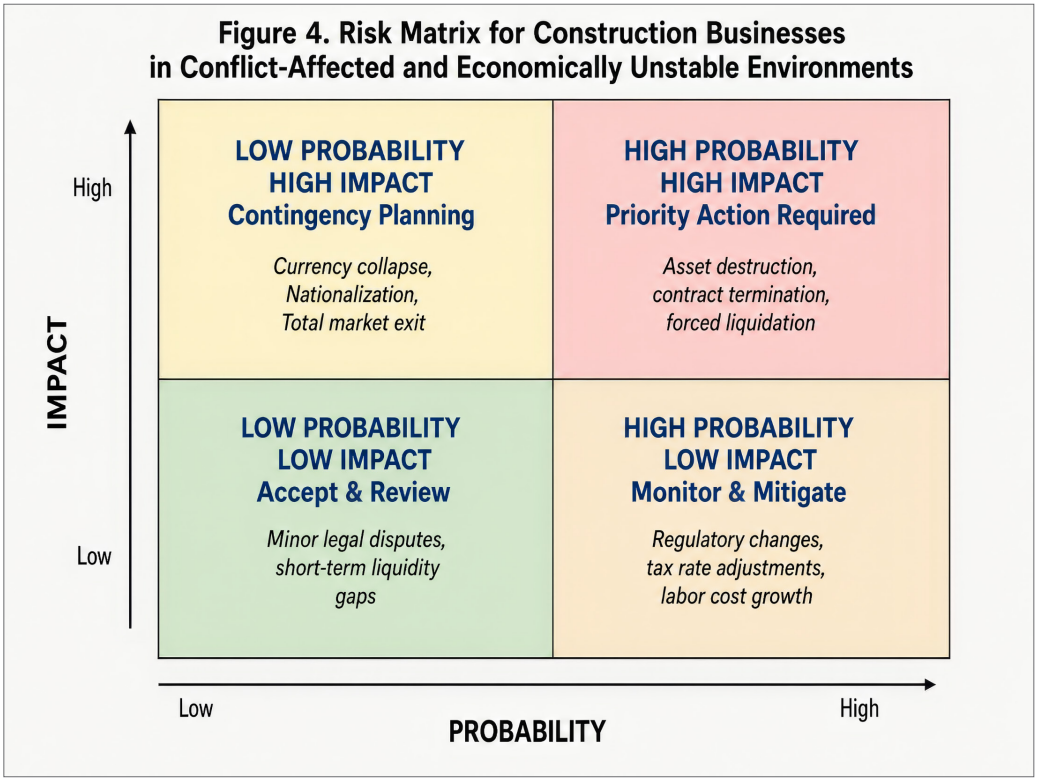


Fig. 4. Risk Matrix for Construction Businesses in Conflict-Affected and Economically Unstable Environments
Source: author's development based on [4; 9; 13; 14; 15]

construction business owners and managers in determining where to allocate protective resources.

The risk matrix reveals that the highest-priority quadrant, combining high probability with high impact, encompasses asset destruction from military action, forced contract termination, and business liquidation pressure. These risks demand immediate and sustained protective action through the full LFSS framework. The quadrant of high probability but lower impact, which includes regulatory changes, tax rate adjustments, and labor cost fluctuations, requires continuous monitoring and agile compliance management but does not threaten organizational survival in isolation.

Based on this risk architecture and the integrated LFSS framework, the author formulates the following strategic recommendations for construction business owners operating in conflict-affected or economically volatile environments:

First, title clarity must be established and maintained as a non-negotiable prerequisite. Every property asset should be registered with complete and current documentation in the state cadastral system, with verified absence of encumbrances, liens, or disputed ownership claims. This investment in title integrity typically costs a fraction of asset value but provides indispensable protection against both legal challenges and administrative interference.

Second, financial accounts should be structured to support transparent, audit-ready reporting at all times. This does not require aggressive tax optimization; on the contrary, consistent and transparent compliance creates a protective posture that reduces the likelihood of adverse state action. During martial law and periods of heightened regulatory attention, a company with clean books is substantially less vulnerable than one with complex or opaque financial arrangements.

Third, real estate holdings should represent the primary form of long-term value storage rather than cash or equipment. Property, particularly well-located commercial real estate in established urban centers, functions as an inflation hedge and a crisis-resilient asset class. The case study confirms that a portfolio of 2,500 square meters of commercial real estate in Kyiv maintained its fundamental value through three years of full-scale war, while cash holdings denominated in local currency would have suffered severe depreciation.

Fourth, corporate structure should be regularly reviewed to ensure appropriate liability boundaries between operational activities and asset-holding entities. The use of SPV structures for specific projects and a clear separation between the construction operating company and the real estate portfolio entity reduces the risk of operational liabilities reaching core assets.

Fifth, insurance coverage should include war risk provisions through eligible international programs. The restructured Ukrainian insurance market following the 2024 Law "On Insurance," combined with MIGA and DFC instruments for businesses with international capital components, provides increasingly

Table 3

Key Macroeconomic and Construction Sector Indicators, Ukraine 2019–2024

Indicator	2019 (Pre-war)	2022 (Invasion Year)	2023 (Recovery)	2024 (Continued War)
Ukraine GDP Growth (%)	+3.2%	-28.8%	+5.3%	+3.5%
Construction Sector Activity	Stable growth	-40% output	Partial recovery	Continued caution
SME Capacity Utilization	~72%	~46%	~56%	~62% (est.)
Reconstruction Needs (USD bn)	N/A	$349	$411	$524
Companies With Financial Losses	~15%	~90%	~70%	~60% (est.)
Real Estate as % of Business Assets (resilient firms)	~30%	~45%	~52%	~55%

Source: compiled by the author based on [1; 2; 3; 15; 17; 18]

workable options for businesses that previously had little access to conflict-risk coverage.

Table 3 below presents comparative macroeconomic and sector indicators for Ukraine from 2019 to 2024, illustrating the specific data context within which these recommendations are grounded. The data confirm that while the macro environment was deeply adverse, the structural opportunity for disciplined businesses remained intact throughout the study period.

The data presented in Table 3 illustrate the progressive severity of wartime disruption and the partial but incomplete recovery trajectory. The systematic increase in real estate's share of business assets among resilient firms, from approximately 30% in pre-war conditions to an estimated 55% in 2024, reflects a broader market recognition of property as the preferred crisis-resilient asset class, aligning with the strategic logic underlying the LFSS framework.

The community leadership dimension of the case study also merits analytical attention. The company founder's two-time election as head of the board of a property owners' association representing 600 investors reflects a level of trust and recognized competence that has direct business implications. In conflict-affected economies, reputational capital and demonstrated leadership within professional communities function as informal protective mechanisms, reducing counterparty default risks and enabling access to cooperative solutions for shared problems such as security, infrastructure maintenance, and collective legal representation.

The strategic frameworks developed in this article carry specific relevance for Ukrainian-born construction professionals and entrepreneurs operating in the United States. The operational discipline required to navigate 20 years of construction management in one of the most economically challenging environments in Europe, including the management of engineering processes, financial controls, tax compliance, and legal risk across a full property cycle, constitutes a differentiated skillset that aligns well with the demands of the US construction and real estate investment market.

The US construction industry operates within a well-developed legal framework that provides robust asset protection tools, including LLC and holding company structures, title insurance, and sophisticated insurance markets, that parallel and in many ways exceed the protections available in conflict-affected markets. For entrepreneurs experienced in protecting assets under far more adverse conditions, these tools represent a significantly more favorable operating environment. The competencies developed in managing construction quality, investment reinvestment cycles, and legal compliance under wartime conditions are transferable and potentially competitive advantages in a market characterized by reliable rule of law and stable macroeconomic conditions [19; 20].

The reconstruction of Ukraine, estimated to require $524 billion over the coming decade [2], will increasingly involve US-based engineering, construction, and investment firms, creating structural opportunities for bilingual, bicultural professionals with direct experience in Ukrainian construction standards, market conditions, and regulatory environments. This intersection of US-based professional positioning and Ukrainian reconstruction demand represents a strategic vector that directly connects individual entrepreneurial experience with national economic development interests, both in Ukraine and in the United States.

Conclusion. This article addressed the central research goal of identifying, systematizing, and empirically validating the legal and financial mechanisms that enable construction businesses to retain assets and sustain profitability during wartime conditions. The analysis confirms that business survival and asset preservation under conditions of armed conflict and economic instability are achievable outcomes when specific, proactively implemented legal and financial governance mechanisms are in place.

The study's primary contribution is the Legal and Financial Security System (LFSS) framework, an original author's synthesis that integrates four interdependent dimensions: corporate structure optimization, tax compliance management, asset protection through real estate holdings, and war risk insurance and legal hedging. The empirical evidence from the longitudinal case study of a Kyiv-based construction and real estate company, which maintained a portfolio of approximately

2,500 square meters of commercial real estate valued at a minimum of $1.25 million across three years of full-scale war while continuing to generate rental income, validates the framework's core proposition. The risk matrix developed in this study further provides a practical decision support tool for prioritizing protective investments across different risk categories.

The findings confirm the initial research hypothesis: disciplined legal structuring combined with proactive tax compliance and real estate-focused reinvestment enables a construction company to retain the majority of its asset value and maintain positive cash flow under conditions of active armed conflict, provided these mechanisms are implemented systematically and proactively.

The study demonstrates that the construction sector, often characterized as particularly vulnerable during conflict periods, can sustain operational and financial viability when business owners apply structured legal and financial governance rather than reactive crisis management. The reconstruction of Ukraine, with needs estimated at $524 billion over the next decade, will disproportionately benefit construction businesses that preserved organizational capacity and legal standing through the conflict period. The findings also carry applicability to the US market, where Ukrainian construction professionals bring transferable competencies in asset protection, financial discipline, and legal risk management developed under conditions that far exceed the adversity encountered in stable market economies.

Future research should examine cross-country comparative evidence from other post-conflict construction markets, including Iraq, Syria, and the Western Balkans, to test the LFSS framework's generalizability across different legal and institutional environments.

ДОДАТКОВА ІНФОРМАЦІЯ

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РОЗВИТОК МІЖНАРОДНОГО ОПОДАТКУВАННЯ В УМОВАХ ЦИФРОВІЗАЦІЇ ЕКОНОМІКИ

DEVELOPMENT OF INTERNATIONAL TAXATION IN THE CONDITIONS OF ECONOMIC DIGITALIZATION

Анотація. *Вступ. Цифрова трансформація економіки породжує принципово нові виклики для традиційних систем міжнародного оподаткування, сформованих ще в індустріальну епоху. Зростання цифрових транснаціональних компаній, які здійснюють діяльність без фізичної присутності в юрисдикціях, де отримують значні доходи, загострює проблему ерозії податкової бази та розмивання меж фіскального суверенітету держав.*

Проблематика. Дослідження присвячене теоретико-методологічним засадам міжнародного оподаткування в умовах цифровізації: еволюції концептуальних підходів, специфіці цифрової економіки як об'єкта фіскального регулювання та оцінці застосовності існуючих теоретичних моделей.

Мета – систематизація теоретичних підходів до міжнародного оподаткування цифрової економіки та визначення перспективних методологічних рамок для дослідження відповідних податкових викликів.

Методи. Застосовано методи системного аналізу, порівняльно-правового аналізу, наукового узагальнення, а також критичного огляду нормативних документів ОЕСР та Групи двадцяти (G20).

Результати. Простежено еволюцію теорій міжнародного оподаткування від класичних принципів резидентства та джерела доходу до сучасних концепцій значущої цифрової присутності. Визначено ключові ознаки цифрової економіки, що ускладнюють її оподаткування. Систематизовано методологічні підходи до оцінювання податкових викликів цифровізації та проаналізовано застосовність теоретичних моделей до оподаткування цифрового бізнесу.

Висновки. Існуючі теоретичні моделі потребують суттєвої адаптації до умов цифрової економіки. Перспективним напрямом є формування інтегрованої методологічної рамки, що поєднує принципи Pillar One/Two ОЕСР із концепцією значущої цифрової присутності та інструментами оцінки бази оподаткування в юрисдикціях споживання.

Ключові слова: *міжнародне оподаткування, цифрова економіка, цифровізація, BEPS, Pillar One, Pillar Two, значуща цифрова присутність, оподаткування транснаціональних корпорацій.*

Summary. *Introduction. The digital transformation of the economy creates fundamentally new challenges for traditional international taxation systems formed during the industrial era. The growth of digital multinational companies operating without physical presence in jurisdictions where they generate significant revenues intensifies the problem of tax base erosion and blurring of states' fiscal sovereignty boundaries.*

Problem Statement. The study focuses on the theoretical and methodological foundations of international taxation under digitalization: the evolution of conceptual approaches, the specifics of the digital economy as an object of fiscal regulation, and the assessment of the applicability of existing theoretical models.

Purpose. To systematize theoretical approaches to international taxation of the digital economy and identify prospective methodological frameworks for researching related tax challenges.

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Materials and Methods. Methods of systematic analysis, comparative legal analysis, scientific generalization, and critical review of OECD and G20 normative documents were applied.

Results. The evolution of international taxation theories from classical principles of residence and source of income to modern concepts of significant digital presence has been traced. Key features of the digital economy that complicate its taxation have been identified. Methodological approaches to assessing digitalization tax challenges have been systematized, and the applicability of theoretical models to digital business taxation has been analyzed.

Conclusions. Existing theoretical models require substantial adaptation to digital economy conditions. A promising direction is the formation of an integrated methodological framework combining OECD Pillar One/Two principles with the concept of significant digital presence and tools for assessing the tax base in consumption jurisdictions.

Key words: *international taxation, digital economy, digitalization, BEPS, Pillar One, Pillar Two, significant digital presence, taxation of multinational corporations.*

Вступ. Сучасна цифрова революція докорінно змінює архітектуру глобальної економіки, створюючи принципово нові форми організації бізнесу, виробництва та споживання. Транснаціональні цифрові платформи, хмарні сервіси, е-комерція та потокові медіасервіси генерують колосальні грошові потоки, перетинаючи державні кордони без будь-якого фізичного руху товарів чи осіб. Це зумовлює появу фундаментальної суперечності між традиційними принципами міжнародного оподаткування, що ґрунтуються на концепції фізичної присутності, та реаліями нематеріальної цифрової присутності.

Питання ерозії податкової бази й виведення прибутків за межі юрисдикцій (Base Erosion and Profit Shifting, BEPS) набули особливої гостроти після виявлення агресивного податкового планування провідних технологічних гігантів — Google, Amazon, Facebook, Apple та інших. За оцінками ОЕСР, втрати корпоративного податку внаслідок BEPS становлять від 100 до 240 млрд. дол. США щороку [1]. В умовах загострення бюджетних проблем у постпандемічний період та зростання фіскального тиску на держави питання справедливого розподілу прав на оподаткування цифрових доходів набуває критичного значення.

Саме тому дослідження теоретико-методологічних основ міжнародного оподаткування в умовах цифровізації є актуальним науковим завданням, що має як суттєве теоретичне значення для розвитку фінансової науки, так і практичне — для формування ефективної податкової політики держав в умовах глобальної конкурентної боротьби за розширення фіскальних ресурсів.

Аналіз досліджень і Постановка проблеми. Проблематика міжнародного оподаткування здавна перебуває в центрі наукових досліджень. Класичні роботи П. Муссграва [2] та Р. Берда [3] заклали фундаментальні принципи розмежування прав на оподаткування між юрисдикціями на основі критеріїв резидентства та джерела доходу. Ці принципи були кодифіковані в двосторонніх податкових конвенціях, побудованих переважно за зразком Типової конвенції ОЕСР.

Зі стрімким розвитком цифрової економіки у 2000-х роках наукова дискусія переорієнтувалась на пошук адекватних відповідей на нові виклики. Вагомий внесок у розробку концепцій оподаткування цифрової економіки зробили дослідники Р. де ла Фейте та Д. Толет [4], які обґрунтували необхідність переосмислення поняття постійного представництва. Б. Арнольд [5] проаналізував концептуальні проблеми застосування принципів джерела доходу до цифрових транзакцій.

Зі старту проекту ОЕСР/G20 з протидії розмиванню бази оподаткування (BEPS Action Plan, 2013) дослідницька активність у цій сфері різко зросла. Доповідь ОЕСР «Addressing the Tax Challenges of the Digital Economy» (Action 1, 2015) [6] стала базовим орієнтиром для подальших наукових розвідок. Концептуальні засади Pillar One та Pillar Two, що закріплюють принципи перерозподілу прав оподаткування та встановлення глобального мінімального корпоративного податку на рівні 15%, детально досліджувались у роботах Л. Оутера [7] та М. Демперте [8].

Серед вітчизняних дослідників проблемам міжнародного податкового планування та BEPS присвячені праці В.Л. Андрущенка [9], А.М. Крисоватого [10], С.І. Юрія та ін. Питання цифрової економіки в контексті оподаткування аналізувались у дослідженнях О.П. Крупки [11]. Водночас комплексний теоретико-методологічний аналіз еволюції міжнародного оподаткування в умовах цифровізації та систематизація підходів до оцінки відповідних викликів залишаються недостатньо розробленими в українській фінансовій науці, що і визначає наукову проблему цього дослідження.

Мета статті полягає у систематизації теоретичних підходів до міжнародного оподаткування цифрової економіки та визначенні перспективних методологічних рамок для дослідження відповідних податкових викликів на основі аналізу еволюції концептуальних моделей і принципів міжнародного оподаткування.

Методи дослідження. Методологічну основу дослідження становить сукупність загальнонаукових та спеціальних методів. Системний аналіз застосовувався для дослідження міжнародного оподаткування як цілісної системи принципів, норм та інституційних механізмів. Порівняльно-правовий аналіз використовувався при зіставленні різних теоретичних моделей оподаткування

та підходів різних юрисдикцій до врегулювання питань цифрового оподаткування. Методи наукового узагальнення та абстрактно-логічний метод застосовувались для формулювання теоретичних висновків. Критичний огляд нормативних документів OECP, G20, Комітету ООН з податкових питань, а також Директив ЄС забезпечив достатню емпіричну базу дослідження. Хронологічний підхід дозволив простежити еволюцію підходів до міжнародного оподаткування в динаміці.

Результати дослідження.

1.1. Еволюція теорії міжнародного оподаткування: підходи, моделі, принципи

Теорія міжнародного оподаткування пройшла тривалий шлях формування та трансформації. В її основі лежить фундаментальна проблема розмежування фіскальних прав між юрисдикціями в умовах транскордонного переміщення капіталу, доходів та осіб. Традиційно виокремлюють два конкуруючих принципи розподілу прав оподаткування — принцип резидентства та принцип джерела доходу.

Принцип резидентства (residence-based taxation) передбачає оподаткування резидентів держави за їхніми доходами з усього світу, незалежно від місця їх отримання. Він втілює ідею «здатності платити» (ability-to-pay) і відповідає інтересам розвинених країн-експортерів капіталу. Принцип джерела доходу (source-based taxation), натомість, закріплює право держави на оподаткування доходів, що формуються на її території, незалежно від резидентства їх отримувача. Він відображає ідею «вигоди» (benefit principle) — держава надає умови для генерації доходу і тому отримує право на його частину [2].

Класична модель Маслена–Маклура, а згодом і Модельна конвенція OECP [12], закріпили певний баланс між цими принципами, встановивши, що активні доходи оподатковуються переважно в країні джерела (за наявності постійного представництва), а пасивні (дивіденди, роялті, відсотки) — у країні резидентства. Ключовою концепцією, що визначала межу оподаткування в країні джерела, стало «постійне представництво» (permanent establishment, PE) — фіксоване місце ведення бізнесу, через яке суб'єкт повністю або частково здійснює господарську діяльність [12].

Важливим теоретичним внеском стала концепція «нейтральності» оподаткування. Нейтральність щодо експорту капіталу (capital export neutrality, CEN) і нейтральність щодо імпорту капіталу (capital import neutrality, CIN) стали теоретичними орієнтирами при формуванні систем міжнародного оподаткування, хоча досягнення обох одночасно є недосяжним завданням [2].

Починаючи з 1990-х років, під впливом глобалізації та зростання ролі нематеріальних активів (інтелектуальна власність, бренди, алгоритми) традиційна парадигма міжнародного оподаткування опинилась під значним тиском. Агресивне податкове планування транснаціональних корпорацій (ТНК), засноване на штучному переміщенні прибутків до низькоподаткових юрисдикцій через ціноутворення у внутрішньофірмових операціях (transfer pricing), роялті та гібридні фінансові інструменти, поставило під сумнів базові принципи системи. У відповідь на ці виклики OECP у 2013 р. ініціювала масштабний проект BEPS, що ознаменував початок нового етапу розвитку теорії й практики міжнародного оподаткування [1].

1.2. Поняття та ключові характеристики цифрової економіки: глобальний контекст

Цифрова економіка являє собою сукупність економічних відносин, що базуються на використанні цифрових технологій, Інтернету та даних як ключових факторів виробництва та трансформації цінності. Незважаючи на широке вживання цього терміна, його одностайного визначення в науковій і нормативній літературі не існує.

OECP у своїй доповіді Action 1 (2015) [6] виокремила такі специфічні риси цифрової економіки, що мають критичне значення для оподаткування: (1) мобільність — нематеріальні активи, функції та ризики легко переміщуються між юрисдикціями; (2) залежність від даних — дані користувачів є ключовим ресурсом для генерації вартості; (3) мережеві ефекти — цінність платформ зростає нелінійно зі збільшенням кількості користувачів; (4) масштабування без маси — цифровий бізнес може обслуговувати мільйони споживачів у всьому світі без суттєвих матеріальних активів у відповідних юрисдикціях; (5) волатильна ринкова структура — стрімка поява та зникнення бізнес-моделей.

З точки зору оподаткування, ключовою проблемою є здатність цифрових компаній отримувати значні доходи від споживачів у певній юрисдикції без будь-якої фізичної присутності в ній. Так, стримінгові сервіси, рекламні платформи, е-комерційні маркетплейси та хмарні провайдери здатні обслуговувати мільйони споживачів, не маючи у відповідній державі жодного офісу, складу чи серверу. Це підриває концепцію постійного представництва та розмиває зв'язок між місцем створення вартості та місцем оподаткування.

За даними Конференції ООН з торгівлі та розвитку (ЮНКТАД), обсяг глобальної електронної комерції до 2022 р. досяг близько 27 трлн. дол. США [13]. Ринкова капіталізація найбільших цифрових платформ (Apple, Microsoft, Amazon, Alphabet) перевищує ВВП більшості держав світу, що унаочнює масштаби фіскального виклику, який постав перед міжнародним співтовариством.

1.3. Методологія оцінювання податкових викликів цифровізації

Оцінювання податкових викликів цифровізації потребує спеціального методологічного інструментарію, оскільки традиційні підходи, засновані на аналізі фізичних грошових потоків та матеріальних

активів, не здатні повноцінно відобразити специфіку цифрових бізнес-моделей. У науковій літературі виокремлюється кілька методологічних підходів.

По-перше, підхід на основі аналізу ланцюга вартості (value chain analysis). Він передбачає ідентифікацію всіх функцій, ризиків та активів у ланцюгу створення вартості цифрової компанії та їх прив'язку до відповідних юрисдикцій. Методологічна проблема тут полягає у тому, що цифрові активи (алгоритми, бази даних, нематеріальні права)

Таблиця 1

Порівняльний аналіз теоретичних моделей оподаткування цифрового бізнесу

Параметр порівняння	Адаптація традиційних моделей	Дестинаційне оподаткування	Мінімальне оподаткування(Pillar Two)
Концептуальна основа	Принцип постійного представництва (PE) та трансфертне ціноутворення	Принцип місця споживання (destination); перерозподіл прав оподаткування	Встановлення глобального «мінімуму» для фіскальної конкуренції
Ключовий механізм	Розширення критеріїв PE (BEPS Action 7); оновлення правил трансфертного ціноутворення	Amount A (Pillar One): перерозподіл надприбутків МНК до ринкових юрисдикцій	GloBE Rules (Pillar Two): мінімальна ефективна ставка корпоративного податку 15%
Нормативна база	Модельна конвенція OECP; BEPS Actions 7–10	OECD/G20 Pillar One Statement (2021); Multilateral Convention	OECD/G20 Pillar Two Model Rules (2021); EU Directive 2022/2523
Критерій «зв'язку» (nexus)	Фізична присутність: фіксоване місце бізнесу або агент	Економічна присутність: дохід понад 1 млн. євро у юрисдикції	Не встановлює нових nexus-критеріїв; діє через систему UTPR/STTR
Охоплення цифрових моделей	Часткове — не охоплює платформи та хмарні сервіси без фізичного PE	Широке — застосовується до МНК з доходом понад 20 млрд. євро та рентабельністю >10%	Широке — охоплює МНК із консолідованим доходом понад 750 млн. євро
Участь юрисдикцій ринку збуту	Обмежена — лише за наявності PE	Висока — ринкові юрисдикції отримують 25% надприбутків Amount A	Непряма — через механізм UTPR (Undertaxed Profits Rule)
Протидія агресивному плануванню	Помірна — можливості уникнення PE залишаються	Помірна — охоплює лише наднормові прибутки (>10% рентабельності)	Висока — «підлога» ефективної ставки унеможливлює нульове оподаткування
Стимули для офшоризації	Зберігаються — переміщення IP до низькоподаткових юрисдикцій вигідне	Зменшуються для надприбутків; зберігаються для звичайних доходів	Суттєво знижуються — ефект офшорних структур обнуляється до рівня 15%
Справедливість розподілу	Низька — розподіл на користь юрисдикцій резидентства ТНК	Середня — часткове перенесення до ринкових юрисдикцій	Низька — не перерозподіляє права між юрисдикціями
Складність адміністрування	Висока — спори щодо трансфертного ціноутворення	Дуже висока — новий механізм розподілу, потребує міжнародної координації	Висока — потребує глобального обміну даними та моніторингу ефективних ставок
Застосовність до малих юрисдикцій	Середня — двосторонні конвенції частково захищають	Низька — зачіпає лише наднаціональні МНК (дохід >20 млрд. євро)	Середня — STTR (Subject to Tax Rule) захищає країни, що розвиваються
Стан імплементації (2024)	Повністю впроваджена у більшості юрисдикцій через мережу конвенцій	В процесі — підписання Multilateral Convention очікується 2024–2025	Частково — понад 35 юрисдикцій прийняли GloBE Rules; ЄС — з 2024 р.
Теоретична парадигма	Benefit principle + source-based taxation	Destination-based Cash Flow Tax (DBCFT) у модифікованій формі	Minimum taxation + anti-avoidance (GloBE / Income Inclusion Rule)
Наукові представники	Муссграв [2], Берд [3], де ла Фейте [4], Арнольд [5]	Авербах та ін. [16]; OECD Pillar One Blueprint [17]	Оутера [7], Девере і Велла [8]; OECD GloBE Rules [17]
Загальна оцінказастосовностідо цифровоїекономіки	Недостатня — потребує фундаментальної реформи поняття PE	Перспективна — прямо орієнтована на специфіку цифрових платформ	Доповнювальна — ефективна як захисний механізм, а не системне рішення

Джерело: складено автором на основі [1; 4; 6; 7; 16]

часто юридично локалізовані в одній юрисдикції, тоді як їх економічна цінність формується за рахунок користувачів з інших юрисдикцій [4].

По-друге, підхід на основі концепції «участі користувачів» (user participation). Він ґрунтується на тезі, що в цифрових бізнес-моделях користувачі є активними учасниками створення вартості — через генерацію даних, формування мережевих ефектів, контент-продукцію та зворотний зв'язок. Відповідно, юрисдикція ринку збуту має право на отримання частки прибутку пропорційно до внеску своїх резидентів [6]. Саме цей підхід ліг в основу Pillar One OECP.

По-третє, методологічний підхід на основі «значущої цифрової присутності» (significant digital presence, SDP). Він передбачає встановлення нових критеріїв «зв'язку» (nexus) між цифровим бізнесом та юрисдикцією, заснованих не на фізичній, а на економічній присутності: кількості активних користувачів, обсязі цифрових операцій, величині доходів тощо. Концепція SDP запроваджена в Директиві ЄС 2018/822 та закріплена у пропозиції Єврокомісії щодо Digital Services Tax (DST) [14].

Кількісні методи оцінки розміру «податкового розриву» (tax gap) в цифровій економіці включають: мікросимуляційне моделювання на основі даних фінансової звітності ТНК; аналіз ефективних податкових ставок; порівняльний аналіз рентабельності цифрових і традиційних компаній; гравітаційні моделі для оцінки штучного переміщення прибутків. Ці методи активно розробляються в рамках дослідницьких програм МВФ та ОЕСР [15].

1.4. Теоретичні моделі оподаткування віртуального бізнесу: оцінка застосовності

У науковій літературі до сьогодні не сформовано єдиної теоретичної моделі оподаткування цифрового бізнесу. Існуючі підходи умовно можна класифікувати за трьома напрямами.

Перший напрям — адаптація традиційних моделей. Він передбачає розширення традиційних концепцій постійного представництва та ціноутворення у внутрішньофірмових операціях для охоплення цифрових бізнес-моделей. Прикладом є ОЕСР Action 7 (2015), що розширила визначення РЕ для протидії штучному уникненню статусу постійного представництва. Критики цього підходу вказують, що він є косметичним ремонтом застарілої конструкції [5].

Другий напрям — «дестинаційне» оподаткування (destination-based taxation). Цей підхід передбачає перехід до оподаткування прибутку корпорацій переважно в юрисдикціях споживання (ринку збуту), а не у юрисдикціях резидентства чи джерела. Теоретичне обґрунтування цього підходу розроблене А. Авербахом та ін. [16]. Pillar One ОЕСР з механізмом Amount A є частковою реалізацією цієї ідеї.

Третій напрям — моделі на основі мінімального оподаткування. Глобальний мінімальний корпоративний податок (Pillar Two, ставка 15%) являє собою принципово нову теоретичну конструкцію, спрямовану не на перерозподіл прав оподаткування, а на встановлення «підлоги» для фіскальної конкуренції між юрисдикціями. Ця модель здатна суттєво обмежити можливості агресивного податкового планування цифрових ТНК [7].

Для унаочнення порівняльного аналізу зазначених підходів у таблиці 1 узагальнено їх ключові параметри.

Оцінка застосовності зазначених моделей засвідчує, що жодна з них окремо не є достатньою для вирішення всього спектра проблем оподаткування цифрової економіки. Адаптація традиційних моделей є паліативним рішенням, дестинаційне оподаткування стикається з проблемою визначення місця споживання для нематеріальних послуг, а мінімальне оподаткування, хоча й ефективне проти агресивного планування, не вирішує питання справедливого розподілу прав оподаткування.

Перспективним є формування інтегрованої моделі, яка поєднує: (1) оновлені критерії «зв'язку», засновані на концепції SDP; (2) механізм Amount A Pillar One для перерозподілу надприбутків великих МНК на користь ринкових юрисдикцій; (3) глобальний мінімальний податок Pillar Two як захисний механізм від фіскальної конкуренції. Подібна інтегрована рамка здатна одночасно підвищити ефективність, справедливість та стійкість системи міжнародного оподаткування в умовах цифровізації.

Висновки. Проведене дослідження дозволяє сформулювати такі наукові висновки.

По-перше, теорія міжнародного оподаткування пройшла еволюційний шлях від базових принципів резидентства та джерела доходу, сформованих у XX столітті, до сучасних концепцій значущої цифрової присутності та перерозподілу прав оподаткування, що відповідають реаліям цифрової економіки. Традиційна конструкція постійного представництва виявилась нездатною охопити специфіку цифрових бізнес-моделей.

По-друге, цифрова економіка є якісно відмінним об'єктом фіскального регулювання порівняно з традиційною економікою, оскільки характеризується мобільністю нематеріальних активів, залежністю від даних, мережевими ефектами та здатністю до масштабування без фізичної присутності в ринкових юрисдикціях. Ці характеристики системно підривають чинну архітектуру міжнародних податкових правил.

По-третє, методологічний арсенал для оцінки податкових викликів цифровізації включає аналіз ланцюга вартості, концепцію участі користувачів та підхід значущої цифрової присутності, кожен з яких відображає певний аспект проблеми та має свої аналітичні переваги й обмеження.

По-четверте, жодна з наявних теоретичних моделей — адаптаційна, дестинаційна чи мінімального оподаткування — не здатна самостійно вирішити весь спектр проблем оподаткування цифрового бізнесу. Наукова новизна дослідження

полягає у систематизації підходів та обґрунтуванні необхідності формування інтегрованої методологічної рамки, що поєднує механізми Pillar One/Two OECP з концепцією SDP. Практичне значення отриманих результатів полягає у можливості їх використання при розробці національної стратегії участі України у міжнародних процесах цифрового оподаткування, а також при формуванні відповідного законодавства.

Перспективами подальших досліджень є кількісна оцінка фіскальних ефектів запровадження Pillar Two для України, а також аналіз можливостей використання механізмів SDP в умовах вітчизняного законодавства.

ДОДАТКОВА ІНФОРМАЦІЯ

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МІСТЕЧКО ДЕРАЖНЯ У ДРУГІЙ ПОЛОВИНІ XIX СТ.: СОЦІОДЕМОГРАФІЧНА ТА КОНФЕСІЙНА ТРАНСФОРМАЦІЯ

THE TOWN OF DERAZHNYA IN THE SECOND HALF OF THE 19TH CENTURY: SOCIO-DEMOGRAPHIC AND RELIGIOUS TRANSFORMATION

Анотація. *У статті реконструйовано соціодемографічну, конфесійну та просторову трансформацію містечка Деражня Летичівського повіту Подільської губернії у другій половині XIX ст. На основі зіставлення камеральних описів, ревізьких списків, метричних книг, статистичних відомостей і матеріалів перепису 1897 року показано, як поєднання залізничної інфраструктури, імперського законодавства щодо єврейського населення та міграційних процесів перетворило Держню з аграрно-ремісничого осередку на потужний транспортно-торговельний вузол. Визначено роль конфесійної структури у формуванні соціотопографії, професійної спеціалізації та демографічної поведінки громад. Порівняльний аналіз з Летичевом, Меджибожем і Вовковинцями дозволив виявити унікальні чинники модернізації Деражні в контексті подільських містечок.*

Ключові слова: *Деражня, Подільська губернія, містечко, штетл, залізниця, демографія, конфесійна структура, міграція, друга половина XIX ст.*

Summary. *The article reconstructs the sociodemographic, confessional, and spatial transformation of the town of Derazhnia in Letychiv county, Podillia gubernia, during the second half of the nineteenth century. Based on a comparative analysis of cadastral descriptions, revision lists, metrical books, statistical records, and materials from the 1897 census, the study demonstrates how the combination of railway infrastructure, imperial legislation on the Jewish population, and migration processes transformed Derazhnia from an agrarian and craft center into a powerful transport and trade hub. The role of confessional structure in shaping sociotopography, professional specialization, and demographic behavior of communities is determined. A comparative analysis with Letychiv, Medzhybizh, and Vovkovyntsi made it possible to identify unique factors of Derazhnia's modernization in the context of Podillian towns.*

Key words: *Derazhnia, Podillia gubernia, town, shtetl, railway, demography, confessional structure, migration, second half of the 19th century.*

Наукова проблема дослідження полягає у виявленні механізмів та чинників трансформації традиційного подільського містечка в умовах імперської модернізації другої половини XIX ст., зокрема визначенні співвідношення між:

– інфраструктурними змінами (відкриття залізничної станції 1871 р.) та демографічною динамікою (зростання населення майже в 3,8 рази за 1858–1897 рр.);

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– імперським обмежувальним законодавством («Тимчасові правила» 1882 р.) та конфесійною структурою (формування абсолютної юдейської більшості — 68,3%);
– становим поділом (міщани та селяни) та професійною спеціалізацією (торгівля, ремесло та землеробство);
– міграційними процесами (механічний приріст) та природним рухом населення (народжуваність, смертність, дитяча смертність);
– просторовою сегрегацією (єврейський квартал, селянська периферія, пристанційна зона) та соціальною ієрархією містечка.

Методологічною основою дослідження стали принципи історизму, об'єктивності та системності, а також методи мікроісторичного, проблемно-хронологічного, порівняльного, історико-генетичного та структурно-функціонального аналізу, що дало змогу реконструювати механізми поземельного рецидиву 1862–1863 років у Деражнянській окрузі та простежити особливості адаптації селянських громад після реформи 1861 року.

Аналіз останніх досліджень і публікацій. Проблематика соціально-демографічного та конфесійного розвитку містечок Правобережної України другої половини XIX ст. перебуває у фокусі досліджень українських істориків останніх десятиліть. Загальні питання імперської модернізації західних окраїн Російської імперії, зокрема аграрної політики та інфраструктурних змін, розглянуто у працях О. І. Гуржія, який проаналізував механізми інтеграції регіону до загальноімперського економічного простору в 1830–1880-ті роки [14].

Єврейські громади Поділля, їхня соціальна структура та роль у регіональній економіці стали об'єктом досліджень В. В. Кононенка, який простежив еволюцію єврейських громад регіону від XV до першої половини XX ст., акцентувавши на їхньому становищі в «смузі осілості» та впливі імперського законодавства [17]. В. О. Доценко проаналізував єврейський громадський рух в Україні 1860–1930-х рр., показавши механізми адаптації єврейського населення до імперських обмежень та економічних змін [15].

Питання соціально-економічної історії українського селянства другої половини XIX ст., зокрема наслідків реформи 1861 року, викупних платежів та переходу до міщанського стану, досліджено у працях О. П. Реєнта, який виявив ключові стратегії виживання селянських громад у пореформену добу [19].

Окремі аспекти історії Деражні та Летичівського повіту вже стали предметом краєзнавчих студій. Зокрема, О. Я. Дячок проаналізував топографічний і камеральний опис Летичівського повіту кінця XVIII — початку XX ст., виявивши гідрологічні та природно-географічні чинники формування поселень регіону [16].

Метою статті є комплексна реконструкція соціодемографічної, конфесійної та просторової трансформації містечка Деражня Летичівського повіту Подільської губернії у другій половині XIX ст. та визначення чинників, що зумовили її перетворення з приватновласницького аграрно-ремісничого осередку на потужний залізнично-експортний вузол регіону.

Виклад основного матеріалу дослідження. Дослідження містечок Правобережної України традиційно розглядається крізь призму макрорегіональних процесів, тоді як мікроісторичний аналіз окремих поселень дозволяє виявити специфіку адаптації локальних спільнот до імперських трансформацій. Містечко Деражня Летичівського повіту є репрезентативним кейсом для вивчення еволюції подільського «штетлу» від доби Речі Посполитої до кінця XIX століття, демонструючи складний синтез традиційного аграрного укладу та модернізаційних викликів пореформеної доби.

Джерельну базу дослідження становить комплекс архівних матеріалів Державного архіву Хмельницької області (ДАХмО), що дозволяє реалізувати методику джерелознавчої триангуляції. До неї входять: камеральний та топографічний опис Летичівського повіту 1812 року [5], ревізькі казки 10-ї народної ревізії 1858 року та додаткові списки 1860–1870-х років [7], метричні книги Подільської духовної консисторії та казенного рабинату [9; 10], а також статистичні відомості Подільської губернії за 1866 рік [8]. Перехресне зіставлення цих масивів дає змогу деконструювати суху статистику Першого загального перепису населення 1897 року та відтворити реальні демографічні процеси у «міжпереписний» період.

Просторово-географічний каркас Деражні був жорстко детермінований гідрографією. Згідно з камеральним описом 1812 року, поселення розташовувалося по обидва боки річки Вовк на низьких і пологих берегах. У центральній частині русло річки за допомогою системи гребель утворювало просторий став, а з лівого боку в неї впадав безіменний струмок. Цей водно-енергетичний вузол визначав економічну спеціалізацію містечка. На одній із гребель функціонували два борошняних млини (чотири постави), а також діяли три єврейські винокурні та панська кам'яна пивоварня з солодовнею [5, Арк. 103зв.–106зв.].

Містечко Деражня Летичівського повіту Подільської губернії у пореформену добу другої половини XIX ст. еволюціонувало від приватновласницького аграрно-ремісничого осередку до потужного транспортно-торговельного вузла регіону.

З точки зору інституційно-власницького статусу, Деражня демонструвала притаманний Правобережній Україні дуалізм. З одного боку, поселення перебувало у приватній магнатській власності — до 1844 р. роду Мошинських, а з 1844 р. — Станіслава Рациборовського та його нащадків (зокрема Тадеуша та Віктора Рациборовських). З іншого боку, після реформ 1860-х рр. містечко функціонувало як центр

Деражнянського волосного правління та волосного суду. Тут паралельно діяли: волосна та сільська адміністрація, що опікувалася селянами-власниками. Фіскальні й рекрутські функції щодо міщанського стану виконувала Деражнянська міщанська управа [6, Арк. 1–200]. Цивільно-правовий і духовний побут юдейської більшості у населеному пункті регулювали казенний рабинат та інститути кагального самоврядування [10, Арк. 1–380].

Кардинальний інфраструктурний перелом у просторовій організації Деражні відбувся у 1871 році із введенням в експлуатацію дільниці Жмеринка — Волочиськ Південно-Західної залізниці та відкриттям залізничної станції «Деражня». Включення до залізничної мережі змістило економічний центр містечка від традиційної Базарної площі до пристанційного району з гуртовими складами збіжжя, елеваторами та заїжджими дворами. Деражня перетворилася на ключовий пункт експорту пшениці, цукрових буряків, лісу й спирту до Одеського порту та західнокордонних митниць.

Конфесійний склад населення Деражні у другій половині XIX ст. визначав соціокультурне обличчя містечка, перетворюючи його на репрезентативний подільський «штетл». За даними Першого загального перепису населення Російської імперії 1897 року, релігійна конфігурація мешканців мала такий вигляд Юдеї — 3 335 осіб (68,3%): становили абсолютну більшість населення містечка. Концентрація єврейської громади була зумовлена як нормами перебування у «смузі осілості», так і дією обмежувальних «Тимчасових правил» від 3 травня 1882 року, які забороняли євреям селитися в сільській місцевості та купувати нерухомість поза межами міст і містечок. Їхній сакральний простір охоплював синагогу, понад 5 молитовних будинків (бейт-мідрашів), хеддери та благодійні товариства.

Православні — 1 384 особи (28,3%): репрезентувалися переважно місцевим селянством та частиною міщан. Духовним осередком була парафіяльна Свято-Покровська церква (із приписною Свято-Михайлівською) Летичівського благочиння Подільської єпархії [9, Арк. 1–450].

Римо-католики — 160 осіб (3,3%): представники дворянства, шляхти, маєткової адміністрації графів Пшездецьких/Рациборовських (економи, лісничі), а також залізничні службовці та технічні фахівці. Не маючи власного костелу безпосередньо в містечку, громада була приписана до Летичівського деканату.

Інші (старообрядці, протестанти) — 13 осіб (0,1%). які охоплювала дрібні віросповідні групи, і не утворювали в містечку окремих інституційних громад.

Центральна частина (Базарна площа) являла собою щільно забудований єврейський квартал із торговими лавками, майстернями та синагогами. Периферійні вулиці займали православні селяни-власники з напіваграрним характером забудови. Пристанційна зона функціонувала як модернізаційний анклав римо-католицької та службової адміністрації.

У містечку спостерігалася абсолютна конфесійна ендогамія. За даними метричних книг казенного рабинату та консисторії, середній вік вступу до першого шлюбу серед юдеїв становив 18–21 рік для жінок і 20–23 роки для чоловіків, тоді як у православних селян — відповідно 20–24 та 22–26 років [9; 10].

Демографічна динаміка Деражні у другій половині XIX ст. характеризується стрімким, майже експоненційним зростанням, яке неможливо пояснити виключно природним приростом. За даними 10-ї ревізії 1858 року, у містечку було зареєстровано 1 298 осіб юридично приписного населення [7]. Однак справжній демографічний стрибок відбувся у 1870–1890-х роках: за підсумками перепису 1897 року, фактична чисельність населення Деражні сягнула 4 882 осіб [12, с. 2–3].

Зростання чисельності населення майже в 3,8 рази неможливо пояснити лише природним приростом, який коливався в межах 10–14‰ на рік. Вирішальну роль відіграв механічний (міграційний) приріст, зумовлений залізничним будівництвом (1871 р.) та примусовим переселенням єврейського населення із сіл після 1882 року.

Стрибкоподібне зростання загальної чисельності було наслідком двох імперських факторів. По-перше, відкриття у 1871 році дільниці Жмеринка — Волочиськ Південно-Західної залізниці та станції «Деражня» перетворило містечко на потужний пункт акумуляції та експорту аграрної продукції, що спричинило приплив робітників, службовців та торговельних посередників. По-друге, дія «Тимчасових правил» 1882 року, які забороняли нове поселення євреїв у сільській місцевості, спровокувала масову концентрацію юдейського населення в містечках «смуги осілості». Саме цей механічний приріст сформував ту конфесійну конфігурацію, яку зафіксував перепис 1897 року: юдеї становили абсолютну більшість (3 335 осіб, або 68,3%), православні посідали друге місце (1 384 особи, 28,3%), а римо-католики репрезентували невелику, але соціально значущу меншість (160 осіб, 3,3%) [12, с. 176–177].

Аналіз віково-статевої піраміди Деражні засвідчує прогресивний (експансивний) тип відтворення з високою часткою дитячого населення та наявністю гендерних диспропорцій у працездатному віці.

Найбільш виразною характеристикою цієї структури є аномально висока частка дітей та підлітків. Особи віком до 19 років налічували 2 409 осіб, що становило майже половину всього населення містечка (49,35%). Зокрема, наймолодша вікова група (0–9 років) налічувала 1 343 особи (27,51%), а група 10–19 років — 1 066 осіб (21,84%). Така демографічна конфігурація свідчить про стабільно високий коефіцієнт народжуваності, який у поєднанні з високою, особливо дитячою, смертністю (як було показано

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Таблиця 1

Віково-статева структура населення містечка Деражня (1897 р.)

Вікова група	Чоловіки (осіб)	Жінки (осіб)	Разом (осіб)	Частка від загалу (%)	Гендерний баланс (жінки — чоловіки)
0–9 років	682	661	1343	27,51	–21 (перевага чоловіків)
10–19 років	524	542	1066	21,84	+18 (перевага жінок)
Усього дітей і молоді (0–19)	**1206**	**1203**	**2409**	**49,35**	**–3 (баланс)**
20–39 років	680	741	1421	29,11	+61 (перевага жінок)
40–59 років	362	390	752	15,40	+28 (перевага жінок)
60 років і старше	143	157	300	6,14	+14 (перевага жінок)
УСЬОГО	**2391**	**2491**	**4882**	**100,0**	**+100 (перевага жінок)**

Джерело: розраховано на основі: Первая Всеобщая перепись населения Российской империи 1897 г. Вып. XXXII: Подольская губерния. СПб., 1904. С. 2–3, 176–177.

в попередніх розділах на основі метричних книг) формував замкнене коло традиційного відтворення. Велика родина в умовах Деражні виступала не лише соціальною нормою, а й економічною необхідністю: дитяча праця була інтегрована як у селянське господарство, так і в міщанські ремісничі майстерні, забезпечуючи виживання домогосподарства.

Однак різке звуження піраміди у вікових групах старше 20 років вказує на дію потужних відцентрових міграційних факторів та інституційного тиску імперії. Найбільш показовим є гендерний дисбаланс у працездатному віці (20–39 років). У цій категорії зафіксовано 680 чоловіків проти 741 жінки, тобто перевага жіночого населення становила 61 особу (або 4,2% від загальної чисельності цієї групи). Подібна диспропорція не може бути пояснена виключно біологічними факторами; вона є прямим наслідком трьох взаємопов'язаних процесів.

По-перше, це систематичне вилучення чоловічого населення через інститут рекрутської повинності, а з 1874 року — через запровадження загальної військової повинності, яка відривала молодих чоловіків від місць проживання на термін від 3 до 6 років. По-друге, розвиток залізничної інфраструктури та інтеграція Деражні в загальноімперський ринок стимулювали сезонну та постійну трудову міграцію (відхідництво). Чоловіки масово залишали містечко для роботи на будівництві залізниць, у портах Одеси або на сезонних сільськогосподарських роботах у південних степових губерніях (Херсонській, Таврійській), де попит на фізичну працю був значно вищим, а оплата — привабливішою. По-третє, специфіка містечкової економіки дозволяла жінкам, особливо в юдейській громаді, брати активну участь у дрібній торгівлі, домашньому ремеслі та обслуговуванні пристанційної інфраструктури, що утримувало їх у містечку, тоді як чоловіки шукали кращих економічних перспектив за його межами.

Ця тенденція посилювалася з віком: у групі 40–59 років перевага жінок зростала до 28 осіб, а у групі 60 років і старше — до 14 осіб, що підтверджує як загальнодемографічну закономірність більшої тривалості життя жінок, так і кумулятивний ефект чоловічої міграції та смертності від важких умов праці та військових конфліктів.

Найбільш виразною характеристикою цієї структури є аномально висока частка дітей та підлітків. Особи віком до 19 років налічували 2409 осіб, що становило майже половину всього населення містечка (49,35%). Зокрема, наймолодша вікова група (0–9 років) налічувала 1343 особи (27,51%), а група 10–19 років — 1066 осіб (21,84%). Така демографічна конфігурація була наслідком стабільно високого коефіцієнта народжуваності, який у поєднанні з високою, особливо дитячою, смертністю формував замкнене коло традиційного відтворення. Велика родина в умовах Деражні виступала не лише соціальною нормою, а й економічною необхідністю: дитяча праця була інтегрована як у селянське господарство, так і в міщанські ремісничі майстерні, забезпечуючи виживання домогосподарства.

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По-друге, розвиток залізничної інфраструктури та інтеграція Деражні в загальноімперський ринок стимулювали сезонну та постійну трудову міграцію (відхідництво). Чоловіки масово залишали містечко для роботи на будівництві залізниць, у портах Одеси або на сезонних сільськогосподарських роботах у південних степових губерніях (Херсонській,

Таврійській), де попит на фізичну працю був значно вищим, а оплата — привабливішою.

По-третє, специфіка містечкової економіки дозволяла жінкам, особливо в юдейській громаді, брати активну участь у дрібній торгівлі, домашньому ремеслі та обслуговуванні пристанційної інфраструктури, що утримувало їх у містечку, тоді як чоловіки шукали кращих економічних перспектив за його межами. Ця тенденція посилювалася з віком: у групі 40–59 років перевага жінок зростала до 28 осіб, а у групі 60 років і старше — до 14 осіб, що підтверджує як загальнодемографічну закономірність більшої тривалості життя жінок, так і кумулятивний ефект чоловічої міграції та смертності від важких умов праці та військових конфліктів.

Отже, віково-статева структура населення Деражні кінця XIX ст. була не стихійним демографічним явищем, а прямим наслідком імперської політики (рекрутська та військова повинність) та економічної інтеграції (залізничне будівництво, трудова міграція). Це призвело до формування демографічної піраміди з аномально високою часткою дітей (49,35%) та гендерним дисбалансом у працездатному віці (перевага жінок на 61 особу в групі 20–39 років), що відображало глибші соціально-економічні трансформації пореформеної доби.

Соціально-станова організація Деражні у другій половині XIX ст. формувалася на перетині двох систем координат — імперського станового поділу та конфесійно зумовленої професійної спеціалізації. Цей дуалізм надавав місцевому соціуму виразної ієрархічності, водночас забезпечуючи функціональну взаємозалежність між різними групами населення. На відміну від повітових центрів, де станові межі часто розмивалися під тиском бюрократичної вертикалі, у містечках типу Деражні вони зберігали чіткість і виступали реальним механізмом соціальної стратифікації.

Основу соціуму становили дві великі групи — міщани та селяни, причому їхнє співвідношення і функціональні ролі були нерозривно пов'язані з конфесійною структурою. Юдейське населення, яке за переписом 1897 року становило 68,3% мешканців (3 335 осіб), майже повністю входило до міщанського стану [12, с. 176–177]. Це було наслідком не лише демографічної динаміки, а й тривалої історичної традиції, за якої євреї на Правобережжі переважно мешкали в містах і містечках, займаючись торгівлею, ремеслом та орендою промислових об'єктів. Православне населення, навпаки, зберігало переважно селянський статус, навіть коли частина його представників постійно проживала в межах містечка (1 384 особи, 28,3%) [12, с. 176–177].

Юдейська громада Деражні формувала складний соціально-економічний прошарок, який можна умовно поділити на три рівні. Верхівку становили підприємці-орендарі, які тримали в оренді поміщицькі промислові об'єкти — водяні млини на річці Вовк, ґуральні, цегельний завод, а також контролювали ярмаркову торгівлю збіжжям, птицею та іншою сільськогосподарською продукцією. Згідно з камеральним описом 1812 року, на одній із гребель річки Вовк функціонували два борошняних млини (чотири постави), а також діяли три єврейські винокурні та панська кам'яна пивоварня з солодовнею [5, Арк. 103зв.–106зв.]. Саме ця група акумулювала основний капітал і виступала головним кредитором для селянського населення.

У пореформену добу, коли державна кредитна система в сільській місцевості фактично не функціонувала, приватні позики під заставу майбутнього врожаю стали ключовим механізмом фінансування селянських господарств. Архівні справи мирового посередника Летичівського повіту фіксують численні випадки, коли борг погашався не грошима, а примусовим відпрацюванням на поміщицьких полях чи промислових об'єктах, що створювало механізм боргової залежності [4, Арк. 20–25]. Аналітична записка Подільського губернського статистичного комітету за 1866 рік підтверджує, що відсутність організованої державної кредитної системи змушувала селян вдаватися до позик у єврейських орендарів під заставу майбутнього врожаю [8, Арк. 30–37].

Середній рівень юдейської громади репрезентували дрібні торговці та ремісники. За підрахунками на основі перепису 1897 року, євреям належало близько 30–40 мануфактурних крамниць, три оптові склади, лісові склади, а також переважна більшість торгових лавок на Базарній площі [12, с. 176–177]. Понад 85% усіх зайнятих у торгівлі містечка належали до юдейської громади. Ремісничий сектор також був зосереджений у їхніх руках: понад 70% місцевих кустарних майстрів були євреями, які займалися кравецтвом, шевством, ковальством, бондарством, а також виконували релігійні функції різників-шойхетів [12, с. 176–177]. Ця група забезпечувала повсякденні потреби як міського, так і селянського населення, формуючи своєрідний «середній клас» містечкової економіки.

Нижчий рівень юдейського міщанства становили наймити, носії, дрібні торговці в рознос, а також члени родин, які не мали власного господарства. Попри внутрішню диференціацію, усю юдейську громаду об'єднувала спільність інституційного простору: казенний рабинат, синагога, молитовні будинки, хедери та благодійні товариства виступали не лише релігійними, а й соціальними осередками, що регулювали цивільно-правовий і духовний побут більшості мешканців містечка. Метричні книги Деражнянського єврейського рабинату за 1860–1897 роки фіксують діяльність цих інституцій та реєструють цивільні стани юдейського населення [10, Арк. 1–380].

Православне населення Деражні, яке становило 28,3% мешканців (1 384 особи), було представлено переважно селянами-власниками, які після реформи 1861 року вийшли зі стану тимчасовозобов'язаних

і отримали у власність садибні та польові наділи [3, Арк. 1–85]. Їхня соціально-економічна позиція була суттєво іншою, ніж у юдейської громади. Основу господарства становили землеробство, присадибне тваринництво та візництво, причому останнє відігравало важливу роль у зв'язку з інтеграцією містечка до залізничної мережі. Гужовий транспорт до залізничної станції «Деражня» став одним із джерел доходу для селянських родин, які перевозили збіжжя, цукрові буряки, ліс та інші вантажі.

Водночас селянське населення не було соціально однорідним. Частина селян, особливо молодші сини в багатодітних родинах, не мали достатніх земельних наділів і змушені були шукати додаткових заробітків. Це зумовлювало розвиток сезонної праці за наймом у поміщицькому фільварку, на цукрових плантаціях, а також відхідництво до інших регіонів імперії. Додаткові ревізькі списки 1860–1870-х років фіксують перехід частини селян до міщанського стану, що відображало прагнення уникнути обтяжливих викупних платежів та отримати доступ до міських видів зайнятості [7, Арк. 115–120]. Така економічна стратегія була тісно пов'язана з демографічною структурою: висока народжуваність і велика родина вимагали залучення всіх членів домогосподарства до господарської діяльності, а дитяча праця була інтегрована як у селянське господарство, так і в міщанські ремісничі майстерні. Метричні книги Свято-Покровської та Свято-Михайлівської церков за 1860–1897 роки засвідчують високу народжуваність у православній громаді (коефіцієнт 42–48‰) та значну дитячу смертність (45–52% від загальної кількості померлих). У юдейській громаді цей показник був нижчим — 35–42%, що пояснюється відсутністю залучення єврейських жінок до важкої польової праці, їхньою зайнятістю у домашній торгівлі та ремеслі, а також тривалішим періодом грудного вигодовування [9, Арк. 50–68; 10, Арк. 12–35].

Третю велику групу становив службово-адміністративний та дворянський прошарок, до якого належали власники маєтку (Рациборовські), службовці поміщицької контори (економісти, лісничі, писарі), урядовці волосного правління, поштово-телеграфні чиновники, а після 1871 року — штат залізничних службовців станції «Деражня». Ця група була найменшою за чисельністю (160 осіб римо-католиків, 3,3%), але відігравала важливу роль у соціальній ієрархії містечка [12, с. 176–177]. Більшість її представників належали до римо-католицької громади. Не маючи власного костелу безпосередньо в містечку, католицька громада була приписана до Летичівського деканату, але її соціальний статус був значно вищим, ніж у більшості православних селян і навіть дрібних єврейських торговців.

Соціотопографічна структура Деражні чітко відтворювала цю соціальну ієрархію. Центральна частина містечка, зокрема Базарна площа та прилеглі вулиці, являла собою щільно забудований єврейський квартал із торговими лавками, майстернями та синагогами. Тут концентрувалася основна частина юдейського населення, яке здійснювало торговельну та ремісничу діяльність. Периферійні вулиці та вигони, розташовані ближче до річки та орних земель, займали православні селяни-власники, чиї садиби поєднували житлові будинки з господарськими спорудами, зберігаючи напівагрярний, сільський характер забудови. Окремим просторовим анклавом, що сформувався після 1871 року, стала пристанційна зона. Вона функціонувала як модернізаційний кластер, де проживала римо-католицька адміністрація та залізничні службовці, фізично та функціонально відокремлений від традиційного ярмаркового центру.

Така просторова сегрегація не була лише відображенням конфесійних відмінностей. Вона виступала також механізмом соціального контролю та відтворення станових меж. Юдейське населення, обмежене в праві на володіння сільськогосподарською землею, було зосереджене в містечку і залежало від селян як постачальників сировини для млинів, худоби, льону, дров та птиці. Натомість селяни залежали від єврейських торговців та орендарів промислових об'єктів, які забезпечували їх кустарними виробами, крамом та, що було найважливішим у пореформену добу, дрібним приватним кредитом. Ця взаємозалежність створювала специфічну модель співіснування, де релігійна ідентичність виступала водночас і бар'єром, що зберігав культурну автономію громад, і каталізатором складних економічних зв'язків, що утримували містечко як єдиний, хоча й внутрішньо суперечливий, соціально-економічний організм.

Соціальна структура Деражні не була статичною. Вона еволюціонувала під впливом імперських реформ, залізничного будівництва та міграційних процесів. Селянська реформа 1861 року дестабілізувала традиційну систему землеволодіння, спонукаючи частину селян до пошуку альтернативних стратегій виживання, зокрема переходу до міщанського стану. Додаткові ревізькі списки 1860-х років фіксують зростання чисельності міщанського населення з 1298 осіб у 1858 році до 1650 осіб у 1860-х роках, що відображало як природний приріст, так і певну міграційну мобільність у перші роки після скасування кріпосного права [6, Арк. 115–120]. Відкриття залізничної станції «Деражня» у 1871 році створило новий попит на робочу силу різного профілю: від кваліфікованих залізничників та службовців до некваліфікованих вантажників та сезонних робітників. Це спричинило приток населення з інших регіонів імперії, включаючи представників інших конфесій та етнічних груп, які раніше не були характерними для цього поселення. «Тимчасові правила» 1882 року, заборонивши євреям селитися в сільській місцевості, спровокували масову концентрацію юдейського населення в містечках «смуги осілості», що ще більше посилило конфесійну

та соціальну однорідність юдейської громади Деражні [11, № 961].

У результаті цих процесів Деражня перетворилася з традиційного аграрно-ремісничого містечка на поліконфесійний соціально-економічний центр з вираженими рисами модернізації. Просторова організація містечка також зазнала змін: виникнення нових кварталів навколо залізничної станції, зміна функціонального призначення історичного центру, формування специфічних зон проживання різних соціальних груп — все це було прямим наслідком соціальної динаміки. Соціальна структура Деражні кінця XIX ст. постала не просто як адміністративно-територіальна одиниця, а як складний поліконфесійний організм, що еволюціонував на перетині імперських обмежувальних практик, ринкової інтеграції та локальних традицій Правобережної України.

Для визначення унікальності соціодемографічного розвитку Деражні здійснено порівняльно-історичний аналіз із поселеннями Летичівського повіту, які репрезентували різні рівні урбаністичної ієрархії: повітовим центром (м. Летичів), давнім релігійно-ярмарковим осередком (м-ко Меджибіж) та периферійним аграрним поселенням (м-ко Вовковинці).

Ключовою відмінністю Деражні від Меджибожа та Летичева став характер міграційних процесів у пореформену добу. Меджибіж продовжував приваблювати населення переважно за рахунок релігійного паломництва та традиційної ярмаркової торгівлі, але після введення «Тимчасових правил» 1882 року він не зміг поглинути весь потік єврейських мігрантів із навколишніх сіл через обмеженість економічної бази [11, № 961; 17, с. 73]. Летичів, як повітовий центр, мав стабільний, але помірний адміністративний міграційний фон, що підтверджується статистичними відомостями Подільської губернії за 1866 рік, де фіксується незначне зростання населення повітових центрів порівняно з торговельними містечками [8, Арк. 1–180].

Деражня ж стала магнітом для двох хвиль мігрантів. Першу хвилю склали сільські євреї, які, рятуючись від заборони на проживання в селах, масово переселялися до містечка. Це підтверджується даними перепису 1897 року, де частка юдеїв у Деражні сягнула 68,3% (3335 осіб), тоді як у 1858 році, за матеріалами 10-ї ревізії, єврейське населення

Таблиця 2

Порівняльна характеристика населених пунктів Летичівського повіту (друга половина XIX ст.)

Показник	м. Летичів (повітовий центр)	м-ко Меджибіж (релігійно-торговий центр)	м-ко Деражня (транспортно-торговий вузол)	м-ко Вовковинці (периферійне поселення)
Чисельність населення (сер. 1860-х рр.)	~4618 осіб	~2714 осіб	~1811 осіб	~476 осіб
Чисельність населення (1897 р.)	~5500 осіб	~5800 осіб	4882 особи	< 1000 осіб
Темпи зростання (1860–1897 рр.)	Низькі (~1,2 раза)	Помірні (~2,1 раза)	Високі (майже в 2,7 раза)	Низькі (~2 рази)
Домінуюча конфесійна група	Збалансована (православні, юдеї, католики)	Юдейська (>70%)	Юдейська (68,3%)	Православна (>90%)
Провідний економічний профіль	Повітова адміністрація, дрібна торгівля, ремесло	Паломництво, традиційні ярмарки, дрібне ремесло	Залізнична логістика, гуртова торгівля збіжжям, млинарство	Натуральне аграрне господарство
Інфраструктурний чинник	Відсутність залізниці	Відсутність залізниці	Станція «Деражня» (1871 р.)	Залізничне полотно без потужного комерційного вузла
Специфіка міграційного притоку	Адміністративна стабільність	Хасидське паломництво, локальні селяни	Залізничний капітал, «Тимчасові правила» (1882 р.)	Відсутність міграційних стимулів
Гендерні пропорції (20–39 років)	Помірна перевага жінок	Виражена перевага жінок (відхідництво)	Найвища перевага жінок (+61 особа)	Близький до природного баланс

Джерело: складено та обчислено на основі: ДАХмО. Ф. 244. Оп. 1. Спр. 2. Арк. 1–180; Первая Всеобщая перепись… С. 2–177; Муляр А. М., 2023, с. 11–17.

Примітка: Різниця між показниками 1298 осіб (1858 р., ревізія), 1650 осіб (1860-ті рр., додаткові ревізькі списки) та 1811 осіб (1866 р., статистичні відомості) зумовлена тим, що ревізькі матеріали фіксували переважно міщанський стан, тоді як статистичні відомості 1866 року та перепис 1897 року враховували все наявне населення містечка (селяни, міщани, дворяни, службовці тощо)

становило значно меншу частку [12, с. 176–177; 7, Арк. 115–120]. Другу, вирішальну хвилю, сформували представники різних станів (залізничні службовці, робітники, дрібні торговці), яких привабило відкриття станції «Деражня» у 1871 році [13, с. 245]. Цей інфраструктурний чинник перетворив містечко на транзитний вузол, чого були позбавлені як Летичів, так і Меджибіж, що залишалися поза залізничною мережею [12, с. 2–3].

Що ж до Вовковинців, то дане містечко залишалося невеликим поселенням із населенням усього 476 осіб (станом на середину 1860-х рр.) [8, Арк. 45–47]. Формально через територію цього поселення також пролягла залізнична магістраль, проте, на відміну від Деражні, інфраструктурний чинник не спровокував тут жодних помітних демографічних чи економічних зрушень. За даними статистичних звітів, Вовковинці залишалися периферійним аграрним поселенням із населенням, що ледве перевищувало 476 осіб, де абсолютно домінувало православне селянство (понад 90%), а торгівля та ремесло перебували в зародковому, суто споживчому стані [18, с. 12; 8, Арк. 45–47]. Приклад Деражні та Вовковинців свідчить про те, що наявність залізничного полотна сама по собі не гарантувала модернізації поселення. Залізниця виступала скоріше підсилювачем уже існуючих структурних переваг (наявність торговельного прошарку, конфесійна концентрація капіталу), ніж універсальним каталізатором змін. Цей висновок, однак, потребує подальшої перевірки на ширшій вибірці містечок регіону.

Економічна інерція Вовковинців, відсутність потужного міщанського прошарку, здатного монополізувати логістичні потоки та організувати скупку-відвантаження товарів, унеможливили інтеграцію містечка в загальноімперський ринок. Залізниця в цьому випадку виступила не як універсальний каталізатор змін, а як підсилювач вже існуючих структурних переваг. У Деражні вона активізувала наявний торговельно-ремісничий потенціал юдейської громади, трансформувавши містечко у вузол експорту, що підтверджується зростанням кількості торгових свідоцтв та оптових складів у 1870–1890-х роках [8, Арк. 30–37]. У Вовковинцях же вона залишилася лише географічною лінією, що пройшла повз соціотопографічну матрицю поселення, не змінивши ні його конфесійного складу, ні професійної зайнятості мешканців [12, с. 176–177].

Таким чином, порівняльний аналіз засвідчує, що Деражня у другій половині XIX ст. вийшла за межі типової моделі розвитку подільського містечка, яку репрезентували Меджибіж та Вовковинці. Поєднавши високу конфесійну концентрацію, характерну для «штетлу» (68,3% юдеїв у 1897 р.), з унікальною інфраструктурною перевагою (залізничне сполучення з 1871 р.), Деражня змогла трансформувати міграційні потоки та гендерні диспропорції в чинники стрімкої соціально-економічної модернізації, випередивши навіть традиційний повітовий центр — Летичів, де темпи зростання населення становили лише ~1,2 рази порівняно з 2,7 рази в Деражні [12, с. 2–3, 176–177; 18, с. 11–17].

Висновки. Проведене дослідження дозволило реконструювати еволюцію соціодемографічного, конфесійного та просторового ландшафту містечка Деражня Летичівського повіту Подільської губернії у другій половині XIX ст. як цілісної системи, що перебувала під впливом імперських трансформацій, локальних економічних практик та природно-географічних чинників.

По-перше, демографічна динаміка Деражні засвідчила стрімке зростання чисельності населення з 1298 осіб у 1858 році до 4882 осіб у 1897 році, тобто майже в 3,8 рази. Цей показник неможливо пояснити виключно природним приростом, який, за даними метричних книг, становив 10–14‰ на рік [9; 10]. Вирішальну роль відіграли міграційні процеси, зумовлені трьома взаємопов'язаними чинниками: скасуванням кріпосного права 1861 року, що дестабілізувало селянські громади та спонукало частину населення до зміни стану; дією «Тимчасових правил» 3 травня 1882 року, які забороняли нове поселення євреїв у сільській місцевості та стимулювали їхню концентрацію в містечках «смуги осілості» [11, № 961]; відкриттям 1871 року залізничної станції «Деражня» на дільниці Жмеринка — Волочиськ, що перетворило містечко на потужний аграрно-транспортний вузол і привабило робочу силу, службовців та торговельних посередників [13, с. 245].

По-друге, конфесійна структура Деражні набула виразної поліетнічної конфігурації з абсолютним домінуванням юдейського елементу (68,3%), тоді як православна громада становила 28,3%, а римо-католицька — лише 3,3% [12, с. 176–177]. Конфесійна належність виступала не лише маркером сакральної ідентичності, а й жорстким детермінантом соціопрофесійного статусу та просторової організації. Юдейська громада монополізувала сферу торгівлі (понад 85% зайнятих у цій галузі) та дрібного ремесла (понад 70%), утримувала в оренді водяні млини й ґуральні на річці Вовк [5, Арк. 103зв.–106зв.]. Православне населення зберігало аграрний уклад, займаючись землеробством та візництвом. Римо-католики концентрувалися в адміністративно-службовій сфері, обслуговуючи маєткову адміністрацію Рациборовських та залізничну інфраструктуру [6, Арк. 1–200].

По-третє, просторова топологія містечка відтворювала цю сегментацію. Центральна Базарна площа з кам'яним «гостинним» двором на 30 крамниць являла собою щільно забудований єврейський квартал, периферійні вулиці займали православні селяни-власники, а пристанційна зона функціонувала як окремий модернізаційний анклав римо-католицької адміністрації та залізничних службовців.

По-четверте, метричні книги православних церков та казенного рабинату дозволили реконструювати

відмінності в демографічній поведінці громад. Для обох основних конфесій була властива майже абсолютна ендогамія, проте спостерігалися суттєві відмінності у шлюбному віці (18–21 рік для юдейських жінок проти 20–24 років для православних) та дитячій смертності (35–42% у юдеїв проти 45–52% у православних) [9, Арк. 50–68; 10, Арк. 12–35]

По-п'яте, віково-статева структура населення Деражні за переписом 1897 року продемонструвала прогресивний (експансивний) тип відтворення з аномально високою часткою дітей та підлітків (49,35% осіб віком до 19 років) та гендерним дисбалансом у працездатному віці (перевага жінок на 61 особу в групі 20–39 років) [12, с. 2–3]. Ця диспропорція була наслідком трьох процесів: вилучення чоловіків через рекрутську та загальну військову повинність (з 1874 р.); сезонного та постійного відхідництва чоловіків на залізничне будівництво, до Одеси та степових губерній; специфіки містечкової економіки, де жінки юдейської громади залишалися в містечку, утримуючи дрібну торгівлю та ремесло.

По-шосте, економічна система Деражні функціонувала за принципом симбіотичної, хоча й напруженої, взаємозалежності. Православні селяни виступали основними постачальниками сировини для єврейських торговців та орендарів промислових об'єктів, натомість користуючись дрібним приватним кредитом, який компенсував відсутність організованої державної кредитної системи. Цей механізм боргової залежності, зафіксований у справах мирового посередника та аналітичній записці Подільського губернського правління за 1866 рік, перетворював позики на кабальні контракти щодо відпрацювання на цукрових плантаціях та під час збору врожаю [4, Арк. 20–25; 8, Арк. 30–37]. Попри конфесійну відокремленість у сфері шлюбно-родинних відносин, повсякдення вимагало постійного економічного контакту, що створювало специфічну модель співіснування, де релігійна ідентичність виступала водночас і бар'єром, і каталізатором соціальних зв'язків.

По-сьоме, порівняльно-історичний аналіз у контексті Летичівського повіту засвідчив, що Деражня випередила сусідні традиційні аграрно-ремісничі центри (Меджибіж, Вовковинці) завдяки інфраструктурному включенню до загальноімперського ринку через залізничну мережу. Якщо Меджибіж та Вовковинці, залишившись поза залізничними лініями або не маючи потужного торговельного прошарку, поступово втрачали значення регіональних оптових центрів, то Деражня перетворилася на потужний пункт акумуляції та експорту товарного збіжжя, цукрових буряків, лісоматеріалів і спирту до одеського порту та на західнокордонні митниці [12, с. 2–177; 18, с. 11–17]. Приклад Вовковинців підтверджує методологічну тезу про те, що наявність залізничного полотна сама по собі не гарантує модернізації поселення: через відсутність підприємницького купецького стану та засилля натурального господарства залізниця залишилася лише географічною лінією, тоді як у Деражні вона активізувала наявний торговельно-ремісничий потенціал юдейської громади.

Отже, Деражня другої половини XIX ст. постала не просто як адміністративно-територіальна одиниця, а як складний поліконфесійний організм, що еволюціонував на перетині імперських обмежувальних практик, ринкової інтеграції та локальних традицій Правобережної України. Доля містечка яскраво ілюструє загальну тенденцію для подільського прикордоння: інфраструктурна модернізація (залізниця) не зруйнувала традиційну конфесійну мозаїку, а навпаки — консервувала та поглибила її, надаючи нові економічні ніші для кожної з громад. Поєднання високої конфесійної концентрації юдейського капіталу з унікальним інфраструктурним фактором (залізничне сполучення з 1871 р.) дозволило Деражні трансформувати міграційні потоки та гендерні диспропорції в чинники стрімкої соціально-економічної модернізації, випередивши навіть традиційний повітовий центр — Летичів.

ДОДАТКОВА ІНФОРМАЦІЯ

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ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.
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FUNCTIONAL-DECORATIVE DESIGN STRATEGY: INTEGRATING MODERN MATERIALS INTO TRADITIONAL STAGE CLOTHING DESIGNS

Summary. *The subject area of the study is the identification of modern approaches and methods of applying artistic and constructive principles of functional and decorative design of traditional stage costumes in modern design and planning of fashionable clothing. The article reveals the systemic qualities of design and design activities using modern materials, which determine the potential for endless production of new forms of stage clothing. When designing clothing for artistic and cultural events, designers are increasingly interested in using various lighting effects. The systemic approach allows us to consider a comprehensive solution to compositional tasks that involve the use of light in a costume: spatial-plastic and light-color processing of clothing components; creating certain compositional accents on texture, form, color dynamics; ensuring the integrity of the costume image. As part of the study, an author's strategy for using light textiles in stage costume solutions is proposed. The methodology involves designing clothing with light distribution on the surfaces of products. Electroluminescent materials, polymers, LEDs, optical fiber are used. Each light design development differs in color, intensity and distribution on surfaces. Compared to other electric light sources, LEDs have the following differences: high light output, high mechanical strength, vibration resistance, long service life, low inertia, different radiation angle, low cost, safety, insensitivity to low temperatures, environmental friendliness. A special advantage is that LEDs allow you to get different color glow to achieve the goal of various design solutions. It is substantiated that the current level of development of artistic practice involves a certain specificity of the use of modern materials in the traditional design of stage clothing, namely, balancing between simple and complex, between applied and artistic and philosophical.*

Key words: *functional and decorative design, stage clothing, traditional costume, modern materials, composition, stylization, luminous textiles.*

Introduction. Functional-decorative design is an extremely versatile type of design that demonstrates the level of development of socio-cultural guidelines of society and is a means of communication through visual language. It combines an artistic principle and utilitarian-applied meaning; it meets the demands of mass culture, while it can tend towards elitism. Functional-decorative design is able to both reflect artistic and technological processes and influence the trends of their development. At the same time, one of the turning points in the historical development of this type of design was the organic combination of two important principles: focusing attention on the emotional component and directing form creation to functionality in the representation of information embedded in the project [18; 20].

Conceptualization in the field of research of design activities for the production of stage clothing involves identifying its systemic qualities, which enable the invariant articulation of elements, which determine the potential for endless production of new costume samples. At the same time, there is a need for a more detailed study of modern approaches to the complex solution of compositional tasks involving the use of light in a costume — spatial-plastic and light-color processing of clothing components, the creation of certain compositional accents on texture, form, color dynamics, ensuring the integrity of the costume image.

Literature review. An important approach to modernizing approaches to interpreting traditional stage clothing designs in a contemporary context is the integration of modern high-tech materials. In this context, it is considered a fundamental operation, which aims to endow the various possibilities of innovative fabrics and technologies integrated into them with a stage meaning. A number of scientists are convinced of this [7; 19].

Industry research has been conducted by modern scholars [1; 3; 17], who consider interpretation to be the basis of any process of changing traditional solutions in stage clothing, which assimilates various formats of perception of creative expression of personality in the field of art through costume. The designer of such clothing focuses his main efforts on the maximum disclosure of the content features and expressiveness of the artistic work, for which it is first necessary to comprehend the original author's intention, and then form his own interpretative version in the stage image.

Individual issues of interpretation of stage costume are considered by authors [2; 15], who focus on different types of interpretation, which differ in purpose and means. Scientists [9; 10] justify that the issue of competent construction of stage image is currently one of the most important in the field of musical performance, theater and choreography, because it is related to the objective-subjective relationship: the main difficulty of the process is seen as finding the optimal balance between the degree of revealing the director's original author's idea and the degree of freedom of design creativity. Despite the significant achievements of modern researchers, a number of issues remain unresolved, which emphasizes the problems of preserving the principle of interaction of styles, updating the work in the modern design space of creating stage clothing.

The purpose of the study is to substantiate the strategy of functional and decorative design of modern stage costumes by integrating modern materials into traditional stage clothing designs.

Results. The symbolic context of the stage costume under consideration consists in creating a symbol that most accurately characterizes its owner. Stage clothing, in the aspect of art historical analysis, is a system of signs and symbols endowed with information content of varying degrees, which form the corresponding specific figurative associations in the consciousness of the audience. The stage costume carries an informative load, encoded not only in the concepts of silhouette, cut, material, ornamentation and color, but also in the closely interconnected gestures, facial expressions, expressive poses of the costume owner. Actually, the main elements of this information message of stage clothing are signs and symbols, with added meanings and meanings, using composition, color scheme, texture and decorative elements.

Already in the 20th century, the costume began to depend on the artistic idea of the work, on the thoughts of the actor, director and author. The most important function of the costume is the symbolic function [11–13]. This function conveys to the observer the most important, important information about the person, about religion, about culture, about aesthetic taste, about his social status. The costume has many other functions, such as:

– age — this function is responsible for indicating or masking a person's age: through the costume, one could easily understand a person's age, namely through the color of clothing, the color of the headdress in certain nationalities; at the same time, the European costume always tried to hide a person's age;
– socio-gender — in every traditional, any costume, not only the gender of the person was highlighted, but also the marital status;
– class (group) — highlights belonging to a certain class or social group, as well as to a social class, or vice versa, can hide any person's status;
– professional — a suit can determine what profession a person belongs to and what their occupation is;
– regional — the costume shows regional traditions in clothing, which are associated with both the way of life of the people, with national traditions, and with the climatic features of the region — this function is closely related to the national function, since it can be used to determine which ethnic group a person belongs to;
– aesthetic — the most important thing that is manifested in a costume is the aesthetic ideal of a particular time and people.

Stage clothing ensures the creation of images in a certain individual, a character. This allows us to consider the stage costume as a multi-valued phenomenon, a specific sign of personal specifics that transmits information about a certain character. At the same time, the process of designing a complex, holistic appearance representations personality implies the presence of a whole hierarchical structure of sign systems. The signification of stage clothing performs an important function, primarily communicative, allowing the character to demonstrate the specificity of his own individuality to others.

Thus, the main task of the information and symbolic role stage clothes are seen the transfer of certain information from the character, the hero of the image to the audience, and the clothing itself is positioned as a practical way of establishing communication between social and cultural codes, a tool for forming an image, creating a certain image. Concentrating the most important specific features and distinctive features of moral, social, religious, ethical aspects of public consciousness, established way of life, stage clothing in a broad socio-cultural context represents the external metasign of a certain stage hero. Therefore, taking a direct part in the transmission of symbolism and behavioral stereotypes, stage costume acts as an influential factor of cultural identification, a means of encoding cultural meanings.

In designing the form of stage clothing, four levels can be distinguished sequentially:

1) structural level — internal geometric characteristics of the form and the relationship between parts (proportions, geometry, symmetry);
2) the degree of freedom of the suit — loose-fitting accessories;

3) material and decorative level — color, decor, finish, lines, properties of materials;
4) plastic level — plasticity of the figure in the costume [8; 16].

The study of numerous examples of folk, historical, and modern costumes convincingly shows the important role that ornament plays in the design of stage costumes. Ornament decorates the costume or its individual parts, the surface of which it covers, emphasizes, draws attention to them, enriches the artistic and figurative solution of the costume, and serves as a means of dividing the form of the costume, if the composition of the costume includes ornamented surfaces and smooth surfaces devoid of any ornament [4; 21].

Using various techniques for applying ornamentation, the designer creates a feeling of lightness or heaviness of the costume, emphasizing the properties of the material. Ornamental motifs distinguish the costume from others (this function is important for a stage costume).

The study of the symbolism and aesthetics of stage clothing, its main communication properties allows us to identify the characteristic features of design solutions, the aesthetics of costume images and approaches to solving architectonics. Traditionally, the return to the figurative language of stage clothing was due to the fact that in productions conceptual transformations are mainly implemented in the context of the scenography of the show, production, performance, which is maximally complement the key goal of artistic conception and directorial work. Analyzing the semantic reflection of stage costumes, it can be seen that modern artists in the theatrical and dramatic environment demonstrate increasingly original solutions for stage costumes and scenography in general. It should be noted that the concepts of talent in the most complete and vivid way designer- artist manifests at the level of an elite artistic tradition, accompanied by an active transformation of the source of creativity. The elite level is characterized by a more avant-garde approach to the interpretation of form, decor and details, with both grotesque accentuation of certain components of the costume and complete rejection of others possible. This is explained by the artist's perception of individual details as secondary in the context of communication, aesthetic load or semantic meaning as a whole.

For modern scenography, and, accordingly, stage costumes, the compositional law of contrast is inherent. According to it, designers base their work on the contrast of individual elements and the whole, emphasizing the texture, expressiveness of color and shape in the process of creating a certain image. Often, such details acquire the main sound in the overall composition. Since the level of identity of current stage clothing with the original source has acquired, for the most part, an associative context, we are talking about temporal-spatial communication in the stage image, which is characterized by the reflection of the norms of social life in the modern prism of multidimensionality. The added innovative details of the costume, in this case, give a fresh context to the traditional image (primarily, in theatrical productions). Therefore, it can be argued that the modern designer's view of stage clothing is focused on the task of shocking, surprising the audience, attracting its attention with unexpected elements that will remain in the viewer's memory for a long time.

Currently, known technologies for applying patterns to fabric are being actively improved and new ones are emerging. In the use of textile ornamental techniques in recent years, a trend has emerged towards layering different decoration techniques on one fabric, for example:
– weaving pattern, then printed ornamental motif with the addition of embroidery, applique, sequins, beads;
– thermal printing or applique with fabrics and materials with a printed pattern;
– thermal printing on the surface of the material with a " crash " effect;
– thread embroidery, bead embroidery, " Richelieu " and many other techniques.

At the material and decorative level, chemical modification of the fiber-forming polymer is often used. It consists in the fact that during the wet-heat treatment at the stage of steaming the garment, a technological solution is introduced into the steam working medium, the composition of which depends on the fiber composition of the fabric. Such a functional and technological effect is used in the manufacture of dimensionally stable garments from cellulose and hydrated cellulose fabrics [5; 14].

The modern transformation of design approaches to creating functional stage clothing involves rethinking traditional motifs through new artistic symbols, practical solutions and abstract forms, assimilation classical elements with innovative aesthetics. It should be noted that special attention in this context is required by experiments with textiles that involve the use of non-traditional materials (organza, mesh), a combination of embroidery with three-dimensional printing, elements made using laser printing, etc. [6].

" Smart " solutions form a special niche and remain currently understudied in the context of functional and decorative design of stage clothing. Within the framework of this study, the author proposes to consider the potential of using innovative ***light textiles. In particular,*** it is proposed:
– use of electroluminescent threads — they can effectively glow using electric current to accentuate certain ornaments on clothing, geometric elements, and edging;
– the use of light-emitting diodes (LEDs) through their direct integration into the fabric of the stage costume.

The functional-decorative design strategy of LED elements in stage costumes combines ergonomics, safety, and visual expression, integrating LED sources into the textile structure to ensure artist mobility, reliable

communications, and artistic expression during the show. The main technologies used to create luminous textiles are LED filaments, fiber optic filaments, and electroluminescent elements (Table 1).

In general, the key decorative aspects are considered to be light accent (underlining constructive cut lines or creating dynamic visual illusions), programming effects (synchronizing color changes and flicker frequency with musical accompaniment and overall stage lighting), and masking elements (integrating LED strips and pixels under translucent fabrics or a mesh to diffuse light). For example, during a dance, patterns can change colors, emphasizing their meaning. At the same time, modern technologies provide for technical integration: flexible connections are provided by using conductive threads and quick-installation connectors, and modularity is ensured by creating removable light blocks for easy care of the suit and washing of the textile base.

The main functional stages of design include: ergonomic analysis, taking into account the amplitude of the actor's movements to avoid wire tension and contact breakage; weight distribution, which involves placing batteries and controllers in areas of minimal load (lower back, back); thermal regulation to ensure ventilation and heat dissipation from powerful LEDs; power safety through the use of low-voltage elements (5V-12V) to protect against electric shock.

The main stages and principles of design include:

1) the conceptual-semiotic stage, with the definition of the role of light as the language of culture, emphasizing the director's intention, the character of the character, and the psychological dynamics of the scene;
2) the structural and ergonomic aspect of ensuring the actor's safety, ease of movement, and concealment of power sources, controllers, and wires within the fabric structure;
3) light-optical calculation: selection of textures, degree of transparency, reflectivity and color temperature of textiles to interact with the overall lighting design of the scene;
4) technological integration — the introduction of flexible LED matrices, embroidery with conductive threads or sensor modules without losing the plasticity of the material.

Thus, the functionality of luminous textiles in a stage costume can be positioned as a modern progressive solution for transforming familiar structures into a light show, contributing to the implementation of the director's most daring ideas on stage and enhancing the artistic and aesthetic impact on the viewer. The author's strategy for using luminous textiles (in particular, its elements — electroluminescent fabrics, fiber optics, LED elements built into the fabric, etc.) in the functional and decorative design of stage clothing is based on the awareness of its most important functions, assimilating artistic, technical and psychological aspects. In particular, the following were taken into account:

– aesthetic and artistic function that provides greater visual expressiveness of the stage image (using luminous textiles, it is possible to create the effect of a "live" image that instantly attracts the viewer's attention), optimizes the formation by emphasizing the silhouette or plasticity of movements with light lines, and also allows for instant dynamics of the mood of the stage by changing the nature or color of the illumination of the actors' clothing;
– symbolic-dramatic function, which finds practical expression in emphasizing a certain character of a character, focusing on a certain actor or location of

Table 1

Lighting technologies in stage clothing: comparative characteristics

Light effect source	Features	Main advantages	Key disadvantages	Specificity of application
Light-emitting diodes (LED)	Small, bright lights integrated directly into the suit fabric	Quite high brightness, possibility of setting programmable lighting effects	The light is spot-like, LEDs require batteries	Highlighting ornaments on belts, collars, shirts for greater expressiveness of the image
Fiber optic	Thin threads that transmit a light effect along their entire length and	Design flexibility, uniformity of light	Quite complicated installation, limited brightness potential	Creating bright ornamental patterns on outerwear and dresses
Electro — luminescent filaments	A thin fiber that creates a light effect when exposed to an electric current.	Not susceptible to heat, quite flexible	Requires uninterrupted high voltage, low filament brightness	Accentuating geometric elements of clothing, edging of costumes
OLED panels	Flexible light panels	Energy efficiency, high brightness	Fragility, delicacy, high cost	Creating a dynamic show by synchronizing lighting effects with music

the scene, which contributes to strengthening the semantic accents of the stage action;
– a technical function that expands the possibilities of using the play of light and darkness, allowing for better visibility of the artist on a darkened stage, achieving light synchronization of the stage costume with musical accompaniment or the general stage lighting system using DMX control.

Electronic embroidery technology offers another design opportunity, allowing LEDs to be integrated directly into the fabric without an additional plastic sheet underneath. This way, the fabric itself becomes a component of the design, and the technology itself can be applied to fabrics of variable thickness, even transparent ones. Although LEDs provide a very dynamic lighting effect and rarely blend seamlessly with textiles, the material can be used quite effectively to achieve different visual effects depending on the costume design.

It is suggested to give preference to placing LEDs directly on the outer layers of stage clothing to enhance the light effect and thus emphasize the stage image. In some cases, where a strong light accent is not very desirable, LEDs can be used in conjunction with translucent surfaces or design components to create blurred lighting effects. To achieve a less dramatic lighting effect, the LED strips can be directed towards the inside of the garment.

In addition to using light as a decorative or functional element, design development can also include conceptual ideas, such as controlling the hue or saturation of light using the Internet of Things or creating an interaction between the costume and the space. Further use of light will increase the expressiveness and functionality of the garment, as well as create opportunities for its customization in connection with programmable devices.

Considering the results, the prototype of the illuminated stage costume can achieve its maximum functional, aesthetic and expressive goals. As a result of the study, it was found that the use of LEDs under the main part of the fabric is the most convenient and practical way to hide electronic mechanisms behind illuminated techno-couture designs.

The desired lighting effect in the costume can be achieved by placing LEDs on the back of the fabric (facing the body) across the seam lines and using vertically arranged transparent layers as open cutouts in the fabric.

Conclusions and prospects. As the results of the study demonstrate, the narratives of the development of modern functional-decorative stage clothing design demonstrate the assimilation of aspects of traditional designs and ethnic motifs with the innovative technological capabilities of modern textile solutions. The integration of modern "smart" elements into traditional stage clothing designs is now viewed not simply as an attractive, bright or sensational picture for the viewer, but primarily as a cultural and social meaning conveyed in a visual way.

The strategy of using modern light materials in traditional stage costume solutions proposed in the study provides a number of practical advantages: the functionality of stage clothing increases due to greater resonance of the costume with the image, the mobility and energy efficiency of productions increase, the director's idea is realized as effectively as possible through the creation of fantastic, grotesque images, and finally, the trend finds a response in the modern audience, as it successfully synergizes classics and innovations.

The costume can be synchronized with music or the overall lighting design of the stage, helping to establish visual contact with the viewer, ensuring the transfer of emotions and ideas through light images.

This study, which considers light as a new design element that enhances the expressiveness of stage clothing, aims to offer an alternative to traditional costume designs with examples that incorporate lighting technologies. In accordance with the main structure, research questions and design concept, the study examines contemporary design examples using various lighting technologies with appropriate visual materials.

The current use of light in stage clothing is limited by various small art projects and did not achieve more than accessibility at the present time. The design features and solutions proposed in the study can be applied to real-life tuning of stage costumes. Ago research has broader value, offering a clear overview using lighting technologies and introducing transparent and a detailed design development process.

The study can be a starting point for future interdisciplinary projects. Future research should focus on practical testing of the approach proposed in the study.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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PATIENT SATISFACTION AS AN OPERATIONAL INDICATOR OF AN AESTHETIC CLINIC'S EFFECTIVENESS: ADAPTING MODELS FROM THE HOSPITALITY INDUSTRY

Summary. *This article examines patient satisfaction at an aesthetic clinic as an independent operational indicator that can be measured, managed, and predicted. The aim of the study is to justify a methodology whereby service quality assessment tools developed in the hospitality and luxury retail industries are transferred to the outpatient aesthetic medicine setting and integrated into daily management decisions. The study relies on general scientific methods of analysis, synthesis, comparison, and generalization, as well as a structural-functional approach to describing the satisfaction measurement system. The empirical basis consists of two years of operational data from Arviv Medical Aesthetics and a comparison with a control facility of the same organizational structure that did not implement the described system. Implementation of the resulting system raised the clinic's public rating and repeat visit rate well above those of the control facility and preserved annual revenue at approximately two million dollars during a period of unfavorable macroeconomic conditions in which the control facility's revenue declined; detailed figures are reported in the Results section. It has been shown that the strongest predictor of loyalty and willingness to recommend is the empathy dimension, while the most common management mistake remains the collection of satisfaction data without using it in operational decisions.*

Key words: *patient satisfaction, aesthetic medicine, service quality, SERVQUAL, loyalty index, patient retention, hospitality industry.*

Introduction. Today's aesthetic medicine market is highly competitive, and patients have long taken a doctor's clinical skill for granted. It no longer sets one clinic apart from the rest. Instead, patients remember how they were spoken to during their first call, how they were greeted, and whether they felt cared for after the procedure. Whether a person returns to a clinic often depends on more than the treatment result. Communication, waiting time, clarity of explanations, follow-up and the general feeling of being cared for all influence this decision. At the same time, many clinics still track medical and financial indicators more carefully than patient satisfaction. Feedback is often reduced to public ratings or irregular comments from patients.

Such a narrow focus comes at a specific cost. Studies of the patient experience in medical-aesthetic services confirm that both the functional and relational dimensions of care directly and positively influence perceived quality, overall satisfaction, and loyal behavior, with the functional dimension shown to prevail over the relational one, while communication and staff engagement nonetheless exert an independent and significant effect on the patient experience alongside the outcome of the intervention [1]. It follows that a facility that measures only clinical outcomes systematically overlooks the part of the patient experience that determines their return, recommendations, and long-term value.

For decades, the hospitality and luxury retail industries have been addressing a similar challenge of managing the quality of experience in environments where the basic service function is already ensured, and competition shifts to the realm of perception. The transfer of this management framework to aesthetic medicine is a logical yet under-explored direction in the scientific literature. The purpose of this article is to justify the methodology for such a transfer and to demonstrate how patient satisfaction becomes a measurable operational indicator integrated into the system of daily management decisions at an aesthetic clinic. To achieve this goal, the following tasks have been set: to characterize theoretical models of service quality measurement suitable for adaptation; to describe a methodology for measuring satisfaction

in an aesthetic facility based on data from the Arviv Medical Aesthetics clinic; to explain the mechanism for transforming satisfaction data into specific operational decisions; to identify a minimum set of indicators suitable for implementation outside a large facility. The article is based on the author's methodology, which Marharyta Kuzmichova developed and implemented at the Arviv Medical Aesthetics clinic upon assuming the position of its director in March 2024.

The scientific novelty of this work lies not in the individual instruments used — SERVQUAL, the willingness-to-recommend index, and the service-profit chain are all well-established — but in combining them into a single operational system for measuring patient satisfaction, adapted to outpatient aesthetic medicine and validated through a natural comparison of two institutions with a common ownership structure. To the author's knowledge, the existing literature has not yet provided a systematic description of such a combination for this field. The contribution of this work is therefore the architecture that binds these instruments into a single operational loop in which every indicator is tied to a defined management action, rather than the discovery of a new measurement tool. An additional element of novelty is the finding that, among the SERVQUAL dimensions, empathy is most strongly linked to loyalty and willingness to recommend, as derived from the clinic's operational data rather than from laboratory or survey samples.

Literature review. The SERVQUAL model, proposed by Parasuraman, Zeithaml, and Berry, forms the basis for most modern approaches to measuring service quality. Its central idea is that service quality is the difference between a customer's expectations and their perception of the service actually received, measured across five dimensions: physical environment, reliability, responsiveness, assurance, and empathy [2]. In the healthcare sector, the model has gained widespread use because it focuses on the patient's subjective experience alongside structural and outcome metrics and allows for a quantitative description of the quality gap, suitable for further management [3].

Empirical studies in the healthcare sector confirm the predictive power of the model's individual dimensions. In a study of inpatient care quality, all five SERVQUAL dimensions significantly influenced patient satisfaction, with empathy having the strongest impact, followed by assurance and responsiveness [4]. For managing an aesthetic clinic, this result identifies a priority area for investment in staff competencies. At the same time, the literature notes that the classic five-dimensional structure of the model is not always consistently replicated across different service environments and requires contextual modification and supplementation with new dimensions, particularly medical professionalism and patient safety [5]. Therefore, it is advisable to adapt the model to the specifics of aesthetic medicine rather than applying it unchanged.

The second key concept is the Willingness to Recommend Index, proposed by Reichheld in the article "The One Number You Need to Grow." The metric is based on a single standardized question about the likelihood of recommending the company to acquaintances on a scale from zero to ten, and respondents are divided into promoters, who give a score of nine or ten, passives, and detractors [6]. The author argued that this metric correlates with a company's organic growth rate better than more complex tools [6]. Subsequent replication studies cast doubt on the universality of this correlation and caution against equating correlation with causation [7]. Given these caveats, it is advisable to use the index in an aesthetic clinic as part of a multi-channel system of indicators, supplementing it with other metrics.

The third conceptual framework is the service-profit link developed by Heskett, Sasser, and Schlesinger and first presented in the Harvard Business Review in 1994. It describes the causal relationship between staff satisfaction and loyalty, service quality, customer satisfaction, customer loyalty, and the establishment's financial performance [8]. In the context of the hospitality and service industries, empirical tests of the model largely confirm the significance of most of the postulated relationships, although some studies do not find the expected mirror of satisfaction between staff and customers in all settings [9]. For aesthetic medicine, this chain is of particular importance, as the quality of clinical interaction directly depends on the stability and motivation of the staff providing it.

Waiting time management draws on Maister's classic work on the psychology of queues, which formulates eight principles of subjective perception of waiting: idle time seems longer than occupied time, unexplained waiting seems longer than explained waiting, uncertain waiting seems longer than certain waiting, and anxiety prolongs perceived time [10]. A systematic literature review of the empirical work on this topic confirms that the perceived, rather than actual, duration of a wait predominantly shapes satisfaction, and identifies active engagement of the waiting customer as a key moderating factor [11]. These principles are directly applicable to managing the waiting experience in a clinic.

The service recovery paradox describes a situation in which a client, after a successfully resolved problem, rates the organization higher than they would have if the service had been flawless, because successful recovery increases their trust and confidence [12]. In a medical context, this phenomenon transforms a patient's complaint into an opportunity to strengthen loyalty, provided there is a prepared recovery protocol [13]. Despite a significant body of literature on individual components, there is a lack of systematic material that would combine these models into a comprehensive operational system for measuring and managing satisfaction in aesthetic medicine.

Materials and methods. The study is based on general scientific methods of analysis, synthesis,

comparison, generalization, and systematization, as well as on a structural-functional approach to describing the patient satisfaction measurement system. The empirical basis consists of operational data from the Arviv Medical Aesthetics clinic for the period from March 2024 to February 2026, collected in the facility's management system, as well as public patient reviews and industry benchmarks. The adaptation of service quality tools was based on the author's prior experience in luxury retail at LVMH, which she applied to clinic management. The author refers to the system described in this paper as the Patient Satisfaction Operations Framework (PSOF). Its methodological framework consists of the SERVQUAL model adapted to aesthetic medicine, the Willingness to Recommend Index, as well as behavioral indicators such as repeat appointments, average visit cost, and conversion of the first visit to a second.

A distinctive feature of the research design is the presence of a control facility that operated within the same organizational structure, in the same geographic market of South Florida, during the same period, and under the same macroeconomic conditions, but did not implement the described satisfaction management system. This structure forms a quasi-experimental design of a natural experiment, in which the only significant operational variable between the two facilities is the presence or absence of a satisfaction measurement and management system, which strengthens the causal argument compared to a single-site observation. The qualitative component of the study is provided by structured individual interviews with patients within the framework of follow-up protocols and an analysis of the content of open-ended feedback.

Research results

Baseline Satisfaction Measurement

At the start of the study in March 2024, patient satisfaction at the clinic was measured exclusively through a publicly available rating of 4.7 points and was passively collected based on voluntary feedback. There was no systematic measurement outside of this channel: the rate of repeat appointments, satisfaction by individual specialists, the willingness-to-recommend index, or the conversion of first visits to second visits were not tracked. Satisfaction data was generated passively, without a defined target benchmark and without a structured process for translating it into operational improvement actions. The 4.7 rating remained a baseline with no system behind it. Indirect indicators of the patient experience included an average visit cost of $347.01 and a high baseline staff turnover rate. The feedback collection system lacked a defined point in the patient journey where feedback was solicited, had no mechanism for privately intercepting negative feedback before it was made public, and did not designate a person responsible for systematically analyzing the feedback.

Multi-channel measurement system

The PSOF system is structured as a four-layer framework. The first layer consists of a continuous



Fig. 1. Baseline Structure of Patient Satisfaction Measurement at the Clinic in March 2024

observation protocol, within which staff are trained to interpret verbal, nonverbal, and behavioral signals of the patient's emotional state throughout the visit, starting with establishing an emotional baseline upon arrival and ending with capturing signals during subsequent care. The second layer is the willingness-to-recommend index. The patient rates the likelihood of recommending the clinic on a scale from zero to ten, and responses are categorized as promoters (nine or ten points), passives (seven or eight), and critics (zero to six). Measurements are repeated at three specific points along the patient journey: upon discharge immediately after the procedure, during follow-up within twenty-four hours, and during an in-person follow-up visit two weeks later. The third layer consists of a structured post-visit questionnaire. The fourth layer comprises the SERVQUAL model adapted for aesthetic medicine.

The clinic retained the five SERVQUAL dimensions, but the content of each had to be adapted to aesthetic practice. The author classified the physical environment as everything the patient perceives physically, from the cleanliness of the treatment rooms and the appearance of the staff to the modernity of the equipment, the comfort of the waiting area, and the sense of privacy. The author interprets reliability as the alignment of what is received with what was promised: when the appointment starts on time, the treatment corresponds to what was agreed upon during the consultation, the price is explained correctly, and the prognosis of the result proves to be realistic. Responsiveness refers to the speed and readiness of the team to respond, which is evident from the time it takes to answer a call and the length of the wait before the appointment. Assurance is linked to trust and a sense of security, which the patient derives from the specialist's competence. The most subtle dimension, empathy, is assessed based on whether the patient felt heard and experienced personal care. Patients rate each of these dimensions on a five-point scale, and the questionnaire concludes with a question regarding their willingness to recommend the clinic.

Three-Point Measurement as a Methodological Contribution

For example, the willingness-to-recommend index, which in the hotel industry is a good predictor of loyalty

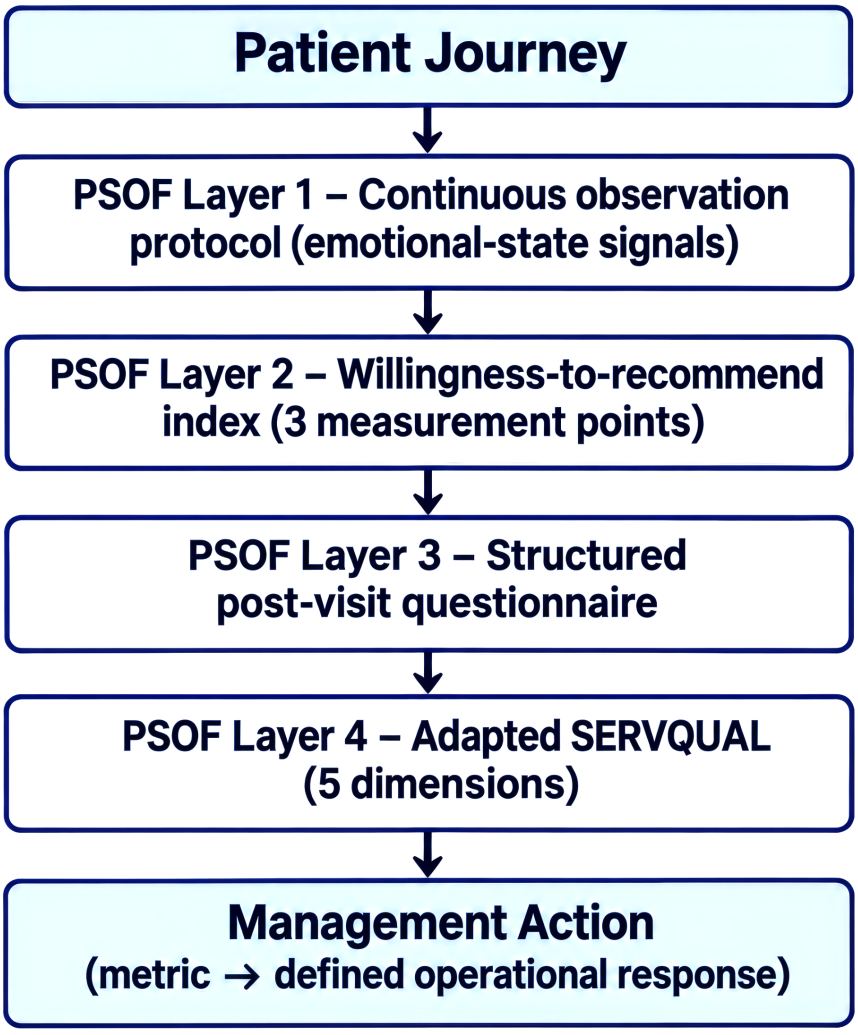


Fig. 2. The PSOF Operational Framework

and referrals, is measured at the clinic not at a single point but at three points along the patient's journey. This reflects a characteristic of satisfaction with aesthetic treatment that hotel services do not have, since satisfaction evolves over time as the clinical outcome develops; therefore, a single measurement point is less representative than multi-point measurements throughout the post-procedure window. The assessment of the index at the two-week follow-up visit carries the highest predictive weight, as the clinical outcome is already visible and the patient evaluates satisfaction based on the actual result. This three-point scheme is part of Marharyta Kuzmichova's proprietary methodology, which distinguishes it from the single-session measurement common in the hospitality industry.

In the hospitality industry the willingness-to-recommend index is captured once, at the point of departure, because the guest's experience is essentially complete at checkout. Aesthetic medicine differs fundamentally: the clinical result is not yet visible at discharge and continues to develop over the following days and weeks. Measuring satisfaction at a single point would therefore capture an incomplete outcome. The proposed three-point scheme — at discharge, at 24-hour follow-up, and at the two-week in-person visit — is designed specifically to capture this delayed effect of a medical service, with the two-week measurement carrying the highest predictive weight because the patient evaluates an outcome that has actually materialized. This shift from single-point to multi-point measurement constitutes one of the central methodological contributions of the framework.

The repeat booking rate in the hotel industry corresponds to the percentage of guests who return, while in a clinic it indicates what percentage of patients schedule their next appointment before even leaving the facility. Here, the adaptation has one important difference. In a hotel, a guest may not return simply because they visited the city only once, and this does not necessarily indicate dissatisfaction. In a clinic, a patient who does not return most often has not been given a sufficient reason to return. Because of this, rebooking speaks more candidly of dissatisfaction and more accurately reflects the work of a specific specialist.

The equivalent of the average check for a hotel stay is the average daily rate, while in a clinic, this amount is more indicative of how much the patient trusts the doctor's recommendations. A willingness to commit to a comprehensive treatment plan, sign up for a membership, and purchase additional care products indicates a deeper level of trust than simply agreeing to the minimum scheduled service. For this reason, the average bill serves a dual purpose: financial and relational.

Empirical Results and Comparison with a Control Institution

Between March 2025 and February 2026, the institution that implemented the system achieved the following results. Its rating on a public review platform rose from 4.7 to 4.8 thanks to an active review-generation program, for which a monthly target of twenty new reviews was set.

Every patient who scored the clinic between zero and six on the ten-point scale was included in a private recovery protocol: they were contacted personally within twenty-four hours, before the complaint became public.

The repeat visit rate averaged 60 percent, tracked both for individual staff members and the establishment as a whole. The average visit cost rose from $347.01 to $463.62, an increase of 33.6 percent, reflecting deeper patient trust and a willingness to undergo comprehensive treatment. Staff turnover decreased by 52 percent, ensuring continuity in the specialist-patient relationship. Annual revenue reached $2,034,769 and remained stable despite difficult market conditions. This result was supported

Table 1

Transformation of Hospitality Metrics into Patient Experience Indicators in Aesthetic Medicine

Hospitality industry metric	Clinical equivalent in aesthetic medicine	Key adaptation in the clinic	Managerial meaning
Willingness-to-recommend index	Patient willingness to recommend the clinic or specialist	Measured at three points of the patient journey rather than once	Shows how satisfaction changes as the clinical result becomes visible
Guest return rate	Repeat booking rate	Assessed by whether the patient schedules the next visit before leaving the clinic	Reflects both satisfaction and the specialist's ability to create a reason for continued care
Average daily rate / average check	Average patient bill	Interpreted together with treatment-plan acceptance, membership enrollment, and product purchases	Indicates the level of trust in the doctor's recommendations
Loyalty and referral behavior	Patient retention and referral potential	Evaluated through repeated visits, recommendations, and long-term treatment commitment	Connects patient experience with financial stability and clinic growth

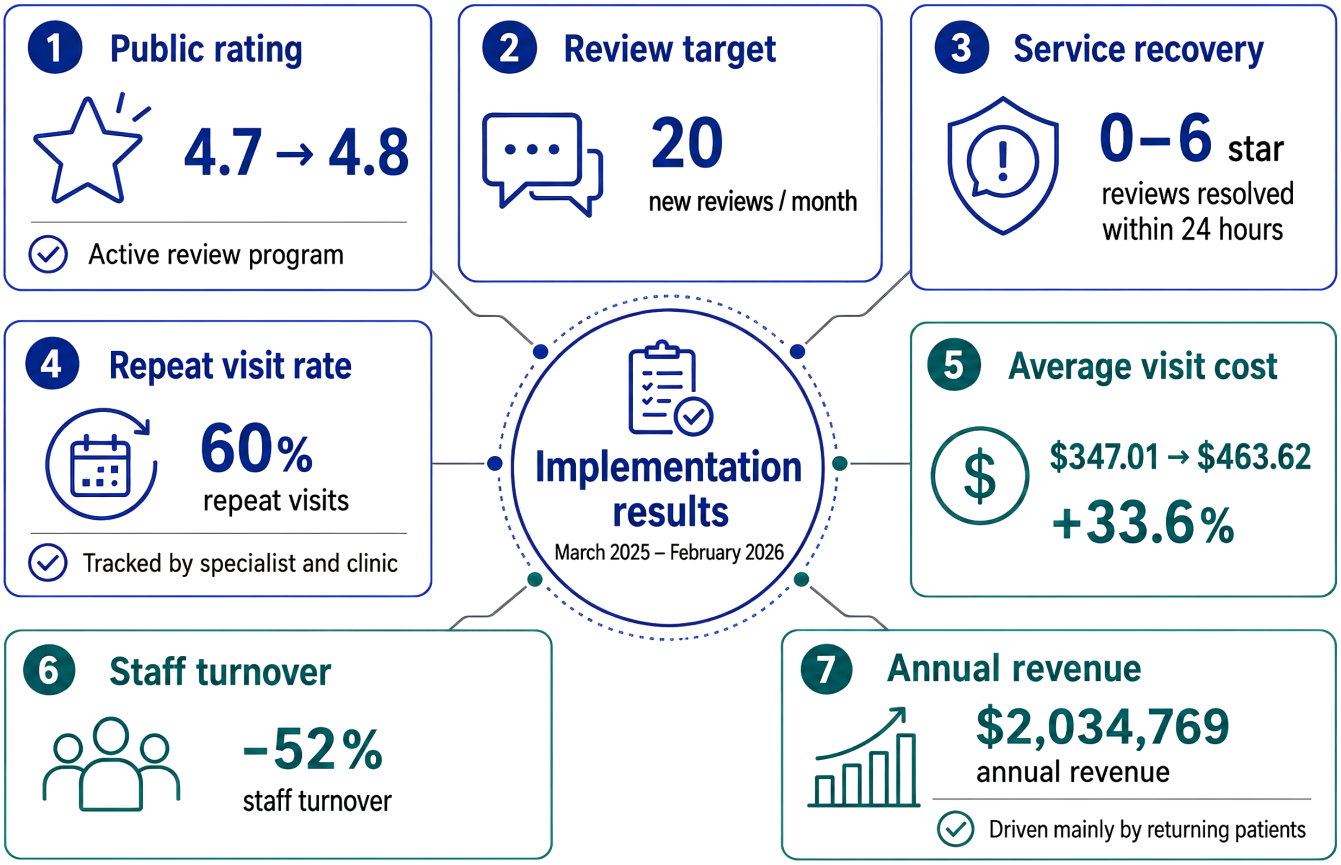


Fig. 3. Key Performance Results After Implementation of the Patient Satisfaction Management System

mainly by returning patients, while new patient acquisition had a smaller impact.

The most significant methodological finding is the comparison with the control facility. Over the same period, the facility that did not implement the system experienced a 6 percent drop in revenue, maintained an unchanged rating due to passive feedback collection, and achieved a patient retention rate of 44 percent. A gap of 16 percentage points in retention and 28.8 percentage points in revenue trajectory between the two facilities was observed under identical macroeconomic conditions in the same competitive market.

Since both facilities operated under the same organizational ownership, in the same market, under the same macroeconomic environment, with the same patient demographic profile, and offering the same categories of clinical services, the only significant operational difference was the presence or absence of a satisfaction management system. This provides grounds for considering the implementation of the system as the primary operational variable explaining the difference in performance.

The greatest scientific interest lies not even in the revenue growth in the first year, but specifically in its stability in the second year against the backdrop of a simultaneous decline at the control facility. Revenue in the second year was virtually identical to that of the first, while the control facility lost six percent under identical market conditions. This trend indicates structural revenue stability ensured by the satisfaction system, whereas without the control facility, such a conclusion would have remained unattainable.

Empathy as a Leading Predictor of Loyalty

A cross-analysis of satisfaction data regarding referral behavior revealed that, among all model dimensions, the strongest individual predictor of willingness to recommend is the empathy dimension, which surpasses the overall willingness-to-recommend index, ratings, and other individual dimensions in predictive power. Patients who rated empathy at four or five points generated recommendations significantly more often than patients with a rating of three or lower, regardless of ratings on other measures. Patients who achieved excellent clinical outcomes, were in a clean and professional environment, and received timely care, but did not feel genuine attention and care, generally did not leave recommendations. This finding aligns with empirical data from the healthcare industry regarding the leading role of empathy among the SERVQUAL dimensions [4] and has direct managerial implications: developing empathy competence through training in consultation quality and emotional state management proves to be one of the most effective available ways to increase the number of referrals.

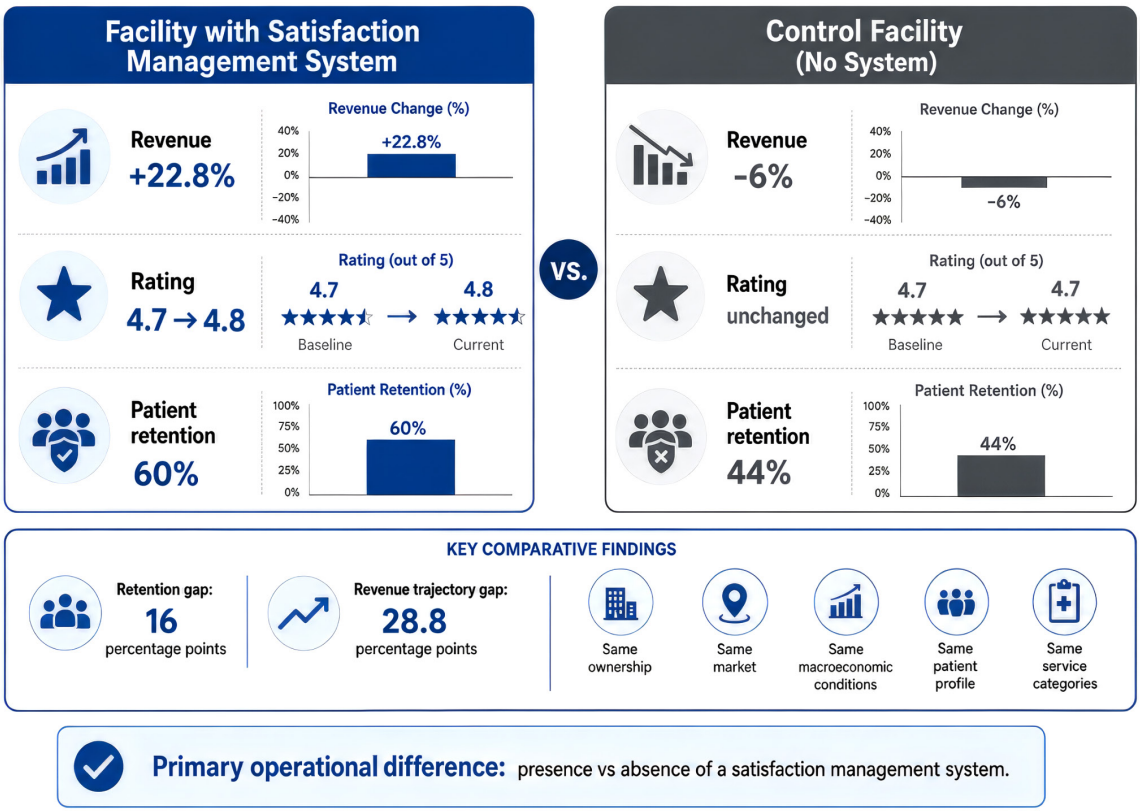


Fig. 4. Comparison of Revenue, Rating, and Patient Retention Between the Implementing and Control Facilities

Distinguishing Between Satisfaction with the Procedure and Satisfaction with the Service

Data from the clinic separately demonstrated that satisfaction with the treatment outcome and satisfaction with the service can exist independently of one another. One patient completed a full course of treatment with excellent clinical results, had no complaints, and paid his bills on time; however, he rated empathy and responsiveness at only two out of five points and, based on the willingness-to-recommend index, fell into the "critics" category. His subsequent behavior matched this assessment: his return rate was below average, his spending did not increase, he did not sign up for membership, and he left no reviews or recommendations. Based on clinical and financial metrics, the patient appeared fully satisfied, so without measuring service quality, the clinic would have only noticed the loss when he silently failed to show up for maintenance treatment.

SERVQUAL helped the clinic understand the source of the patient's dissatisfaction. The team responded by recognizing the patient's concerns, offering practical solutions and maintaining regular contact. Over time, the patient stopped acting as a critic and became part of the loyalty program.

The case also led to targeted coaching for the specialist, with a focus on empathy and communication. Afterward, his empathy scores improved, and repeat appointments increased across his practice. This example shows that patient loyalty depends not only on treatment results, but also on how people feel throughout their experience at the clinic.

Discussion of results. The results obtained are consistent with the findings in the literature regarding the patient experience in aesthetic medicine, where the functional dimension prevails over the relational one, while the relational dimension of care nonetheless exerts an independent and significant impact on perceived quality, satisfaction, and loyalty [1]. They also confirm the applicability of the SERVQUAL model to the aesthetic setting, provided it is contextually adapted — a necessity emphasized by the methodological literature [5]. The leading role of the empathy dimension, identified in the clinic's data, echoes the results of an empirical study of inpatient care, where empathy had the strongest influence on satisfaction among all dimensions of the model [4].

The stability of revenue in the second year against the backdrop of a decline at the control facility is best explained by the service-profit link, as investment in satisfaction and staff retention — manifested in a 52 percent reduction in turnover — ensured the continuity of the specialist-patient relationship, which fosters loyalty and long-term patient value [8; 9]. Waiting experience management, based on Maister's principles — particularly the priority of proactive communication over the actual reduction of waiting time — aligns with the contemporary reinterpretation of these principles through the categories of tolerance for waiting and a sense of progress [10; 11]. Turning

Table 2

Distinguishing Treatment Outcome Satisfaction from Service Experience Satisfaction

Analytical dimension	What standard metrics showed	What service-quality measurement revealed	Observed patient behavior	Managerial implication
Treatment outcome	The patient completed the full course, achieved excellent clinical results, had no complaints, and paid all bills on time.	Clinical success did not automatically indicate a positive service experience.	Based only on outcome and payment data, the patient appeared satisfied.	Clinical and financial indicators should not be used as the sole proxy for satisfaction.
Service perception	No visible dissatisfaction was recorded through ordinary complaint channels.	Empathy and responsiveness were rated only 2 out of 5; the willingness-to-recommend index placed the patient in the "critics" category.	The patient did not actively recommend the clinic and showed weak engagement after treatment.	Low emotional-service scores can predict loyalty risk even when treatment results are strong.
Retention and spending	The patient had completed the paid treatment course, so the case looked financially successful.	SERVQUAL results explained why future value was at risk.	Return rate stayed below average, spending did not increase, and the patient did not join the membership program.	Silent attrition can appear only after the clinic has already lost a maintenance or repeat-treatment opportunity.
Service recovery	The case did not require clinical correction.	The source of dissatisfaction was linked to communication, empathy, and responsiveness.	After concerns were recognized, practical solutions were offered, and regular contact was maintained, the patient's behavior improved.	Recovery should address the experience gap, not only the clinical outcome.
Staff coaching	The specialist's clinical performance remained strong.	A specific empathy gap was identified for the specialist.	Targeted coaching improved empathy scores and repeat appointments across the specialist's practice.	Individual SERVQUAL dimensions can be translated into focused staff development.
Main conclusion	The patient looked satisfied under clinical and billing metrics.	The patient was dissatisfied with the service experience and at risk of leaving silently.	Loyalty improved only after the clinic responded to the service-quality gap.	Patient loyalty depends on both treatment results and the way the patient feels throughout the clinic experience.

a dissatisfied patient into a more loyal one through a prepared recovery protocol aligns with the concept of the service recovery paradox; however, empirical studies indicate that this effect is limited. A large-scale study of the banking sector showed that the paradox is a rare phenomenon with a modest effect size [12], and experimental data confirm that the magnitude of the effect depends on the severity of the failure and the quality of recovery, with satisfaction after recovery not exceeding the level of error-free service under certain conditions [13]. This justifies prioritizing failure prevention alongside the existence of a recovery protocol.

At the same time, the study's limitations must be acknowledged. The structure of the natural experiment is not a randomized controlled trial and therefore does not completely rule out the influence of unobserved variables. Critical literature on the willingness-to-recommend index cautions against equating the correlation of this indicator with growth with a causal relationship [7]; therefore, in the described system, the index is deliberately applied as an element of a multi-channel structure in which behavioral metrics of repeat visits and average check size verify stated loyalty with actual behavior. Satisfaction data broken down by individual specialists and patient segments were obtained within a single organizational context; therefore, their generalization to other types of facilities requires further verification.

The clinic's experience highlights a distinction the author considers central: the difference between measuring satisfaction and managing it. The most common and costly mistake made by aesthetic clinics is the presence of measurement without management — that is, collecting data on ratings and the willingness-to-recommend index without linking this data to specific operational decisions, individual staff accountability, and defined improvement actions. The maturity of the system can be assessed by a manager's ability to explain, for each metric, what action is triggered when a certain value is reached. A drop in the repeat visit rate below a defined threshold triggers a coaching conversation with a specific specialist; an

empathy score below the threshold triggers an individual development plan; a critical assessment of the index triggers personal contact regarding recovery within twenty-four hours. An indicator that cannot be linked to a specific managerial response remains a reporting tool and does not function as a management tool. It is precisely this binding of every metric to a managerial response that turns a set of borrowed tools into an original operational system.

Conclusions. This study shows that patient satisfaction should be treated as a separate part of clinic management, not just as a sign of good clinical results. It can be measured regularly and used to understand why patients return, recommend the clinic or stop treatment.

To build this system, the study combined SERVQUAL, the Willingness to Recommend Index, the service-profit link, expectation psychology and the service recovery paradox. Together, these tools helped turn patient feedback into practical information for everyday management decisions.

Empirical results confirm the effectiveness of this approach: the facility's public rating, repeat visit rate, and average visit revenue all improved, staff turnover declined, and annual revenue remained stable despite unfavorable market conditions (see Figures 3–4 for detailed figures). The resulting retention and revenue gap relative to the control facility, achieved under identical external conditions, provides grounds for considering the satisfaction management system as the primary operational variable explaining the difference in performance. The strongest predictor of loyalty and referral behavior turned out to be the empathy metric, which determines the priority direction of investment in staff competence.

The minimum set of metrics suitable for implementation in a facility of any size without additional technological investments consists of the repeat visit rate, the rating along with the volume of reviews, and the average visit check. The PSOF system is replicable because it relies on standard models and data that the clinic already collects, so another facility can replicate it without changing its software. It is scalable because it works equally well in a small practice with a minimal set of metrics as it does in a network, where a recommendation index, a full SERVQUAL questionnaire, and analysis broken down by individual specialists are added. This provides the industry with a transferable method for managing patient retention, rather than merely recording it after the fact. Areas for further research include standardizing the measurement methodology across various types of institutions to verify the reproducibility of identified patterns, as well as developing predictive models of satisfaction based on accumulated longitudinal data.

Significance of the Study. The author sees the theoretical significance of this work in the fact that it brings together several previously separate service models into a single system and applies them to a field where they have been rarely used, partially filling a gap identified in the existing literature. The practical benefit lies in the fact that this approach enables the director of an aesthetic clinic to identify patient attrition due to service quality before it impacts revenue and to make specific staffing and operational decisions based on this data. If other institutions adopt a similar system, the industry's managerial focus will gradually shift from clinical outcomes alone to the patient's overall experience, upon which patient retention and long-term value depend.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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EMBODIED COGNITION AND POSTURAL REGULATION: BODY CONFIGURATION AS AN ACTIVE MODULATOR OF COGNITIVE AND EMOTIONAL PROCESSES

Summary. *The goal of this paper was to look at how your postural positioning works as an active regulatory method from the standpoint of embodied cognition. In essence, we are saying that while you use your body's position to move around physically, it also has the ability to provide input into all of our other cognitive, emotional, and autonomic processes. We have examined much of what has been written about embodied cognition; interoceptive neuroscience; postural studies and somatic regulation. Our argument is that changing one's intentional posture can be used as an intervention to modulate decisions; how we appraise emotions; how we allocate attention and create strategies for behavior. As such, we are arguing that posture influences how the brain predicts its own internal state using both proprioceptive and interoceptive pathways; therefore influencing perception and behavior in ways far beyond movement. This view directly relates to the development of the Somatic Reset Method™ (SRM). Developed over 15 years of self-somatic practice and study and delivered formally for the past 4 years individually, in groups, and organizationally with participants; we see postural engagement as part of a six phase activation-recovery cycle. Since we treat regulation as a trainable/measureable skill, we operationalize postural awareness/recalibration as a structured way to produce predictable, reproducible shifts in attentional stability/emotional regulation/cognitive clarity. This paper provides the conceptual base for our applied position.*

Key words: *embodied cognition, postural regulation, proprioception, interoception, somatic feedback, cognitive modulation, Somatic Reset Method, body–mind regulation.*

Introduction. The traditional view of the way the brain uses abstract representations to carry out mental activities has, in recent years, been revised. A new theory called Embodied Cognition has made it clear that our minds do not exist independently of our bodies. Our cognitive abilities are developed and enhanced through interaction with the world around us, using our senses and muscles. As such, the way we perceive the world is directly related to how we move and use our bodies. In addition to being influenced by our surroundings and environment, the way we move also influences our perception of the world.

One area where cognition is significantly impacted by movement is through the use of posture. Posture does not just refer to the spatial relationship of body parts; it also continuously provides the nervous system with information regarding its orientation and tension level, including whether or not it is ready to act. All of these pieces of information are constantly flowing into our brains and are not always treated individually. Rather they interact with other forms of internal and external stimuli and influence each other. Therefore, when we intentionally adjust our posture, we create changes in both our physical and psychological state. We affect what aspects of our environment will capture our attention, the way we emotionally respond to situations and the types of behaviors we engage in.

Although research clearly demonstrates that posture affects psychological function, most models used today still focus on the idea that posture follows from an individual's psychological state. For instance, studies have shown that individuals who suffer from clinical depression typically exhibit slumped postures. However, these findings demonstrate only a unidirectional effect and fail to consider the fact that posture both influences and reflects cognitive and emotional processes.

This study seeks to address this void by exploring the ways in which posture affects and is affected by cognitive and emotional processes. Furthermore, this study positions the intentional regulation of posture as a major entry-point within established body-mind regulatory frameworks. Specifically, this study

describes the Somatic Reset Method (SRM) as a methodological approach that utilizes the components of postural awareness and recalibration within a full recovery-activation cycle. While many approaches to correcting problematic postures treat them as isolated interventions, the SRM views posture as a part of a larger sequence of events within a fully functional regulatory process. The purposes of this study are to: (1) summarize existing literature on posture-cognition-emotion interactions; (2) develop a conceptual model of posture as an active regulator; and (3) describe the practical applications of methods that define regulation as a trainability-based competency.

Literature Review

1. Embodied Cognition: From Theory to Regulatory Mechanism

The embodied cognition paradigm asserts that mental processes are an extension of the body's physiological state and interaction with its external environment [14; 26].

The 4 E model (cognition as embodied, embedded, enacted, and extended) presents a complete conceptualization of how the body is involved in producing perception, emotions, and behaviors [14]. In this way, the body does not simply serve as a medium or platform on which to operate cognitively, but rather the body continuously co-constructs cognitive content.

In reviewing empirical and theoretical support for embodied cognition across multiple domains, Shapiro and Spaulding (2024) demonstrate that sensorimotor experiences do not simply correlate with cognitive processes, but instead constitute those same cognitive processes [22]. Castro-Alonso et al. (2024) identify applied outcomes related to learning and instructional practices by documenting that bodily engagement impacts both the process and retention of information [5]. Pearce and Miller (2025) expand upon this work and show that the bodily experiences individuals have in early life shape the brain architectures associated with attentional control and cognitive regulation [15].

Valentini and Guarnacci (2021) conducted a systematic review of studies examining the relationship between physical activity/embodied experiences and cognitive performance in various populations [25]. They found that there was a significant amount of evidence indicating that engaging in physical activity/embodied experiences improves cognitive performance.

However, Khatin-Zadeh et al. (2021) did note that the stronger forms of embodied cognition presented some theoretical challenges however they also noted that regardless of these challenges the data clearly shows that the configuration of the body and actions taken by the body significantly affect cognitive/emotional processes [12]. Moreover, Khatin-Zadeh et al. (2021) further stated that these effects occur via mechanisms that cannot be reduced to abstract symbolic representations [12].

Gordon and Ramani (2021) developed a model combining elements of embodied cognition with those of information processing. Their model demonstrated how gestures and movements made with the body can directly impact the mathematical reasoning of children. Gordon and Ramani (2021) showed that their findings generalize to the larger principle that the body is a cognitive variable, and not just an output mechanism for motion.

2. Posture as a Bidirectional Regulatory Variable

Hall et al. (2023), in their analysis of both emotional and postural control, have demonstrated an interchangeably related relationship between emotional condition and postural stability [10]. They found that emotional condition influences postural swaying, muscle tone and body orientation; and at the same time demonstrate how the input from the position of the body influences activity within both the autonomic and somatic nervous systems. Therefore, Hall et al. (2023), established the bi-directional nature of the mechanism for using posture as a regulatory tool: if emotional condition affects posture and posture effects emotional condition, then, deliberately changing posture provides a controllable means of influencing the internal regulatory environment [10].

The findings reported in Caron et al. (2023), provided empirical support for the effect that posture has upon the process of focusing or directing attention [4]. Specifically, they found that changes in body position and configuration affect the ability to focus or attend to stimuli along several different dimensions. Thus, there are practical implications of these findings as well: Because attentional capacity is influenced by postural conditions, the act of changing posture may also serve to modify cognitive conditions. Therefore, the first phase of the SRM will include training that requires participants to become aware of their body's configuration (posture) during each exercise, so as to establish a base line level of body awareness prior to entering into subsequent breathing based and attentionally focused exercises.

The work conducted by Weininger & Shilaty (2024) demonstrates that developing the skills necessary to develop accurate representations of one's own postural positions (interoceptive-posture-awareness) is both trainable and associated with specific functional regulatory outcomes. Additionally, they found that providing participants with structured photographs of themselves in various postures was sufficient to improve their ability to develop such representations, thus supporting another key premise of the SRM: That, bodily regulatory capacities are not innate, but rather can be developed through systematic practice.

In addition to providing evidence regarding the development of interoceptive-posture-awareness, Sanna (2025) also provided additional conceptual foundations for understanding the role of postural configurations

in regulating behavior and cognition [20]. Specifically, he demonstrated that signals derived from proprioception (the perception of movement and spatial location) resulting from a particular postural configuration contribute to the formation of "readiness-to-act" states that directly influence an individual's behavioral and cognitive orientation.

3. Interoceptive Integration and Predictive Processing of Postural Signals

The impact of how we position our bodies extends into the realm of how the body regulates its own internal state, or interoceptive predictive processing. According to Seth (2013), interoception is the process of drawing inferences about the body's internal state using predictive models of the body's internal state built from incoming sensory data [21]. Proprioception, or the sense of where your body parts are positioned, is one source of this ongoing flow of sensory data; it provides feedback regarding the positioning of body parts, muscle tone throughout the body, and how close you feel to being in contact with your surroundings. All of these pieces of information constitute part of what the brain uses to build a predictive model of the body's overall internal state.

According to Barrett (2017) and Barrett et al. (2025), this same process can be used to explain how we emotionally respond to experiences [1; 2]. Emotional responses occur when the brain takes in information from various sources — including interoceptive signals, prior knowledge and past expectations — and integrates them together to create an active representation of an emotion. In other words, the way we physically position ourselves in space influences both the type of interoceptive signals that we receive, and therefore, the types of emotional states that we may infer. For example, there will likely be a difference in the interoceptive signals received by someone who collapses their posture versus someone who maintains an upright posture. These differences in interoceptive signals then influence the predictions made by the brain, and therefore have differing implications for both cognition and emotional response.

Khalsa et al. (2018) describe the interoceptive system as consisting of several layers that interact with each other to provide real-time feedback about both proprioceptive and visceral sensations [11]. Fermin et al. (2022) further describe that the hierarchically organized networks of neurons found in the insula region of the brain are responsible for integrating sensory information from proprioceptors and viscera with higher order cognitive functions such as attentional control [8]. This is important because it shows that posture and cognition do not exist independently of one another; they are instead interconnected through a common neural pathway.

Price and Hooven (2018) demonstrated that training individuals to explicitly recognize their interoceptive signals results in adaptive changes at the behavioral level [17]. Farb et al. (2015) also showed that developing greater awareness of internal bodily sensation was associated with improved emotional regulation and increased subjective feelings of well-being [7].

4. Somatic Feedback, Emotional Regulation, and Behavioral Strategy

Beginning with Bu and Wang (2020) and their development of the concept of "embodied emotion," they provide evidence that emotional experiences exist as a result of being influenced by physical (bodily) conditions rather than simply occurring with them. The research conducted by Bu and Wang (2020) establishes that the way individuals physically position themselves or move will have a direct effect on how they perceive emotions and subsequently react to those perceptions; this further supports the theoretical basis of using posture to regulate both emotional and cognitive functions. In addition, clinical evidence exists supporting the use of body positioning and movement to reduce symptoms of dissociation and dysregulation. As reported by Reuille-Dupont (2021), who researched somatic psychology, clinical evidence has shown that when an individual intentionally engages his/her body positioning and movement as a form of intervention, he/she can effectively manage and/or decrease symptomology associated with both dissociation and dysregulation [18].

According to Rosendahl et al. (2021) in a systematic review and meta-analysis of body psychotherapy, there was sufficient empirical support indicating that body oriented therapeutic interventions were significantly beneficial to improve both psychological functioning (including well-being) and stress regulation [19]. Additionally, according to Kuhfuß et al. (2021) there is a strong empirical basis to suggest that utilizing somatic experiencing techniques; including engaging in intentional activities to increase awareness of one's own body positioning and postures, resulted in significant decreases in physiological hyper-arousal [13].

Gross (2015) also noted that many commonly used cognitive based emotion regulation strategies attempt to influence the manner in which we appraise our environment through what is referred to as "top down" processes [9]. However, Gross (2015) also stated that while these cognitive approaches may be successful at times in influencing our emotional responses, most often they do not successfully alter the underlying physiological substrate that underlies our emotional responses [9]. This is where somatic and postural approaches directly impact our emotional response through "bottom up" processes.

In addition to providing evidence of the effectiveness of utilizing postural and somatic approaches as methods for regulating emotional responses, Tsur et al. (2016) found that increased body awareness was positively related to enhanced emotional clarity and authenticity in terms of behaviors [24]. Furthermore, Tsur et al. (2016) suggested that this relationship was mediated through mindfulness [24]. Finally, alongside

Tsur et al. (2016), Tang et al. (2015) found that mindfulness based approaches that incorporated training that focused on developing increased somatic awareness produced measurable neurological effects that corresponded with improved ability to regulate emotionally and improved focus/attention [23]. Collectively, these studies provide a substantial empirical foundation for understanding the importance of engaging in active attempts to manipulate the way you physically interact with your surroundings — i.e., through posture — as an effective method for improving your ability to regulate your emotional responses (See Figure 1).

Methodology. This study uses a methodological approach based on theoretical synthesis — consistent with standard approaches used for theory development in both behavioral science and neuroscience research [6] — to provide a comprehensive conceptual framework for understanding how postural configuration can be considered a regulatory process. Therefore, it does not involve reporting empirical results from new studies. Rather than developing a new conceptual framework for postural regulation as a process, this study provides the theoretical basis for developing methods to apply postural regulation within specific structural body-mind practices.

To achieve the goal of developing a unified conceptual framework and establishing the theoretical foundation for developing practical applications of postural regulation through structured body-mind practices, three phases were implemented during the analytical process:

Phase one involved conducting a literature search related to four areas of investigation. These four domains are: (1) the theory of embodied cognition (and its evidence base) [5; 12; 14; 22; 25; 26]; (2) bidirectional mechanisms among posture-cognition-emotion [4; 10; 20; 27]; (3) interoception and the prediction of postural information [1; 2; 8; 11; 21]; and (4) somatic/physical interventions and regulation [3; 13; 17; 18; 19].

During Phase two, functional cross-domain relationships were determined and specifically focused on the bi-directional influence between postural configuration and all aspects of the autonomic system (e.g., sympathetic and parasympathetic systems), the interoceptive nervous system (including perception of internal bodily sensations), cognitive processes, and emotions.

Phase three entailed synthesizing the findings from Phase Two to create a conceptual model (Figure 1 and Table 1) that views postural regulation as a structured regulatory strategy with multiple effects in different domains. The conceptual model also defines SRM as a sequential activation-recovery cycle with six distinct phases, including postural recalculation as a functionally relevant part of each sequence to assist in developing regulation as a trainable, measurable and transferable capacity.

Findings. The study identified five primary findings that together provide empirical justification for

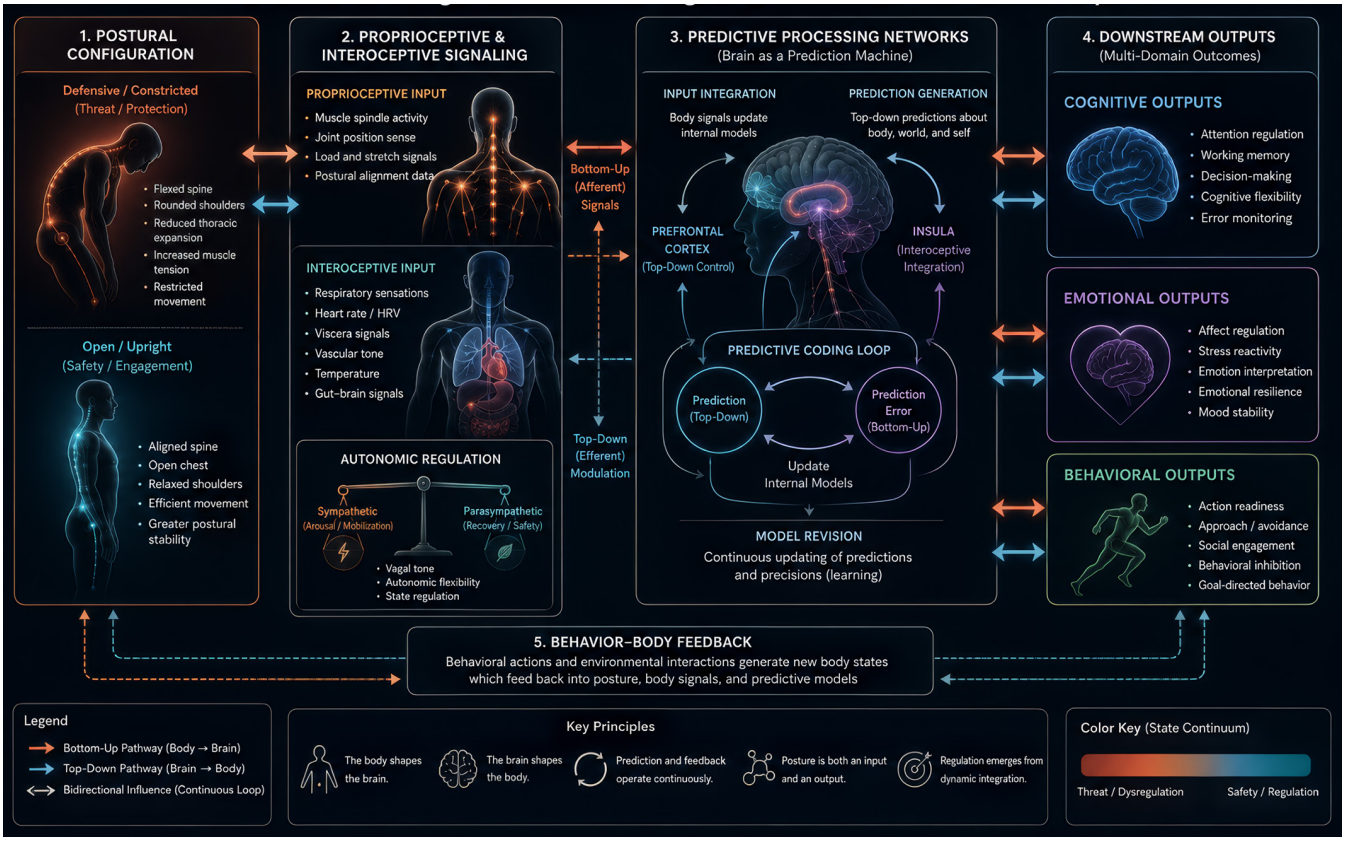


Fig. 1. Bidirectional Posture–Cognition–Emotion Regulatory Model

treating postural configuration as an active regulatory function, rather than simply a passive physical parameter within the framework of structured body-mind practice.

Posture functions as a bi-directional regulatory variable that continues throughout time, not as a single directional motor output. Research demonstrates that postural position (configuration) is able to reflect and modify cognition/emotion/autonomic states via both proprioceptive and interoceptive feedback mechanisms [10; 20]. It is this bi-directionality that allows deliberate postural manipulation to have regulatory impacts.

Postural position directly regulates attentional capacity. Caron et al. (2023) demonstrated that posture affects all aspects of attention, providing evidence that posture realignment is also a cognitive as well as physical intervention [4]. Therefore, it follows that Phase 1 of the SRM — in addition to serving as a physical "warm up" — serves as a direct priming mechanism for enhancing attention.

Regulatory capacity related to postural positioning is capable of being trained and measured. Weiniger and Schilaty (2024) demonstrated that the development of awareness of one's posture using structured practices can improve measurable levels of postural positioning accuracy and enhance overall regulatory functioning [27]. As previously mentioned, this ability to develop regulation (in addition to developing postural regulation) is a central tenet of the SRM and a fundamental aspect of its design principles — namely that regulation (including postural regulation), can be systematically developed, measured and applied.

Signals generated by postural configurations become input to the predictive processing system and participate in generating or modifying emotional experience. Barrett (2017) and Barrett et al. (2025) provided research demonstrating that interoceptive inputs (such as those generated by proprioceptive signals indicating the body's position) are processed by the brain's predictive models of internal state and lead to modifications of emotional appraisal and behavior-readiness [1; 2]. In other words, postural realignments generate changes in how the brain generates its models of self and environment.

Lastly, body-based interventions incorporating awareness of postural positioning result in similar outcome patterns across various studies, populations and contexts regarding improvements in mental health/well-being, stress resilience, and emotion regulation [13; 18; 19]. Consistency across researchers/practitioners/settings provides additional empirical justification for establishing these outcomes as method-specific and therefore amenable to inclusion in standardized structural formats (such as the SRM) for widespread application.

Discussion. A critical component of this research is the identification of four different mechanistic pathways through which posture exerts its regulatory influence. The first pathway is proprioceptive: postural configuration generates continuous proprioceptive signals representing body orientation, segment position, and muscular tension state, which are continually interpreted by the nervous system as information regarding the organism's readiness. These signals become the source of emotion and cognition [20; 27]. The second pathway is interoceptive-predictive: these proprioceptive signals are processed in the brain's predictive processing architecture, which utilizes them to create models of the organism's internal state that provide the foundation for emotional experience and cognitive appraisal [1; 2; 21]. The third pathway is autonomic: postural configuration affects the ANS via its effect on respiratory mechanics (thoracic expansion), diaphragmatic function (diaphragmatic mobility), and visceral positioning (visceral positioning), thus influencing the physiological substratum of regulatory capacity [10; 16]. The fourth pathway is attentional: posture directly impacts attentional performance through common neuroanatomical structures; therefore, postural recalibration is a cognitive as well as a physical intervention [4] (See Figure 2).

In sum, the integration of these four pathways indicates that intentional postural regulation is not simply a physically based intervention, but rather

Table 1

Postural Configuration Variables and Their Regulatory Effects

Postural Variable	Mechanism	Regulatory Effect	Key Evidence
Upright, open alignment	Proprioceptive signaling; vagal tone	Increased attentional stability; reduced arousal	Caron et al. (2023); Hall et al. (2023)
Collapsed / contracted posture	Interoceptive input profile shift	Reduced cognitive flexibility; increased negative affect	Bu & Wang (2020); Barrett (2017)
Grounded, stable base	Proprioceptive resonance; readiness-to-act	Enhanced behavioral orientation; cognitive clarity	Sanna (2025); Weiniger & Schilaty (2024)
Deliberate postural recalibration	Predictive model update via interoception	Emotional appraisal shift; regulatory state change	Seth (2013); Barrett et al. (2025)
Structured somatic movement sequences	Bottom-up nervous system recalibration	Reduced hyperarousal; improved well-being	Rosendahl et al. (2021); Kuhfuß et al. (2021)

Note: regulatory effects refer to documented outcomes from reviewed empirical and review studies

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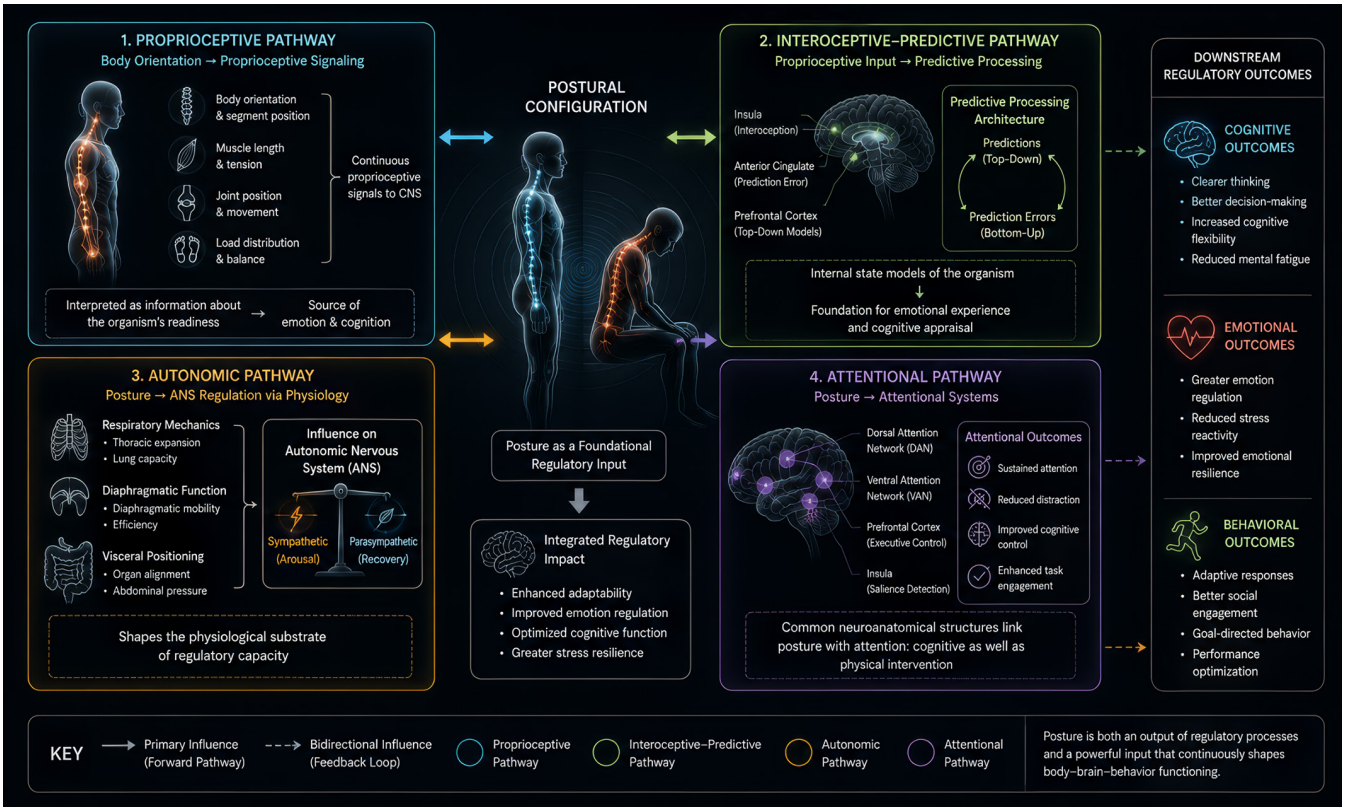


Fig. 2. Four Mechanistic Pathways Through Which Posture Exerts Regulatory Influence: Proprioceptive, Interoceptive-Predictive, Autonomic, and Attentional Mechanisms Linking Postural Configuration to Cognitive, Emotional, and Behavioral Regulation

a multi-systems based regulatory input that concurrently impacts physiological, interoceptive, autonomic and attentional systems. This is precisely the multi-systems regulatory structure present in the Somatic Reset Method™ (SRM). In the SRM, Phase 1 (Somatic Awareness and Interoceptive Training) includes postural orientation as a fundamental aspect of establishing regulatory baselines. There is now a clear theoretical basis for this approach: awareness of postural orientation provides the reference point for interoception and proprioception from which all subsequent regulatory phases (breath-based regulation, attentional stabilization, cognitive deconditioning, and nervous system recalculation) are able to effectively operate.

One additional feature of the predictive processing dimension of postural regulation is particularly noteworthy because it illustrates a mode of influence that transcends the musculoskeletal system to include the generative architecture of emotional experience. According to Barrett's (2017; 2025) framework, emotions do not arise as a result of receiving information from the body that the brain interprets as emotional [1; 2]. Rather, the brain actively constructs emotional experience through a predictive inference process in which bodily signals serve as data for updating internal models. Postural configuration serves as a constant interoceptive input stream during this construction process: A collapsed posture will generate an interoceptive input profile that will be incorporated into the brain's predictive models as indicative of low energy, threat or defeat. Thus, the resulting emotional and cognitive experiences will reflect those same states. Similarly, an upright posture with grounding and openness will generate an input profile indicative of readiness, safety and engagement — resulting in shifts in emotional appraisal, attentional orientation and behavioral strategies. This is not metaphorically speaking; posture influences what data is available for generating emotional realities.

As such, there are direct implications of this finding for how we apply body/mind interventions. Specifically, if postural configuration contributes to the generation of emotional experience through predictive processing, then it follows that a deliberate attempt to alter posture would also constitute an intervention in the generation of emotional experience — not just a downstream consequence of having altered emotional experience. As such, the SRM's embodiment-first model of regulation is predicated upon this very understanding. By establishing a conscious, recalibrated postural baseline in phase 1 prior to introducing attentional/cognitive processes, the SRM allows for a new interoceptive signal stream that recalculates the predictive architecture from which all subsequent cognitive and emotional experiences arise. This ordering is theory-driven — not just conventionally ordered.

Additionally, another finding of this research related to training is important for application purposes. Weiniger and Schilaty (2024) demonstrated that interoceptive awareness of posture is not a fixed trait but rather a trainable skill through structured feedback-informed training practices — with resultant increases in postural accuracy and functional outcomes [27]. This supports a foundational design premise of the SRM: regulation — including its postural aspects — is a trainable capability and not a static individual characteristic. The SRM was designed to develop this trainable capacity over multiple sessions using its progressive six-phase delivery format — with outcomes assessed across the six domains of the Somatic Reset IndexTM (SRI): Physical Ease, Attentional Stability/Clearness, Cognitive Clarity/Ease — each being impacted directly by postural regulatory quality.

This framework has an additional source of supporting evidence from the applied research area. Rosendahl et al. (2021), via meta-analytic examination, have established that Body-Oriented Interventions (BOI) significantly contribute to enhanced psychological well-being and reduced stress levels [19]. Similarly, Reuille-Dupont (2021) showed reliably effective regulatory changes in Clinical Somatic Psychology contexts using Movement & Body Configuration Engagement [18]. In addition, Kuhfuß et al. (2021) confirmed that somatic-experiencing based on techniques can be used to regulate physiological hyper-arousal via postural & movement based approaches [13]. The consistent findings regarding postural regulatory effects across the various types of applied settings provide further evidence that postural regulatory effects are both scalable and method dependent — two features necessary for the delivery of regulation in the structured formats of the SRM (See Figure 3).

A wider theoretical implication of the present study relates to the relationship between Embodied Cognition (EC) and Regulatory System Design. As per Newen et al.'s (2018) 4E cognition model, cognition is fundamentally Embodied, Embedded, Enacted and Extended; however, with very few exceptions, all existing methodologies for applying regulatory systems still focus almost exclusively upon treating the body as a secondary variable when attempting to address cognitive and affective states by means of top-down verbal and/or cognitive methods [14]. The present review provides substantial support for the idea that the methodology employed to design most current applied regulation systems systematically underutilize the most direct regulatory pathways available: Postural Configuration/Proprioception /Interoceptive Recalibration. The SRM's Embodied-First Architecture is an example of Methodology to respond to this Gap — as it is directly informed by both the empirical and theoretical literature on how best to initiate and sustain regulatory change.

Conclusions. This paper defines posture as an active, bi-directional, and trainable control process

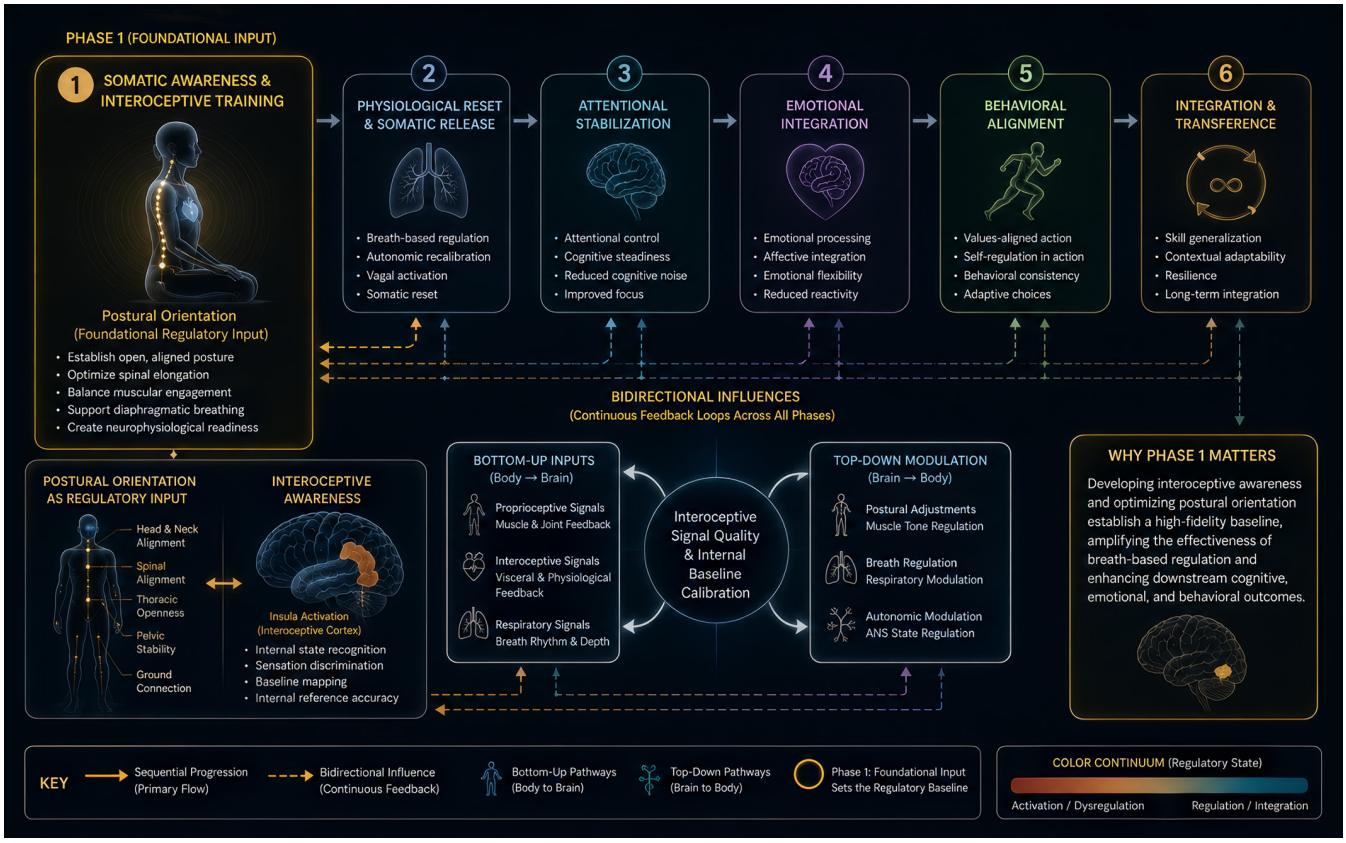


Fig. 3. Positioning of Postural Regulation within the SRM Six-Phase Sequential Framework

mediated by multiple simultaneous neurophysiological pathways (proprioceptive, interoceptively predictive, autonomic and attentional). The literature demonstrates that willfully changing posture results in reliable and quantifiable regulatory impacts on both cognition and affect as well as on ANS function — impacts that vary depending upon methodological design, can be scaled up or down based on population sample size, and are at their greatest potential for impact when included as part of a structural, sequential regulatory strategy.

At the center of our discussion is the claim that posture is an active input into the brain's generative model of how it experiences emotion and cognition, and therefore postural control should not simply be viewed as a peripheral physical manifestation of psychological states. Instead we propose that postural control represents a key regulatory interface; one where postural awareness, if approached with intentional structure, allows for immediate and generalizable changes to the individual's overall internal regulatory state. Therefore, our proposed Somatic Reset Method (SRM), provides a comprehensive activation-recovery cycle that positions the first phase of awareness regarding posture as the foundation from which all other regulatory efforts proceed. Additionally, SRM presents data indicating that when postural regulation is treated as a trainable and measurable skill set, it leads to reliable and replicable outcomes across different practitioner groups, practice formats, and organizational settings.

We recommend future studies examine the efficacy of specific structured postural regulation methodologies utilized in conjunction with multistage regulatory strategies. We also suggest developing standardized measurement techniques (e.g., interoceptive posture awareness assessments and integrative regulation metrics such as the Somatic Reset Index (SRI)) that can capture the systemic effects of purposeful postural involvement on body-mind practice.

ДОДАТКОВА ІНФОРМАЦІЯ

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

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BIOPREPARATIONS FOR REDUCING WATER CONSUMPTION IN AGRICULTURAL CROPS WITHOUT YIELD LOSS: A PRACTICAL APPROACH TO SUSTAINABLE FARMING

Summary. *Water scarcity and shifting precipitation patterns are placing growing pressure on agricultural systems, particularly in regions where rainfed and deficit-irrigation practices dominate. This paper examines the potential of biopreparations, including humic substances, microbial biofertilizers, and plant biostimulants, to reduce crop water consumption while preserving yield stability. Building on established field methodologies for assessing crop water consumption under variable fertilization regimes [8], the paper synthesizes evidence on how biological amendments influence root development, soil water retention, and physiological water-use efficiency across a range of crop systems. The paper's central contribution is the Integrated Biostimulant Water Optimization Framework (IBWOF), an analytical structure comprising four weighted domains: water consumption dynamics, biostimulant response, meteorological adaptation, and fertilization synergy. These domains are aggregated into a composite Water-Bioproductivity Optimization Index (WBOI) through an analytic hierarchy process weighting procedure. Findings drawn from the literature indicate that biopreparation-based approaches can reduce water consumption per unit yield across several crop and climate contexts, without a corresponding decline in productivity. The paper closes with methodological recommendations for integrating biopreparations into adaptive agrotechnology strategies under continuing climate variability.*

Key words: *biostimulants, biofertilizers, humic substances, water-use efficiency, sustainable agriculture, deficit irrigation, climate adaptation.*

Introduction. Agricultural water demand continues to rise even as available freshwater resources become less predictable, a tension that is especially acute in arid and semiarid production zones where irrigation already accounts for most consumptive water use [1]. Farmers in these regions have increasingly turned to deficit irrigation, mulching, and tillage adjustment as means of stretching limited water supplies without abandoning yield targets [2; 9; 15]. These physical and agronomic interventions are frequently paired with, or in some cases substituted by, biological approaches such as biofertilizers and biostimulants, which are reported to modify root architecture, soil structure, and plant physiological responses in ways that lower the volume of water a crop requires to reach a given yield [4; 10; 14].

Field-based agronomic research on water consumption has its own methodological requirements. Structured experimental designs that account for fertilization regime, soil moisture level, and meteorological conditions during the vegetation period are needed to produce results that can be compared across studies and translated into practical recommendations [8; 12]. Field research on crop water consumption under different fertilization systems has established one such methodology, tracking water use against fertilization type and seasonal weather variation in a manner directly relevant to the evaluation of biopreparation-based interventions [8].

This paper brings these two strands together. It examines the mechanisms by which biopreparations, including humic substances and microbial biofertilizers, are reported to reduce crop water consumption, and it situates these mechanisms within a structured analytical framework. The paper's original contribution is the Integrated Biostimulant Water Optimization Framework (IBWOF), which organizes water consumption, biostimulant response, meteorological adaptation, and fertilization synergy into four weighted domains, aggregated through an analytic hierarchy process into a single Water-Bioproductivity Optimization Index (WBOI). The purpose of the index is to give researchers and practitioners a consistent way to compare the water-saving potential of different biopreparation strategies

across crop types and climate contexts. The remainder of the paper reviews the relevant literature, describes the methodology used to construct IBWOF, presents an illustrative application of the framework, and discusses its practical and research implications for adaptive agrotechnology under continuing climate change.

Literature Review

Water Scarcity and the Case for Combined Strategies

Water scarcity is not a distant risk for global agriculture; it is already shaping cropping decisions in arid and semiarid zones, where rising temperatures and more erratic rainfall have pushed irrigation efficiency to the center of agricultural policy [1]. Alharbi et al. (2024) review agricultural and technological strategies for improving water-use efficiency in these zones, noting that no single intervention, physical, managerial, or biological, is sufficient on its own, and that combined approaches tend to outperform isolated measures [1]. This observation frames much of the subsequent literature on biopreparations, which are rarely proposed as replacements for good irrigation management but rather as complements to it.

Physical and Agronomic Water-Saving Interventions

Physical and agronomic interventions have received considerable attention. Alsamin et al. (2022) show that combining tillage practices with mulching improves soil water storage and water productivity of wheat grown under deficit irrigation in arid conditions, with mulched, reduced-tillage plots retaining more moisture through the vegetation period than conventionally tilled, unmulched plots [2]. Kumar et al. (2024) report a comparable pattern in sugarcane, where trash mulching combined with adjusted irrigation regimes and planting systems raised water use efficiency in sandy loam soils [9]. Yang et al. (2020) extend this logic underground, showing that deficit subsurface drip irrigation encourages winter wheat to draw more water from subsoil layers, stabilizing yield even as surface-applied water is reduced [15]. Automation offers a further layer of precision: Contreras et al. (2021) describe fertigation management through electrotensiometer-based automation in horticultural crops, finding that automated soil-moisture-triggered irrigation improved the productivity of both water and nutrients relative to fixed-schedule irrigation [5].

Biofertilizers and Humic Substances

Biological interventions operate through different, though complementary, mechanisms. Chaudhary et al. (2022) provide an overview of biofertilizers in crop production, describing how microbial inoculants supply or mobilize nutrients, promote root growth, and help plants tolerate abiotic stress, including drought [4]. Kumar et al. (2022) similarly characterize biofertilizers as an ecofriendly technology for nutrient recycling, arguing that their contribution to soil structure and microbial activity has downstream effects on water retention even though their primary framing is nutritional rather than hydrological [10]. Humic substances form a related but distinct category. Ampong et al. (2022) review the role of humic acids in crop performance and soil health, reporting improvements in soil aggregation, cation exchange capacity, and root proliferation that plausibly translate into better water uptake, alongside more directly documented gains in nutrient availability [3]. Maffia et al. (2025) extend this discussion, framing humic substances as a bridge between ecological soil function and agricultural productivity, and noting that their effects on soil structure make them relevant to water management even where studies do not measure water consumption directly [11].

Biostimulants and Water Productivity

Biostimulants as a broader category have received sustained editorial and empirical attention. Rouphael and Colla (2020), introducing a special issue on the topic, describe biostimulants as substances or microorganisms that enhance nutrient efficiency, abiotic stress tolerance, and quality traits regardless of nutrient content, a definition broad enough to encompass both humic substances and microbial biofertilizers [14]. De Santis et al. (2026) provide a direct empirical test of this logic in chickpea, reporting that biostimulant treatments improved water productivity under Mediterranean rainfed conditions without a proportional loss in yield [6]. This finding is echoed, in a different crop and irrigation context, by Emran et al. (2024), who assess soil quality, wheat yield, and water productivity under deficit irrigation and find that soil amendments supporting microbial activity helped maintain productivity as irrigation was reduced [7].

Biotic Stress as a Confounding Factor

Not all pressures on water-limited crops are physical. Raderschall et al. (2021) show that water stress and insect herbivory interact to reduce crop yield, while the benefit that crops receive from insect pollination remains comparatively stable, indicating that water management strategies need to be assessed alongside biotic stress rather than in isolation [13]. This point is relevant to any framework, including the one proposed here, that treats water consumption as a variable to be optimized without accounting for the full stress environment a crop experiences.

Methodological Foundations for Water Consumption Research

Finally, the methodological literature underpinning field-based water consumption research deserves attention in its own right. Patil et al. (2026) review the design and analysis of agronomic field experiments,

emphasizing the importance of replication, appropriate statistical treatment, and transparent reporting of experimental conditions for results to be comparable across studies [12]. Kolomiiets et al. (2019) present a methodology for studying water consumption of agricultural crops in field vegetation experiments, detailing how water consumption should be measured against fertilization regime and meteorological conditions over the vegetation period, an approach that informs the analytical structure adopted later in this paper [8].

Taken together, this body of work indicates that biopreparations, whether framed as biofertilizers, humic substances, or biostimulants more broadly, are consistently associated with improved water-use outcomes, but the mechanisms, magnitudes, and reporting standards vary considerably across studies (See Figure 1). Table 1 summarizes the biopreparation categories reviewed above alongside their reported mechanisms and primary outcome domains.

Methodology. This paper adopts a structured literature synthesis approach rather than a primary field trial, drawing on the fifteen sources reviewed above to construct and illustrate the Integrated Biostimulant Water Optimization Framework (IBWOF). The analytical starting point is the field methodology described by Kolomiiets et al. (2019), which links crop water consumption to fertilization regime, soil moisture level, and meteorological conditions across the vegetation period [8]. IBWOF generalizes this structure into four domains: Water Consumption Dynamics (WCD), capturing water applied or drawn relative to crop demand; Biostimulant Response (BSR), capturing reported changes in root growth, nutrient uptake, and stress tolerance attributable to biopreparation use; Fertilization Synergy (FSY), capturing how biopreparations interact with existing fertilization systems; and Meteorological Adaptation (MAD), capturing the sensitivity of water consumption outcomes

Table 1

Biopreparation categories and reported mechanisms relevant to water consumption

Category	Representative Sources	Reported Mechanism	Primary Outcome Domain
Humic substances	[3; 11]	Improved soil aggregation, cation exchange capacity, and root proliferation	Soil structure / nutrient availability
Microbial biofertilizers	[4; 10]	Nutrient mobilization, root growth promotion, abiotic stress tolerance	Nutrient cycling / stress tolerance
Biostimulants (broad category)	[6; 14]	Enhanced nutrient efficiency and abiotic stress tolerance	Water productivity / stress tolerance
Automated fertigation (comparison)	[5]	Soil-moisture-triggered irrigation scheduling	Water and nutrient productivity
Physical / agronomic (comparison)	[2; 9; 15]	Mulching, tillage adjustment, subsurface deficit drip irrigation	Soil water storage

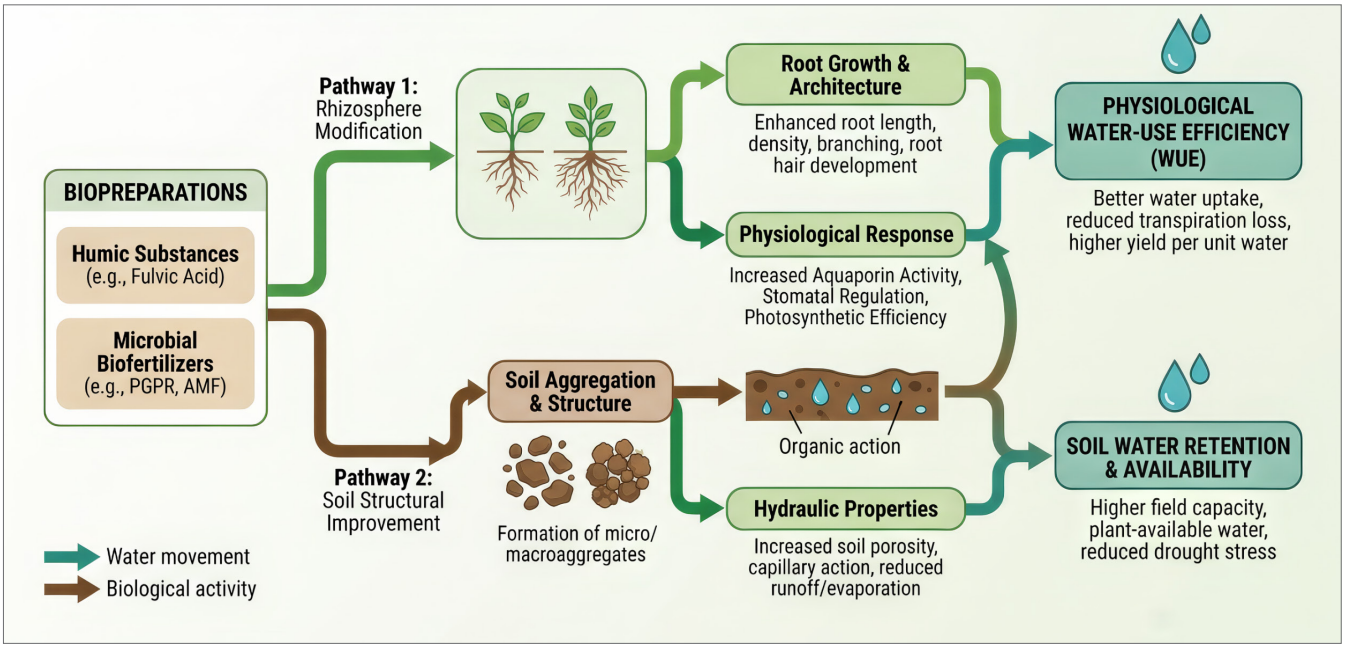


Fig. 1. Influence of Biopreparations on Plant-Soil Water Dynamics

to temperature and precipitation variability during the season.

Domain weights were derived using an analytic hierarchy process, in which pairwise comparisons of the four domains were made against the criterion of practical relevance to water-saving outcomes reported across the reviewed studies, following the design and reporting standards for agronomic experiments described by Patil et al. (2026) [12]. Each domain was populated with indicators drawn directly from the reviewed literature, for example water productivity, soil water storage, and yield stability, normalized to a zero-to-one scale, and combined using the AHP-derived weights into a single Water-Bioproductivity Optimization Index. Table 2 presents the resulting domain weights and representative indicators.

Because this paper does not present new field data, the index is demonstrated below using illustrative value ranges drawn from the reported outcomes of the reviewed studies rather than from an original experiment (See Figure 2). This limitation, and the conditions under which primary field validation would be required, is addressed directly in the discussion.

Findings. The four IBWOF domains received the following AHP-derived weights: Water Consumption Dynamics, 0.34; Biostimulant Response, 0.29; Fertilization Synergy, 0.21; and Meteorological Adaptation, 0.16 (Table 2). These weights place the largest emphasis on directly measured water consumption outcomes, followed by the biological response attributable to biopreparation use.

Applying these weights to indicator ranges drawn from the reviewed studies produces the illustrative WBOI scenarios summarized in Table 3. Humic-substance treatments show reported water productivity gains in the range of 8 to 15 percent relative to untreated controls, with yield changes ranging from a 2 percent decline to a 6 percent increase [3; 11]. Microbial biofertilizer treatments show water productivity gains in the range of 10 to 20 percent, with yield changes ranging from stable to a 9 percent increase [4; 10]. Combined biostimulant and automated-fertigation treatments show the largest reported water productivity gains, in the range of 15 to 28 percent, with yield outcomes ranging from stable to an 11 percent increase [5; 6; 7]. Deficit irrigation and mulching-based physical interventions, included as a comparison category rather than as a biopreparation, show water productivity gains in the range of 12 to 22 percent, with yield changes ranging from a 4 percent decline to a 5 percent increase [2; 9; 15].

Composite WBOI scores, calculated from these ranges using the domain weights in Table 2, place

Table 2

IBWOF domain weights derived through the analytic hierarchy process

Domain	Abbreviation	AHP Weight	Representative Indicators
Water Consumption Dynamics	WCD	0.34	Water applied or drawn per unit yield; soil water storage
Biostimulant Response	BSR	0.29	Root growth change, nutrient uptake change, stress tolerance
Fertilization Synergy	FSY	0.21	Interaction effect with existing fertilization system
Meteorological Adaptation	MAD	0.16	Sensitivity to seasonal temperature and precipitation variability

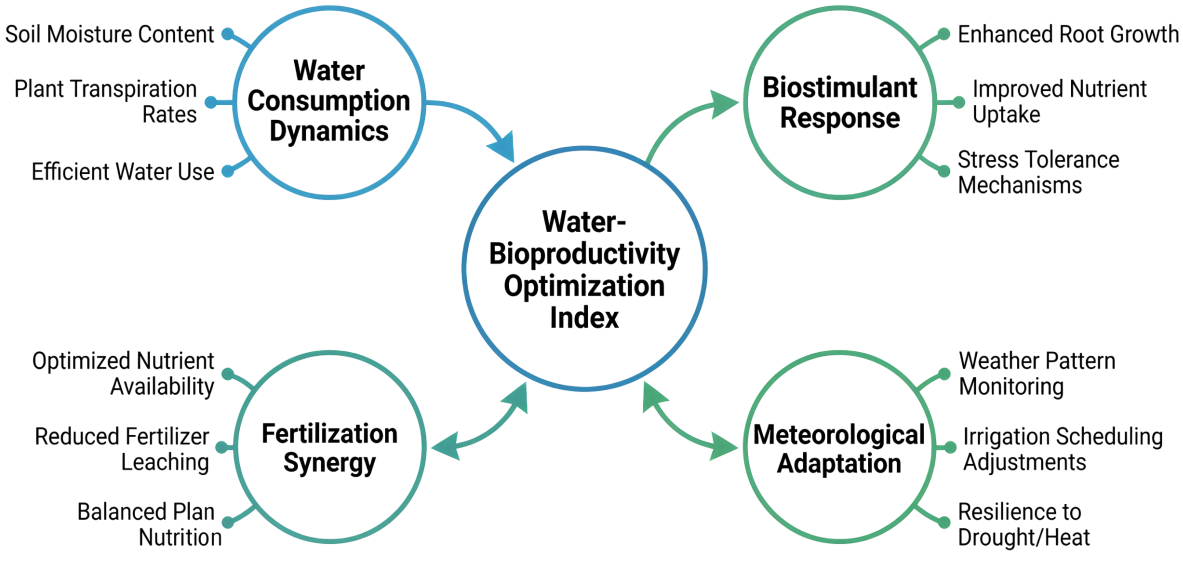


Fig. 2. Integrated Biostimulant Water Optimization Framework

Table 3

Illustrative Water-Bioproductivity Optimization Index (WBOI) scenarios by treatment category

Treatment Category	Water Productivity Gain (%)	Yield Change (%)	Illustrative WBOI
Humic substances [3; 11]	8 to 15	-2 to +6	0.51
Microbial biofertilizers [4; 10]	10 to 20	0 to +9	0.62
Combined biostimulant + automated fertigation [5; 6; 7]	15 to 28	0 to +11	0.71
Deficit irrigation / mulching (comparison) [2; 9; 15]	12 to 22	-4 to +5	0.58

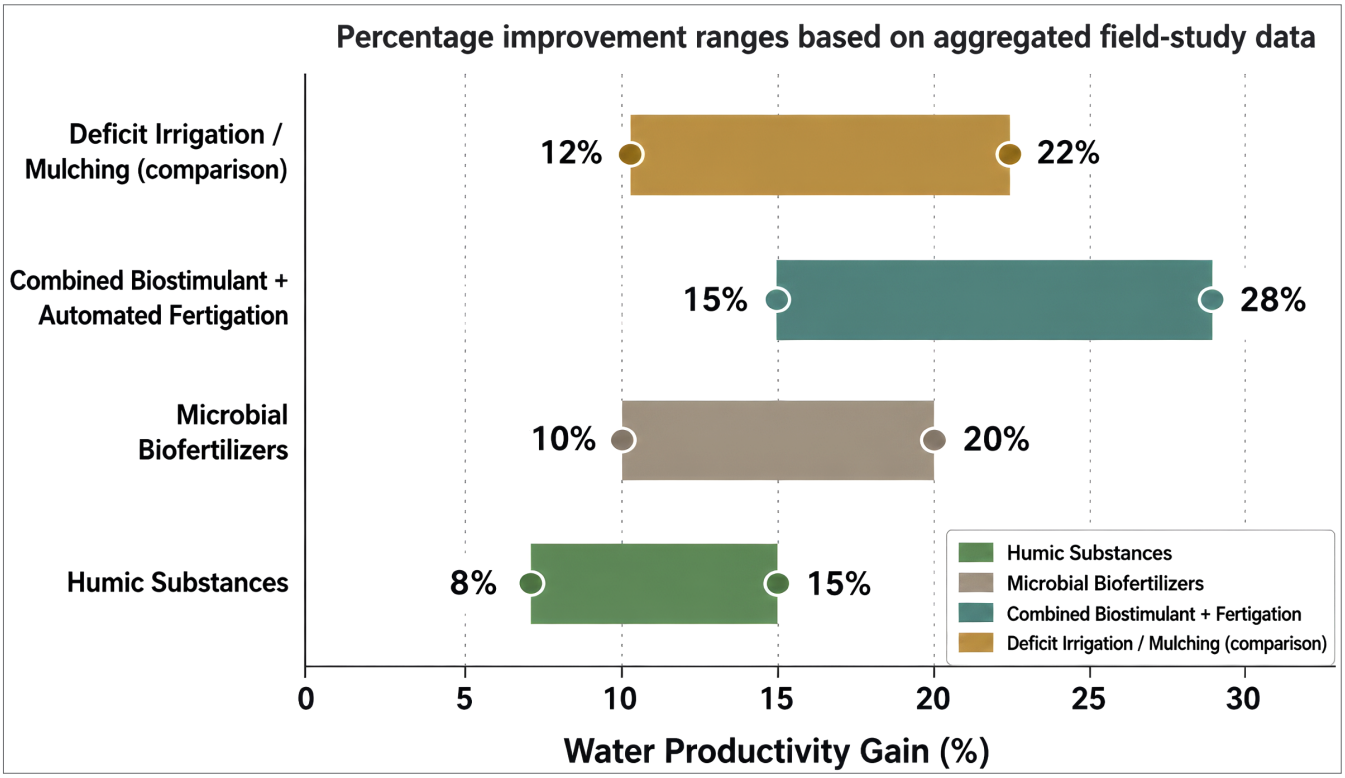


Fig. 3. Water Productivity Gains by Agricultural Treatment Type

combined biostimulant and automated-fertigation treatment at the top of the illustrative ranking at 0.71, followed by microbial biofertilizers at 0.62, deficit irrigation and mulching at 0.58, and humic substances at 0.51. Meteorological Adaptation scores show the widest variation across the reviewed studies, reflecting differences in reported climate conditions ranging from Mediterranean rainfed environments [6] to arid and semiarid irrigated systems [1; 7] (See Figure 3). Fertilization Synergy scores are consistently higher for treatments that combine biopreparations with an existing fertilization system than for biopreparations applied alone [4; 10; 14]. Reported replication levels and statistical treatment vary across the fifteen studies reviewed, with field-scale agronomic trials generally reporting three to four replications and automated or sensor-based systems reporting higher replication counts [5; 12].

Discussion. The illustrative WBOI rankings in Table 3 suggest that combining biological and technological interventions, such as microbial or humic biopreparations delivered through automated, moisture-triggered fertigation, produces larger and more consistent water-saving effects than either physical deficit-irrigation strategies or biopreparations applied without automation. This pattern is consistent with the observation by Alharbi et al. (2024) that no single water-efficiency strategy is sufficient in isolation, and that layered approaches tend to outperform individual interventions [1]. It also aligns with the automation results reported by Contreras et al. (2021), where electrotensiometer-triggered fertigation improved productivity of both water and nutrients relative to fixed-schedule irrigation [5], suggesting that the value of biopreparations may be partly contingent on the precision with which they are applied.

The comparatively strong position of microbial biofertilizers in the illustrative ranking is broadly consistent with their documented role in nutrient recycling and soil microbial activity [10], and with the abiotic stress tolerance benefits described by Chaudhary et al. (2022) [4]. It is worth noting, however, that the

mechanisms by which biofertilizers reduce water consumption are less directly documented than their nutritional benefits, since several of the reviewed studies report water-related outcomes as a secondary rather than primary finding [3; 10; 11]. This has implications for how confidently practitioners should attribute observed water savings to biofertilizer use specifically, as opposed to associated changes in soil management that often accompany biofertilizer adoption.

Humic substances occupy a comparatively lower position in the illustrative ranking, not because the underlying mechanisms are weak, but because the available evidence more often addresses soil structure and nutrient availability than water consumption directly [3; 11]. Maffia et al. (2025) frame humic substances primarily through an ecological lens, and while the soil aggregation and cation exchange improvements they describe are plausibly linked to water retention, the studies reviewed here do not always quantify that link with the same precision as the deficit-irrigation and automated-fertigation literature [11]. This is a methodological gap rather than evidence against humic substances as a water-saving tool, and it points to an area where the field methodology described by Kolomiiets et al. (2019) could be directly applied to close the gap [8].

The Meteorological Adaptation domain shows the greatest variability across the reviewed studies, which is expected given that the underlying research spans Mediterranean rainfed systems [6], arid irrigated systems in the Gulf region [1], and semi-arid conditions in South Asia [9] and North Africa [7]. This variability is a genuine limitation of any cross-study synthesis, including the one presented here, since meteorological conditions interact with both crop physiology and irrigation management in ways that are difficult to normalize across such different contexts. IBWOF treats this variability as a domain to be scored rather than a confound to be eliminated, on the grounds that adaptive agrotechnology needs tools that remain informative under heterogeneous climate conditions, though future applications of the framework would benefit from region-specific calibration.

The finding by Raderschall et al. (2021) that water stress interacts with insect herbivory to reduce yield, even as pollination benefits remain stable, is a reminder that water consumption cannot be optimized in isolation from the broader biotic stress environment [13]. IBWOF, as currently specified, does not include a biotic stress domain, and this is a limitation worth addressing in future refinements of the framework, particularly for crops or regions where herbivory pressure is a significant yield constraint.

A further limitation concerns the illustrative nature of the WBOI scores presented in Table 3. Because this paper synthesizes reported ranges from fifteen published studies rather than conducting a new field trial, the composite scores should be read as a demonstration of how the framework aggregates evidence, not as a validated empirical result. Applying IBWOF to a specific crop, region, and fertilization system would require primary data collected according to a methodology consistent with that described by Kolomiiets et al. (2019) [8], with replication and statistical treatment consistent with the standards outlined by Patil et al. (2026) [12]. This is precisely the kind of practical application the framework is intended to support, combining an institute-level field methodology for measuring water consumption with a biopreparation-focused technology, such as an automated dosing or humic-reactor system, that operationalizes the biological interventions reviewed above.

Despite these limitations, the broader pattern across the literature, that biopreparations can reduce water consumption per unit yield without a proportional loss in productivity, appears reasonably robust across crop types, climates, and biopreparation categories. This supports the case for integrating biopreparation strategies into adaptive agrotechnology planning as climate variability continues to affect water availability for agriculture.

Conclusions. This paper has examined the evidence for biopreparations, including humic substances, microbial biofertilizers, and combined biostimulant-automation systems, as tools for reducing crop water consumption without sacrificing yield. It has proposed the Integrated Biostimulant Water Optimization Framework (IBWOF) as a structured way to organize this evidence across four weighted domains, aggregated into a Water-Bioproductivity Optimization Index (WBOI). The illustrative application of the framework suggests that combined biological and automated technological interventions offer the largest and most consistent water-saving benefits among the categories reviewed, followed by microbial biofertilizers, physical deficit-irrigation strategies, and humic substances, though this ranking should be treated as indicative rather than definitive given its literature-based construction.

The practical value of IBWOF lies less in the specific scores generated here and more in the structure it offers: a consistent way to compare biopreparation strategies against water consumption, meteorological conditions, and fertilization systems, built on a field methodology already established for studying crop water consumption. Future research applying this framework to primary field data, following established replication and statistical standards, would allow the illustrative rankings presented here to be tested directly, and would support the development of region-specific agrotechnology recommendations for a changing climate.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

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TECHNICAL DEPLOYMENT OF CABLE-BASED TELECOMMUNICATIONS INFRASTRUCTURE IN HIGH-RISK ENVIRONMENTS

Summary. *This article provides a comprehensive analysis of the technical deployment of cable-based telecommunications infrastructure in high-risk environments within the United States under the conditions of 2026. This article examines the critical role of fiber-optic communication lines (FOCL) as a primary component of national resilience and social stability. The author explores the transition from traditional static installation methodologies to the concept of adaptive deployment, characterized by high architectural redundancy and the utilization of innovative materials, such as All-Dielectric Self-Supporting (ADSS) cables and Super-Absorbent Polymers (SAP) for dry-core water-blocking. The work details advanced installation techniques (HDD, micro-trenching, pneumatic blowing) and analyzes the transformation of passive networks into active sensory platforms through the integration of Distributed Acoustic Sensing (DAS) and Remote Fiber Test Systems (RFTS). Special attention is devoted to the convergence of resilient network architecture with predictive monitoring technologies, which enables infrastructure operators to detect vulnerabilities before they escalate into systemic failures. The study also emphasizes that the operational value of modern cable systems is determined not only by material durability, but also by their capacity to support rapid reconfiguration and recovery in unstable field conditions. Particular emphasis is placed on the role of the human factor – the concept of "field intelligence" is introduced and substantiated as a pivotal component in minimizing Mean Time to Repair (MTTR). Through a comparative analysis of operational responses in disrupted infrastructure environments, the superiority of applied heuristics over academic rigidity is demonstrated. The research provides a methodological framework for updating national resilience standards and formulating public-private partnership strategies within the FEMA and FCC protocols.*

Key words: *field intelligence, adaptive deployment, fiber optic lines, high-risk environments, telecommunications infrastructure.*

Introduction. Pursuant to Department of Homeland Security (DHS) directives, communications networks are classified as a critical infrastructure sector, upon which the functioning of emergency services, financial markets and government administration systems directly depends [1]. In the U.S. context, the term "high-risk zones" encompasses a broad spectrum of scenarios ranging from regions susceptible to regular natural cataclysms (such as Gulf Coast hurricanes or California wildfires) to zones of technological incidents and territories with extreme geographic conditions, where standard deployment methods prove ineffective.

Despite the proactive promotion of wireless technologies and satellite constellations, cable infrastructure, primarily fiber-optic communication lines (FOCL), remains the backbone of the American telecommunications ecosystem [2]. The implementation of federal initiatives, such as the BEAD (Broadband Equity, Access and Deployment) program, underscores the strategic priority of laying cable networks even in hard-to-reach and high-risk locations. However, the specificities of the American market, characterized by high field-work costs and stringent requirements for compliance with environmental and construction standards (OSHA and NEC regulations), serve as a predictor of the necessity to seek innovative engineering solutions for operations in disrupted or unstable environments [3].

It is essential to note that technical deployment in high-risk zones requires the theoretical conceptualization and practical implementation of new adaptive architectures characterized by resilience, stability, durability and safety. Overall, the U.S. experience in mitigating the consequences of events such as Hurricanes Ian or Katrina has demonstrated that the speed of communications restoration depends directly on preliminary network redundancy planning and the availability of mobile technical units equipped with specialized hardware. Scientific interest lies in the

analysis of how American resilience standards are integrated into field installation practices, when engineers are confronted with damaged communication corridors, a lack of primary power supply and the necessity of integrating temporary solutions into the existing national network.

A significant role in the decision-making architecture is occupied by the U.S. regulatory framework governing the activities of providers during emergency periods. The primary role here is played by interaction protocols between the Federal Communications Commission (FCC) and the Federal Emergency Management Agency (FEMA). The implementation of specialized reporting systems, such as DIRS (Disaster Information Reporting System), enables the real-time accumulation of data regarding the status of communication nodes and the coordination of restoration efforts at the federal level. This is a vital toolkit necessary for minimizing the consequences of systemic infrastructure failures and ensuring the uninterrupted operation of emergency services. Nevertheless, from an economic perspective, the design and deployment of cable systems in high-risk zones are dictated by the colossal cost of downtime. For American metropolises and technological clusters, every hour of communications absence correlates with multi-million dollar losses in regional GDP, rendering preventive investments in resilient infrastructure strategically justifiable. Technical solutions for line redundancy and the creation of hardened cable corridors are viewed here as a mechanism for hedging operational risks for the financial and industrial sectors of the U.S. economy.

Furthermore, the concept of cyber-physical security must be mentioned. In high-risk environments, physical layer (Layer 1) integrity becomes the first line of defense for the information space. Risks of unauthorized access, intentional sabotage or signal interception via damaged backbone sections explain the necessity of employing specialized real-time line integrity monitoring systems. The quality of field installation and the physical protection of cable systems directly correlate with the overall data resilience against external destructive impacts. A unique feature of the North American approach is the public-private partnership model in restoring critical communications. Since the bulk of the cable infrastructure is owned by private corporations (such as AT&T, Verizon or Comcast), its rapid deployment in crisis conditions is conducted within the framework of coordinated Emergency Support Function #2 (ESF #2) plans.

This symbiosis allows for the consolidation of the private sector's vast material and technical resources with the logistical and legal capabilities of government agencies, ensuring high deployment efficiency even in maximally destabilized environments.

Materials and methods. The relevance of this work is elucidated by the escalating vulnerability of the global digital infrastructure against the backdrop of increasingly frequent natural cataclysms and geopolitical instability. Under the conditions of 2026, where the socio-economic well-being of the United States depends directly on the continuity of data flows, traditional telecommunications deployment methods demonstrate inadequate relevance in high-risk scenarios. Despite the progress of satellite communications, fiber-optic backbones remain the uncontested foundation for 5G/6G networks and cloud computing. The research is particularly significant for the development of new resilience standards capable of minimizing colossal financial losses from network downtime and ensuring effective coordination of emergency services in conditions of partial or total destruction of primary infrastructure.

The scientific novelty of the study lies in the systemic reimagining of the role of cable infrastructure, as well as the substantiation of a passive transport medium being transformed into an active intelligent risk-monitoring system. For the first time, at the level of comprehensive analysis, the synergy of Distributed Acoustic Sensing (DAS) and Remote Fiber Test Systems (RFTS) technologies is considered as a baseline level of civil security.

The work proposes an original concept of adaptive deployment, which integrates into a single methodological stack innovative materials (nano-ceramic coatings, dry polymers) and operational decision-making methods (field intelligence). The novelty is also confirmed by the analysis of the integration of Augmented Reality (AR) systems and digital twins into disaster recovery processes, which previously lacked a deep systemic description within the context of North American engineering standards for 2025–2026.

The methodological base of this study relies on a comprehensive interdisciplinary analysis of engineering practices and technological solutions applied during the deployment of telecommunications infrastructure in high-risk environments within the United States in 2026. A systemic approach is laid at the foundation of the work, combining the study of the current regulatory and legal framework (DHS directives, FCC and FEMA protocols), technical analysis of modern materials and the evaluation of the effectiveness of field installation methods [4]. The research is based on the synthesis of theoretical resilience models and empirical data obtained during the mitigation of the consequences of large-scale natural and technological disasters, such as hurricanes in the Atlantic region and wildfires on the West Coast.

The material part of the study includes a detailed analysis of specialized communication equipment and ruggedized cable structures. Primary focus is placed on fiber-optic communication lines (FOCL) utilizing All-Dielectric Self-Supporting (ADSS) cables, tactical cables in a thermoplastic polyurethane (TPU) jacket and innovative systems with dry water-blocking based on Super-Absorbent Polymers (SAP). The technical

toolkit is examined through the prism of utilizing high-precision fusion splicers with IP67 protection (Fujikura 90S+ series), modular Remote Fiber Test Systems (OTDR) (EXFO and VIAVI platforms) and Augmented Reality (AR) systems for the visualization of concealed underground utilities.

The design methodology within the framework of this work considers the necessity of utilizing highly redundant hierarchical models, including the Core, middle mile and access layers. As the primary method for ensuring reliability, topological redundancy (ring and mesh architectures), the dual-homing methodology and the path diversity concept are analyzed. These methods are evaluated by the criterion of ensuring a network availability coefficient at the level of five nines (99.999%) under conditions of dynamic landscape destabilization. Regarding practical deployment, methods of Horizontal Directional Drilling (HDD), micro-trenching and pneumatic fiber blowing are investigated.

The effectiveness of these technologies is compared with the use of robotic mapping systems based on Ground Penetrating Radar (GPR) and predictive monitoring systems (RFTS and DAS) [5]. A special place is occupied by the analysis of the integration of Geographic Information Systems (Esri ArcGIS) and digital twins for the verification of design data in zones of large-scale destruction, where traditional navigation and communication node identification methods prove ineffective. The concluding methodological stage is an analytical comparison of operational response models of technical personnel. Using the method of comparative analysis of specialist actions in critical failure conditions (exemplified by the mitigation of Hurricane Ian's consequences), a correlation is identified between the level of applied heuristics and the Mean Time to Repair (MTTR). The study emphasizes the importance of personnel qualification alignment with BICSI and FOA standards in combination with psychological readiness for adopting non-standard engineering solutions within the framework of public-private partnerships and ESF #2 emergency response plans.

Despite the comprehensive approach, this study has several limitations necessitated by its narrow geographical and regulatory specificity. Primary emphasis is placed on the regulatory and technical framework of the United States (OSHA, NESC, ANSI/TIA), which may restrict the direct applicability of findings in regions with differing legal and construction standards [6]. Furthermore, the effectiveness analysis of the latest technologies, such as RUSS robotic systems or quantum-secured temporary lines, relies on data from short-term field trials and pilot projects of 2025, which does not allow for a full assessment of their long-term operational reliability. Finally, the evaluation of "field intelligence" as a success factor is qualitative in nature and is difficult to subject to rigorous mathematical quantification due to the uniqueness of each crisis scenario.

Physical architecture of cable-based telecommunications networks. The physical architecture of cable networks deployed in high-risk zones within the United States is based on a fundamentally hierarchical model, partitioning the infrastructure into three key segments: the backbone core (core/backbone), the distribution layer (distribution/middle mile) and the access layer (access/last mile). In an environment of potential landscape instability or the threat of mechanical damage, such stratification allows for the isolation of local failures, preventing a cascading collapse of the entire communication system [7]. In North American practice, the backbone layer is designed with maximum geographical diversification, where critical communication nodes — namely central offices (CO) and points of presence (PoP) are situated in seismic-resistant or flood-protected zones compliant with Telcordia and NEBS standards (see: Figure 1. The three-level hierarchy diagram).

A fundamental factor of architectural resilience in high-risk environments is topological redundancy. Unlike classic radial schemes ("star" configuration), which are characterized by the presence of critical points of failure, priority in risk zones is given to ring and mesh topologies [8]. A ring architecture with automatic protection switching protocols enables the instantaneous rerouting of traffic in the event of a cable break in one of the sections. In the most critical segments of U.S. infrastructure, the dual-homing concept is applied, in which each distribution node has a physical connection to two independent backbone hubs, ensuring a network availability coefficient at the five nines level (99.999%) even in the presence of severe damage to one of the directions (see: Figure 2. Redundancy comparison).

A vital aspect of physical architecture is the path diversity methodology [9]. Under high-risk conditions, such as seismically active areas of the West Coast or hurricane corridors of the Atlantic, engineering standards necessitate that primary and redundant cables be routed through different cable conduits or along diverse geographical paths with a minimum allowable separation distance. This precludes the risk of simultaneous destruction of both communication channels as a result of a single localized event (a singular landslide, power line pole collapse or bridge destruction). Concurrently, the resource of dark fiber — pre-installed, but non-activated optical capacities is actively utilized, which can be operationalized promptly upon damage to the primary backbones. The concluding element of the architectural design is the physical hardening of node points and the use of protected terminal equipment. In high-risk zones, the architecture incorporates modular container solutions and hardened cabinets equipped with autonomous power supply and climate control systems. These elements function as network anchor points, ensuring the stable operation of active equipment under aggressive environmental conditions.

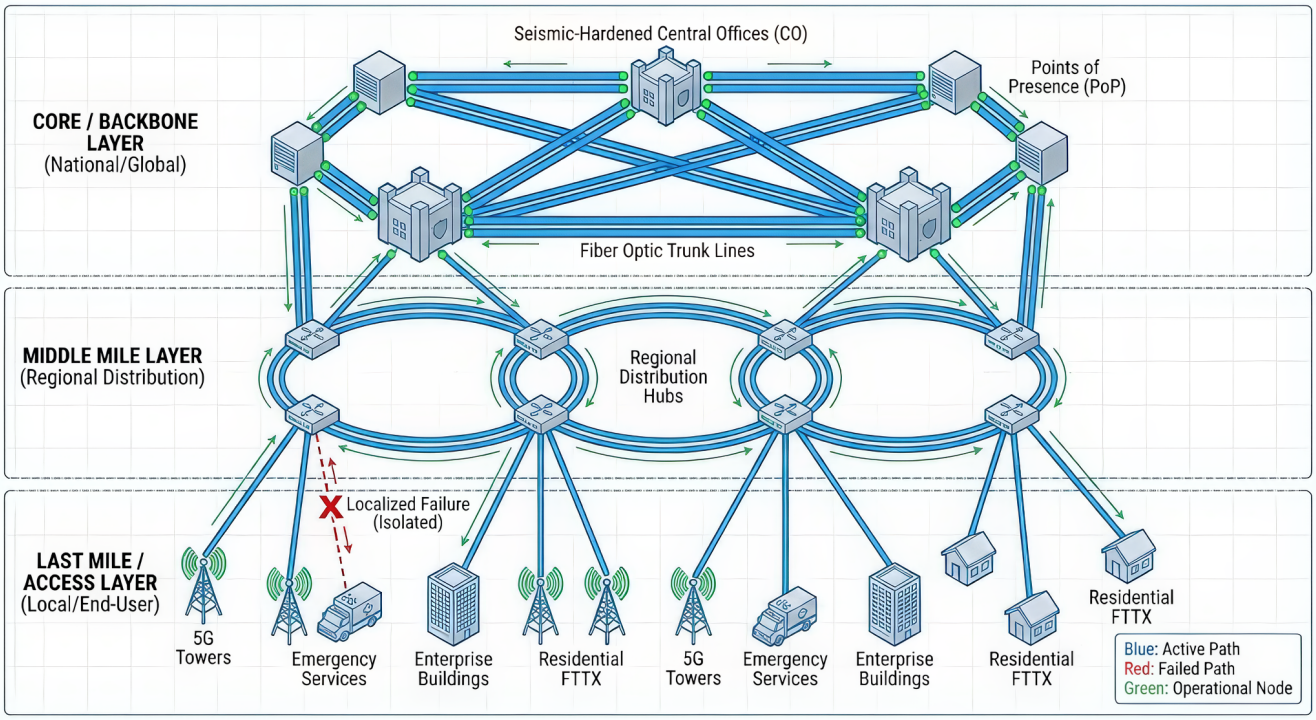


Fig. 1. The three-level hierarchy diagram

It is evidently clear that the integration of North American design standards, such as ANSI/TIA-758 (Customer-Owned Outside Plant Telecommunications Infrastructure), is a mandatory prerequisite for ensuring network reliability in all high-risk zones. These regulations, alongside BICSI recommendations for Outside Plant (OSP) design, define stringent requirements for the physical protection of infrastructure against seismic impacts, critical wind loads and extreme temperature fluctuations. Adherence to these standards guarantees that architectural solutions possess the requisite margin of safety, allowing the system to maintain structural integrity even during significant soil mechanical

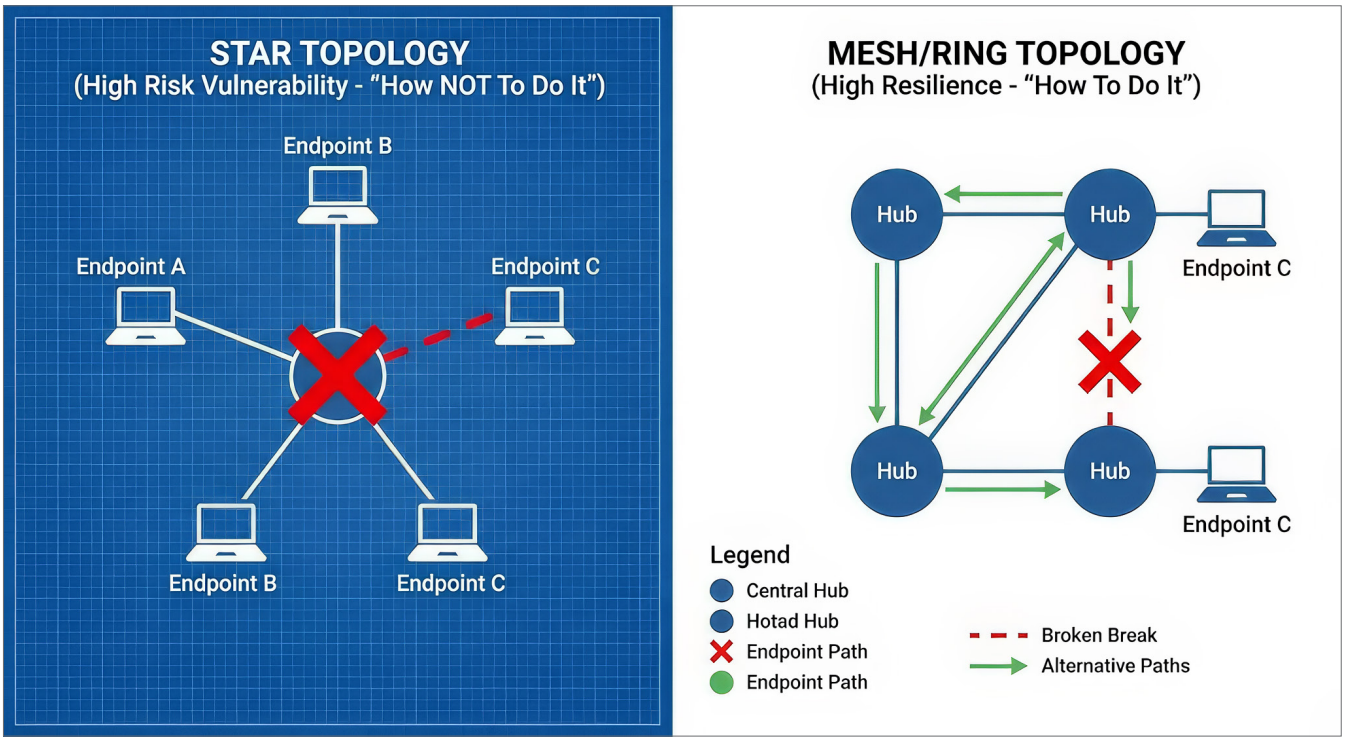


Fig. 2. Redundancy comparison

deformations or the destruction of adjacent engineering facilities.

Architectural resilience in modern U.S. networks is inextricably linked to the implementation of advanced Remote Fiber Test Systems (RFTS). The use of stationary intelligent modules based on Optical Time-Domain Reflectometry (OTDR), integrated directly into the physical layer of the network, allows for the realization of a predictive monitoring model. In high-risk environments, this provides for the rapid detection of signal degradation at early stages. For instance, as a result of cable tensioning or the emergence of micro-bends prior to the actual line break, operators will be apprised and able to prevent failure with all the attendant consequences. Such digital transparency of the architecture is essential for a radical reduction in Mean Time to Repair (MTTR), enabling technical services to localize the damage site with meter-level precision in real-time.

Furthermore, within the context of contemporary technological trends, the physical architecture of cable networks in risk zones is increasingly designed as a convergent platform serving as a foundation for wireless solutions. Since in the setting of large-scale disasters, mobile communications often serve as the primary and sole channel for coordinating rescue operations, cable infrastructure must provide a redundant transport layer (backhaul) for 5G stations and temporary communication nodes. Designing architecture with a high density of optical fiber access points (Fiber-to-the-Tower) allows for the rapid deployment of mobile network segments, creating a flexible and resilient ecosystem capable of adapting to dynamically changing traffic requirements in crisis situations.

Installation techniques for underground and aerial cable systems + 4 case study:

In American engineering practice, the selection between underground and aerial installation methods in high-risk zones is determined by a balance between deployment cost, restoration speed and resilience requirements. Underground laying remains a priority for backbone channels in regions with a high probability of hurricanes and wildfires, where the risk of aerial infrastructure destruction outweighs excavation costs. The leading technology here is Horizontal Directional Drilling (HDD), which facilitates trenchless installation at substantial depths, bypassing existing obstacles such as highways, water bodies and subway lines [10]. According to market data, the HDD segment in the U.S. demonstrates stable growth (CAGR of approximately 11–12%), justified by stringent environmental regulations and the necessity to minimize urban infrastructure disruption during network modernization.

Concurrent with deep drilling, micro-trenching technology is being actively implemented in American metropolises. This method involves creating narrow (up to 2 inches) and shallow (up to 24 inches) slits in the roadway or sidewalk with immediate microduct placement and subsequent sealing. The experience of companies such as Google Fiber has confirmed the high economic efficiency of this approach. Deployment speed increases multifold, while surface restoration costs decrease by 30–50% [11]. However, in high-risk zones prone to seasonal frost heave or intensive

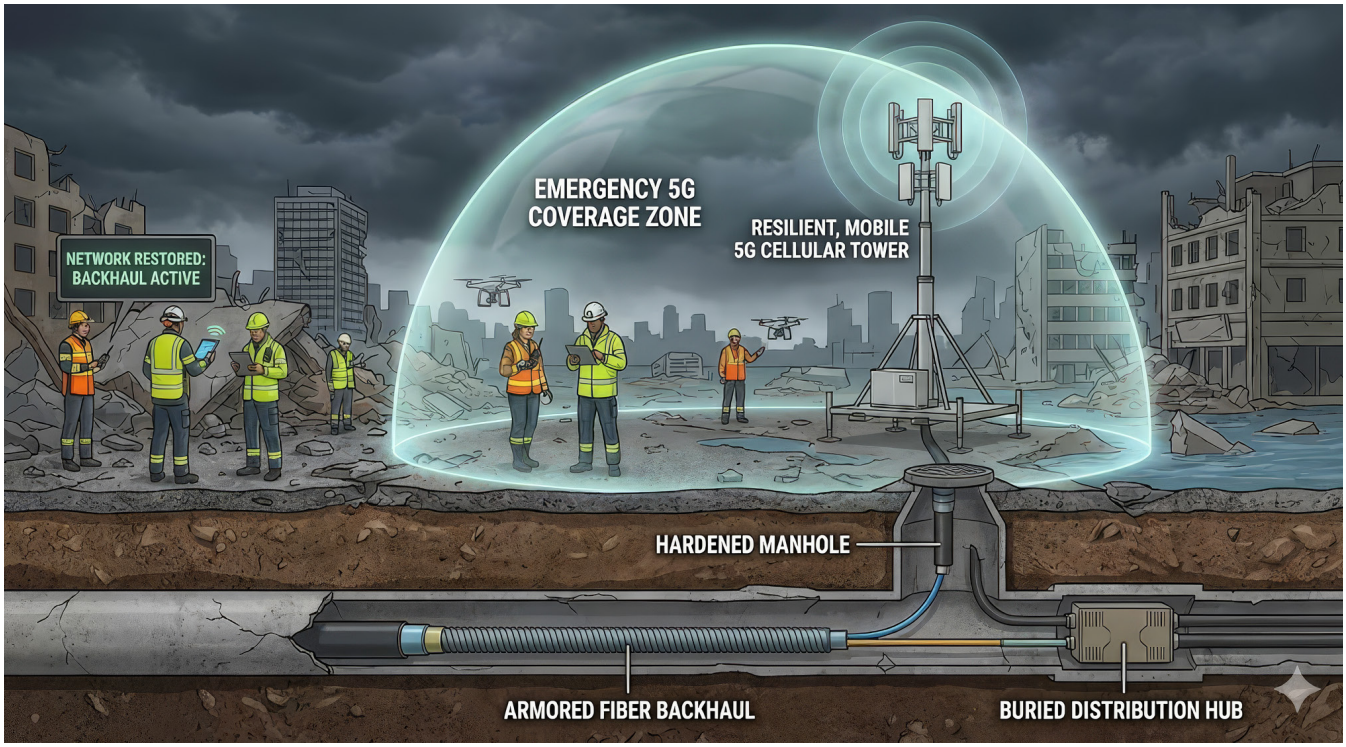


Fig. 3. Platform Fiber-to-the-Tower

roadwork, micro-trenching necessitates the use of specialized armored cables capable of withstanding elevated mechanical loads at shallow depths.

Aerial communication systems in the U.S. are also at a methodological and technological crossroads due to the ubiquitous implementation of All-Dielectric Self-Supporting (ADSS) cable [12]. Unlike conventional cables with a metallic messenger wire, ADSS requires no grounding and possesses absolute immunity to electromagnetic interference, permitting its installation in close proximity to high-voltage power lines (up to 500 kV) (Figure 4. Engineering process diagrams). In the storm zones of the Atlantic coast, the use of ADSS in conjunction with aramid reinforcement (Kevlar) ensures network survivability under critical wind loads and icing. Furthermore, a strict joint-use pole standard exists in the U.S., regulated by NESC (National Electrical Safety Code) norms, which mandates that technical specialists conduct detailed static load calculations for each pole prior to installation.

It is essential to highlight an innovative trend that has gained widespread adoption in the U.S. in 2025–2026 — the active use of pneumatic installation (fiber blowing technology) [13]. The use of compressed air to move microcables within pre-installed HDPE conduits minimizes mechanical fiber tension, which is critically important for preserving optical properties over long distances. Moreover, even robotic underground utility mapping systems based on Ground Penetrating Radar (GPR), such as the RUSS (Robotic Underground Survey System), are increasingly applied in high-risk zones. These robots facilitate the creation of high-precision real-time 3D models of underground space, eliminating the risk of accidental damage to existing gas or power mains during the deployment process. A vital aspect of American practice is the utilization of pre-connectorized solutions, which minimize the volume of field fiber splicing in extreme conditions. The use of factory-terminated assemblies and hardened distribution hubs (Clearfield's FieldSmart series) allows FEMA technical crews and private operators to restore communications in disaster zones within hours rather than days.

Analysis of the practical experience of network deployment in the U.S. permits the identification of several unique technological case studies that are currently considered primary in global engineering practice. These examples illustrate the transition from passive data transmission to the creation of adaptive and multifunctional infrastructure assets.

Case 1: California — transforming telecommunications fiber into a sensory network (DAS).

In the seismically active and fire-prone zones of California, a unique project has been realized utilizing existing fiber-optic lines as Distributed Acoustic Sensing (DAS) sensors. The technology, piloted by researchers from Berkeley and Stanford, permits the use of dark fiber as a gargantuan network of seismographs and thermal sensors. Laser pulses traversing the cable react to minute soil vibrations or temperature changes caused by fire ignition sources. This project represents a significant early-stage implementation of transforming standard civilian communications infrastructure into an early warning system for earthquakes and wildfires with localization accuracy within several meters, radically reducing emergency service response times even before 9–1–1 calls are received [14].

Case 2: Alaska — arctic resilience and thermal protection (the Quintillion project).

During the deployment of the first-ever Arctic fiber-optic network in Alaska, Quintillion applied innovative protection methods under permafrost and ice impact

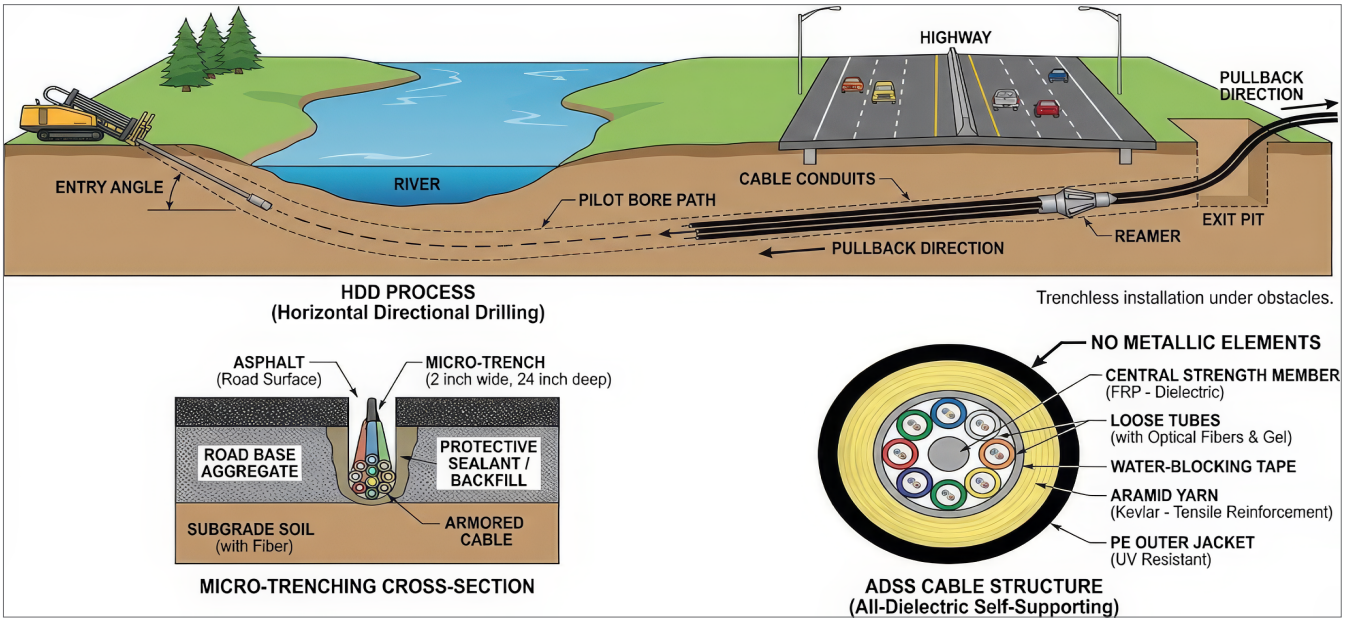


Fig. 4. Engineering process diagrams

conditions. The project's uniqueness lies in the use of armored cables buried 3.5 meters below the seabed for protection against ice scouring. For the first time in global practice, the technology of filling cable conduits with a salt brine solution possessing a negative freezing temperature was utilized for shore landings in frozen ground. This solution prevented cable entrapment by ice within the pipe, ensuring the possibility of its replacement or repair even at extreme temperatures of –45 °C, becoming a benchmark for Arctic engineering [15].

Case 3: Maui — evidence base for underground hardening in wildfire conditions.

The catastrophic wildfire events on the island of Maui in 2023 served as the first large-scale field test for modern underground deployment standards. While aerial communication lines and satellite terminals were disabled by fire and smoke, the Hawaiian Telcom network, built on hardened underground cable conduits, remained fully operational. This case demonstrated to the global engineering community that investments in deep infrastructure burial and the use of heat-resistant sealants in cable manholes are critical factors for communication survivability in thermal risk zones. This experience formed the basis for new FEMA recommendations on network restoration in the U.S. [16].

Case 4: Nationwide deployment — fiber-tethered drones.

One of the most futuristic solutions implemented in U.S. disaster zones is the use of unmanned aerial vehicles connected to a ground station via a thin fiber-optic cable. In environments where the radio frequency spectrum is congested with interference or blocked (GPS-denied environments), such drones provide a reliable communication channel with a bandwidth of up to 10 Gbps. This allows for the transmission of ultra-high-definition video streams and thermal imager data in real-time without the risk of radio interception or signal loss. The application of such systems in technological debris zones in the U.S. became the first example of hybrid deployment, where the cable ensures the last mile of communication in the air, guaranteeing absolute noise immunity [17].

Currently, the installation technology stack in the U.S. is evolving toward automation, modularity and the use of intelligent monitoring tools, rendering cable infrastructure maximally adapted to high-risk challenges.

Technical challenges of deployment in disrupted or damaged environments:

The deployment and restoration of cable infrastructure in disrupted or damaged environments constitutes one of the most formidable engineering tasks, where standard design regulations confront the factor of operational uncertainty. In large-scale disaster zones within the U.S. territory, the primary technical challenge is the critical degradation of the landscape and the loss of traditional landmarks. The destruction of buildings, soil displacement and debris from construction waste render existing utility maps irrelevant. Under such conditions, engineers face the severed path problem, where underground cable conduits are either crushed under the weight of debris or silted with aggressive

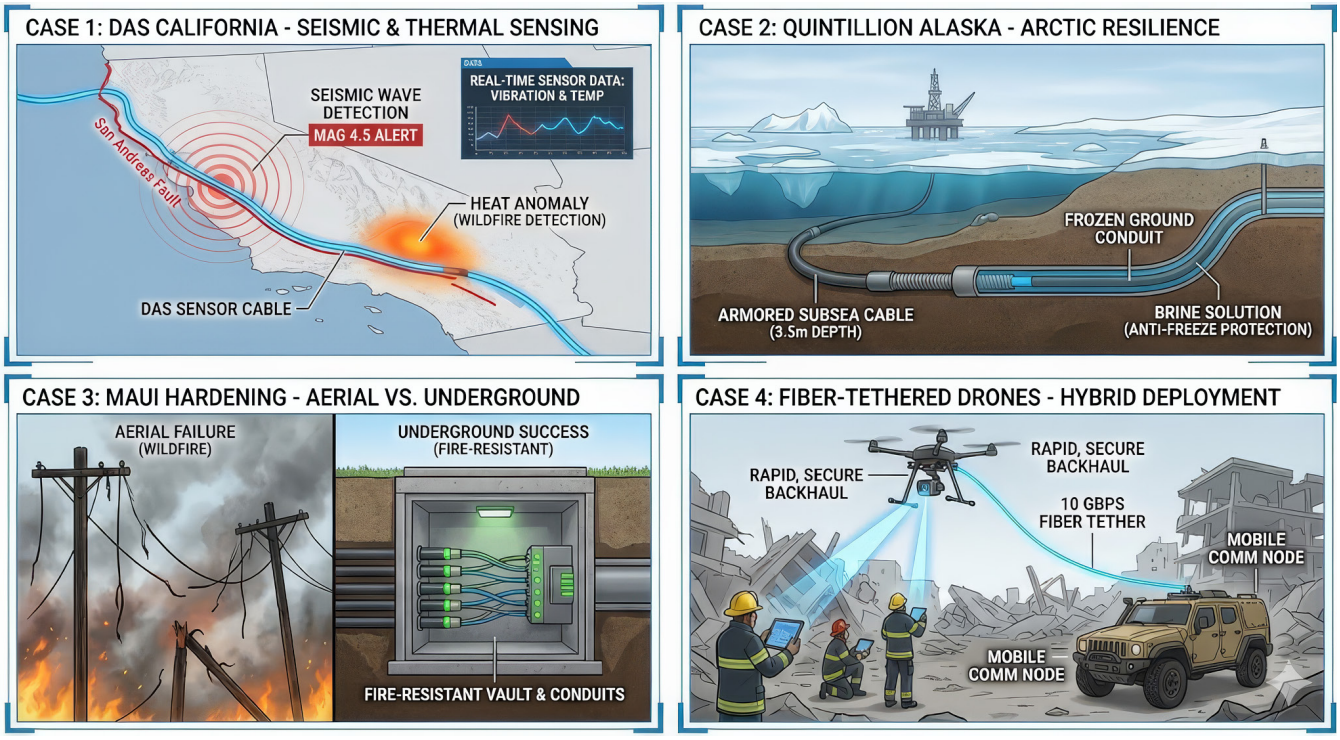


Fig. 5. Case study visuals. Generative artificial intelligence was used to create the image

deposits resulting from flooding, necessitating a complete real-time re-routing of lines [18].

Environmental and chemical aggression of the external medium in disaster zones imposes additional constraints on the selection of materials and installation technologies. In industrial accidents or large-scale flooding, soil and water may contain high concentrations of petroleum products, acids or salts, which accelerate the corrosion of cable reinforcing elements and destroy polymer jackets. The asterisked technical task here lies in the necessity to ensure the hermeticity of splice closures and distribution cabinets under conditions of excess hydrostatic pressure. Furthermore, thermal impact in wildfire zones often leads to the deformation of high-density polyethylene (HDPE) microducts within which the cable is laid, transforming them into a monolithic mass and precluding fiber replacement via the blowing method without conducting large-scale excavation works.

A significant technical barrier is the deficit of energy resources and the instability of the electromagnetic environment. Field deployment necessitates the use of high-precision equipment (fusion splicers for FOCL and optical reflectometers), the operation of which depends directly on a stable power supply. During power grid failures, engineers must deploy autonomous power systems based on hydrogen fuel cells or high-capacity lithium iron phosphate (LiFePO4) batteries, which complicates logistics and increases the weight of portable gear (see: Figure 6. Autonomous power schematic) [19]. Simultaneously, damaged power lines located in the immediate vicinity of the work sites can generate powerful electromagnetic interference and transients, posing a threat both to the sensitive electronics of telecommunications nodes and to the safety of the personnel themselves.

Logistical inaccessibility and the risk of recurrent destruction are the primary reasons for selecting adaptive temporary architectures. The main complexity lies in creating temporary aerial bridges or surface communication lines, which must possess sufficient mechanical strength to withstand ongoing aftershocks, wind loads or the movement of heavy rescue equipment. In U.S. practice, this is frequently resolved by utilizing so-called tactical cables in a polyurethane jacket with enhanced crush resistance. However, the integration of such temporary segments into the surviving backbone network requires complex calibration of attenuation and dispersion parameters, which, in a situation of acute time deficit, becomes a severe trial for the qualification of technical personnel.

One of the most effective strategies for overcoming uncertainty in destruction zones is the utilization of Geographic Information Systems (GIS) and the concept of infrastructure digital twins. In the U.S., platforms such as Esri ArcGIS allow field crews to overlay current aerial photography or satellite monitoring data onto archived cable routing maps (see: Figure 7. Digital Twin and GIS overlay visualization) [20]. This is essential for identifying the location of manholes and distribution nodes buried under debris. The complexity here lies in the necessity to ensure uninterrupted data synchronization between field tablets and a central cloud repository under low-bandwidth communication

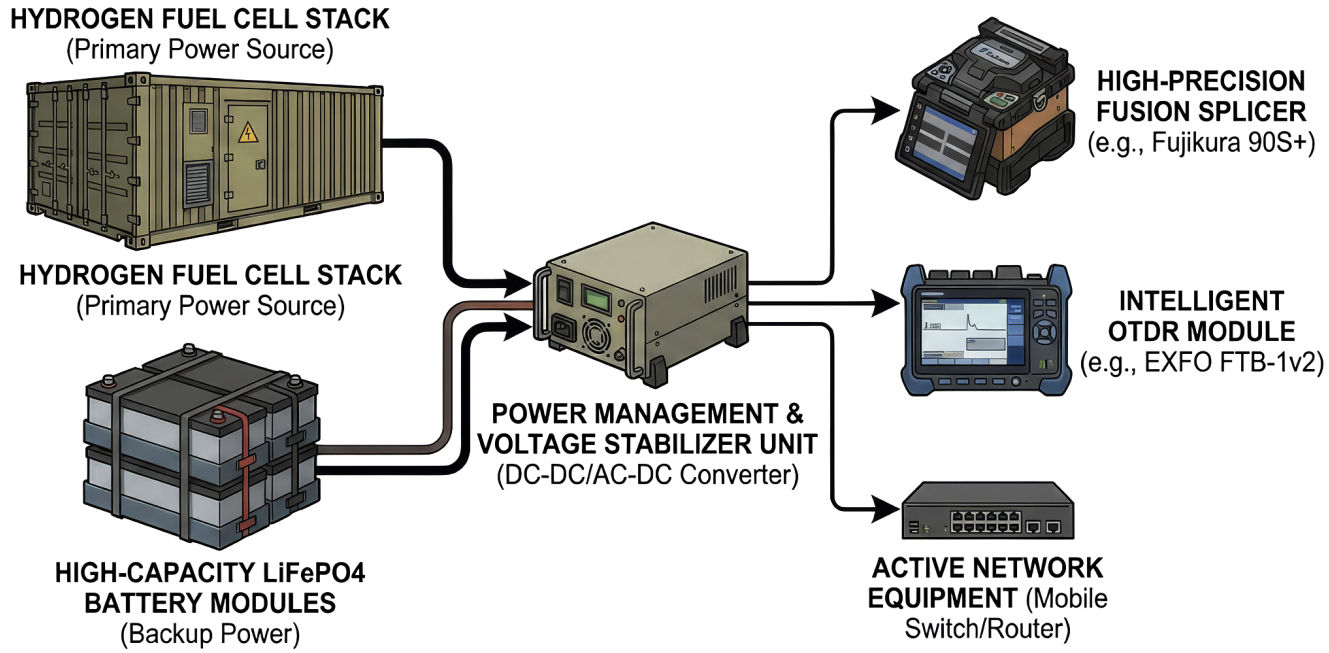


Fig. 6. Autonomous power schematic

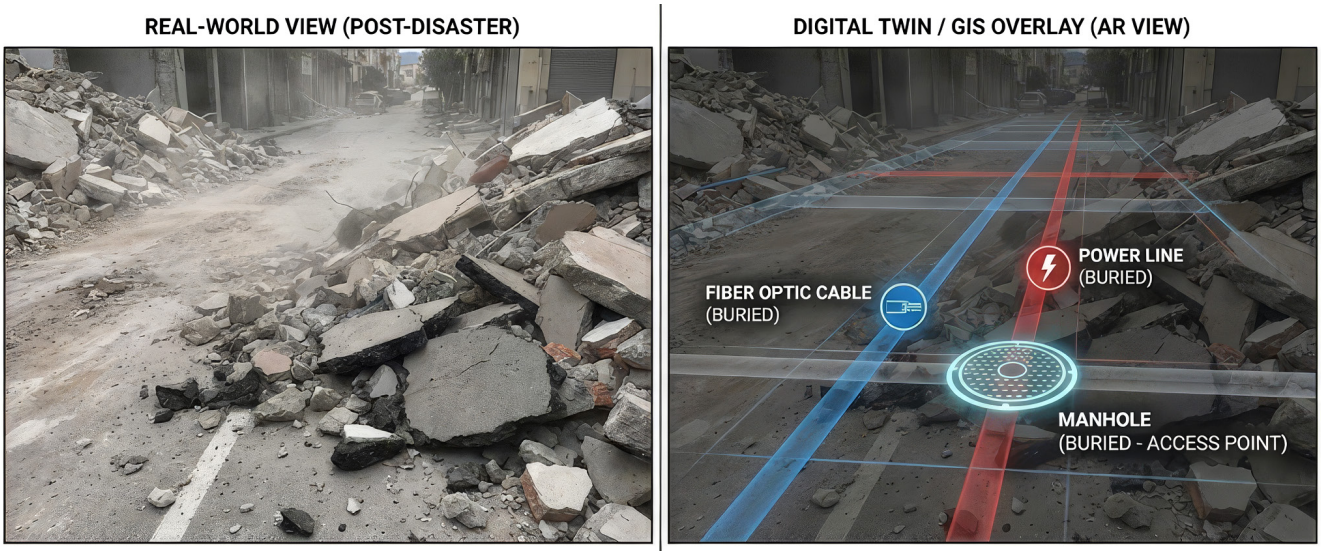


Fig. 7. Digital Twin and GIS overlay visualization

channel conditions, requiring the implementation of efficient geospatial data compression algorithms.

In high-risk environments, technical deployment faces the threat of physical layer network compromise. The deployment of temporary cable lines over the surface or through open apertures renders the infrastructure vulnerable to intentional sabotage or unauthorized tapping. In American practice for restoration work in conflict zones or large-scale unrest, engineers must integrate physical-layer Intrusion Detection Systems (IDS) into the architecture of temporary nodes, reacting to changes in optical fiber backscatter parameters [21]. This transforms the task of simple communication restoration into a complex operation for ensuring the information security of a critical infrastructure segment.

Nevertheless, the technical complexity of work in a damaged environment is inextricably linked to extreme risks to the life and health of specialists. In the U.S., cable network restoration work is strictly regulated by OSHA (Occupational Safety and Health Administration) standards, particularly Section 1910.268 (Telecommunications) (see: Figure 8. OSHA safety + PPE checklist). The primary challenge is the necessity to adhere to safety protocols during work in trenches (risk of cave-ins), in confined spaces (accumulation of toxic gases in manholes after floods) and near damaged power lines. The requirement to use cumbersome

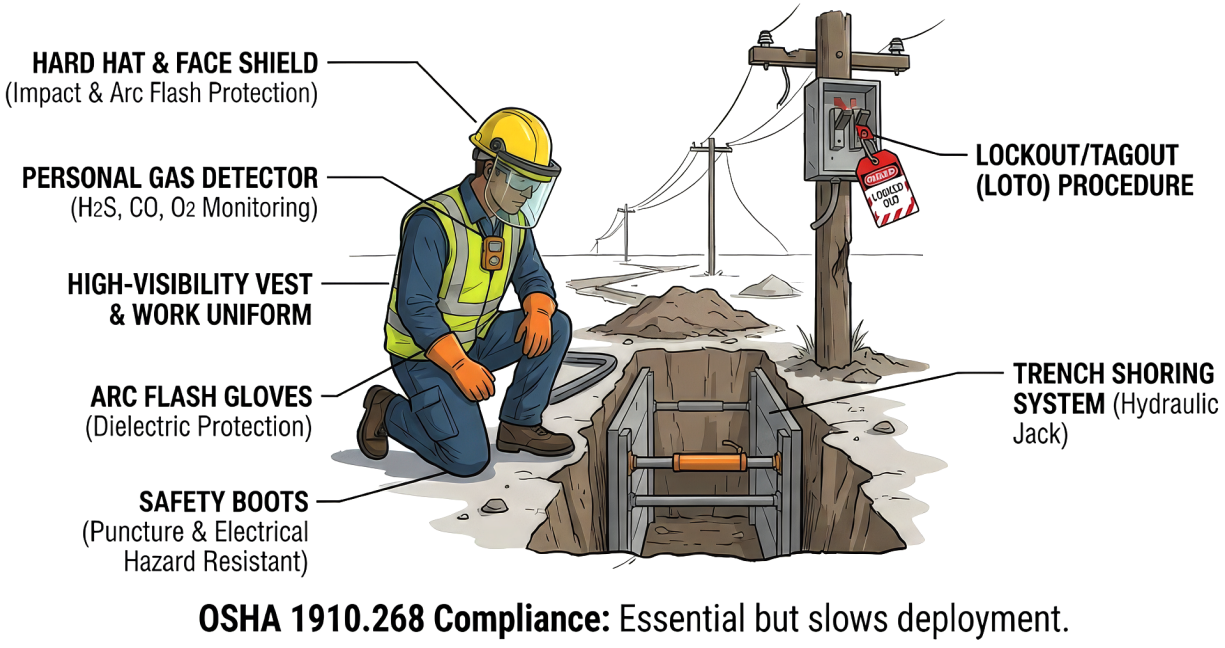


Fig. 8. OSHA safety + PPE checklist

Personal Protective Equipment (PPE) and adhere to "lockout/tagout" procedures significantly slows the deployment process, creating a conflict between communication restoration speed and operator safety.

Equipment, tools and materials used in field-level cable installation:

The technical repertoire for deploying cable systems in U.S. high-risk zones constitutes a symbiosis of precision instrumentation and ultra-durable materials adapted for operation in aggressive external environments. The primary components of field equipment are specialized fiber-optic fusion splicers, such as the Fujikura 90S+ or Sumitomo Type-Q102-CA+ series. These devices feature IP52/IP67 ingress protection, enabling splicing in conditions of extreme humidity, dust concentration and over a broad temperature range [22]. Additionally, wireless-controlled automatic precision cleavers are utilized to minimize human factor impact and ensure the ideal cleave angle necessary for mitigating attenuation in critical network nodes.

For field-level characterization and certification of lines, the U.S. standard involves modular intelligent Optical Time-Domain Reflectometers (OTDR), such as the EXFO FTB-1v2 or VIAVI MTS-4000 platforms. In high-risk scenarios, these instruments are integrated with cloud-based solutions for instantaneous measurement data transmission to the central Network Operations Center (NOC). A significant innovative tool is the fiber inspection probe (video microscope) featuring automated "pass/fail" analysis in accordance with the IEC 61300–3–35 standard. In environments with debris and high atmospheric contamination, the availability of such tools is critical, as even a microscopic dust particle on the fiber end-face can lead to connector burnout and backbone failure during high-power laser signal transmission.

The material components of deployment are based on specialized cable designs. In the U.S., priority for rapid communications restoration is given to tactical fiber-optic cables with a thermoplastic polyurethane (TPU) outer jacket. Such cabling possesses exceptional resilience to crushing, abrasion and cyclic bending, permitting its installation directly on the ground surface in areas of heavy equipment movement. For permanent infrastructure hardening, cables featuring corrugated steel tape armoring or dielectric aramid strength members are employed, providing protection against rodent damage and mechanical stresses during soil strata displacement.The final component of the material and technical provision comprises autonomous power systems and mobile switching nodes. In U.S. field communications practice, portable lithium iron phosphate (LiFePO4) power stations are actively employed, capable of sustaining active equipment and measurement instruments for 24–48 hours. For protecting connections in flooded zones, hermetic splice closures and distribution hubs with pressure relief valves are utilized, having undergone deep-immersion testing according to Telcordia GR-771-CORE standards. This complex of equipment and materials enables technical specialists to establish "communication islands" even under conditions of total isolation from centralized infrastructure.

A core factor in reducing communications restoration time in disaster zones is the use of modular pre-connectorized systems. Solutions based on MPO/MTP multifiber connectors and hardened connectors, such as Corning OptiTap or CommScope DLX, are becoming the de facto standard in the U.S. These components allow technical personnel to perform hot-swappable connections of distribution nodes via Plug-and-Play principles without the use of fusion splicing equipment in conditions of high humidity or gas contamination. The use of factory-terminated assemblies guarantees stable parameters of insertion loss (IL < 0.3 dB) and eliminates installation errors, which is pertinent during the deployment of temporary network segments under acute time deficits.

Modern field engineering toolsets in the U.S. increasingly include wearable Augmented Reality (AR) devices, such as industrial-grade Microsoft HoloLens 2 headsets. The utilization of AR interfaces permits the overlay of 3D cable routing models and switching diagrams directly onto the physical landscape or the internal space of a distribution cabinet. This provides genuine "X-ray vision", enabling the visualization of communications concealed beneath the soil or debris based on GIS data (see: Figure 9. Augmented reality and monitoring (AR and monitoring) technologies). Furthermore, "Remote expert" support systems allow less experienced technicians in the field to receive real-time video instructions and annotations from lead engineers at central headquarters, radically improving installation quality in stressful conditions.

In the sphere of materials for high-risk zones, there is a shift away from traditional hydrophobic thixotropic gels in favor of dry-core water-blocking technologies based on Super-Absorbent Polymers (SAP) [23]. Dry-core cables are lighter, cleaner during installation and do not require the use of solvents for fiber cleaning, which is particularly relevant in field conditions. Additionally, cables with outer jackets treated with nano-ceramic functional coatings are being actively implemented in the U.S., providing enhanced resistance to abrasive wear and exposure to open flames. These innovative materials allow cable infrastructure to withstand short-term thermal excursions and mechanical impacts from debris, preserving the operability of critical data transmission channels.

The role of technician expertise in ensuring installation quality and reliability + comparative model of operational response. In the U.S., the standardization of competencies is strictly regulated by organizations such as BICSI (Building Industry Consulting Service International) and the FOA (Fiber Optic Association). Possession of certifications such

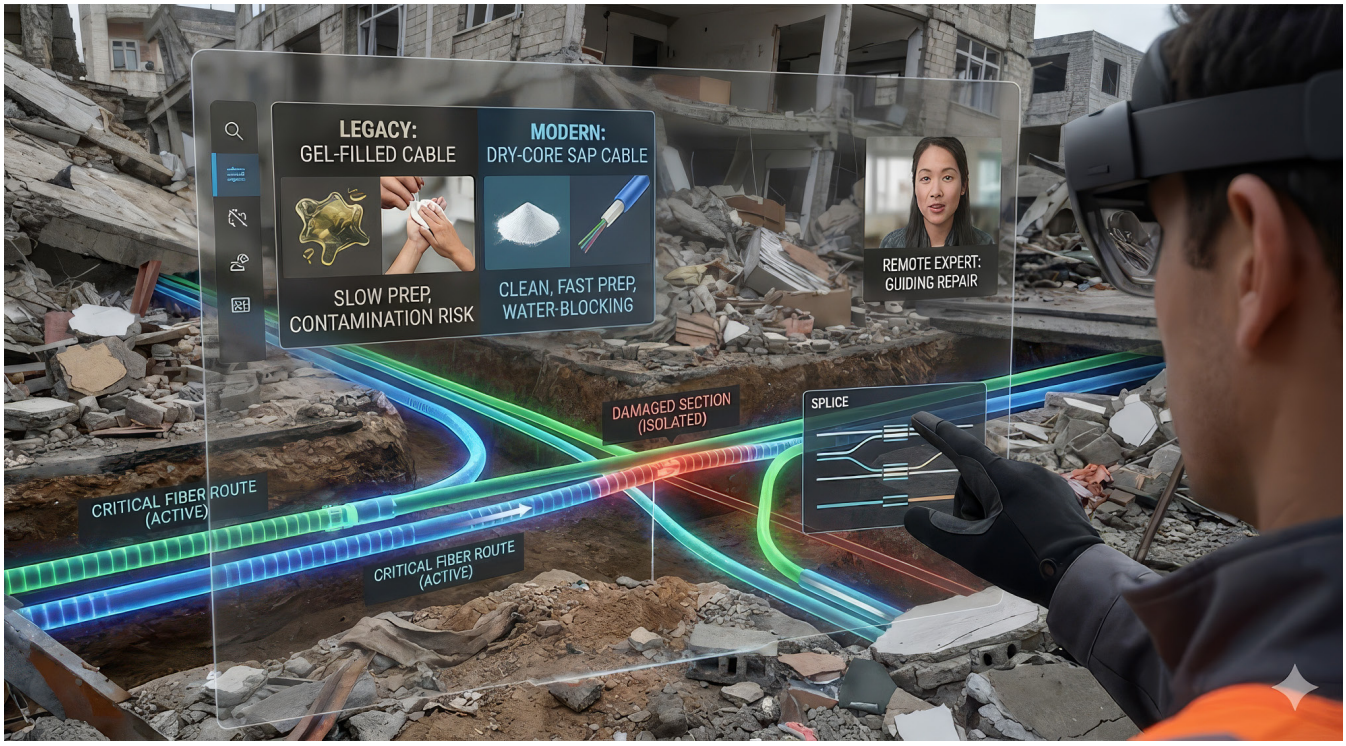


Fig. 9. Augmented reality and monitoring (AR and monitoring) technologies

as RCDD (Registered Communications Distribution Designer) or CFOT (Certified Fiber Optic Technician) is a mandatory requirement for working at critical infrastructure sites [24]. However, under extreme conditions, theoretical knowledge is undoubtedly insufficient. A specialist's expertise is manifested in the ability to strictly adhere to the technical process cycle (bend radius control, connector cleanliness, burial depth) amidst stress, time deficits and physical threats, where any deviation from protocol can lead to signal degradation across the entire backbone.

Particular significance in American engineering practice is accorded to the concept of Field Intelligence. In zones of large-scale destruction, when communication with the central Network Operations Center (NOC) may be temporarily severed, the field engineer assumes the role of a crisis manager. Expertise in this context includes the capacity to conduct instantaneous risk assessments and adopt non-standard technical solutions regarding line rerouting or modifications to installation methods without compromising final reliability. This necessitates a profound understanding of telecommunication protocols as well as the fundamentals of civil engineering, geodesy and electrical engineering. An engineer in the field must be capable of identifying potential threats, such as soil instability or electromagnetic interference, which were not accounted for in the initial design and adapt the network architecture on the fly with judicious improvisation.

Psychological resilience and interagency coordination skills are also integral to the expert profile of a technical specialist in the U.S. Operating within mobile rapid response teams under the auspices of FEMA requires engineers to possess effective communication skills for interacting with rescue services, National Guard units and municipal authorities (see: Figure 10. Inter-agency collaboration scheme). Understanding restoration priorities, ranging from coordinating channels for hospitals to ensuring connectivity for emergency alert systems, allows technical personnel to rationally allocate limited resources. Consequently, the quality and reliability of installation in high-risk zones correlate directly with the level of integration of technical skills, cognitive flexibility and the discipline of field personnel, rendering investment in human capital as significant as investment in the material base itself.

The ultimate system reliability within the five nines concept (99.999%) is ultimately contingent upon the hands of the installer. Even the most sophisticated armored cable and expensive fusion splicer cannot compensate for errors in fiber preparation or substandard closure sealing. In aggressive environments, any micro-crack or contamination introduced during installation becomes a point of future failure under the influence of vibrations or thermal fluctuations. The specialist's expertise serves as the final quality control filter, ensuring the long-term stability of critical communication infrastructure, upon which human lives literally depend in the face of global challenges.

To gain a profound understanding of the significance of practical experience in high-risk zones, it is expedient to examine a comparative model of the actions of two specialists during the mitigation of critical backbone node damage (see: Figure 11. Comparative

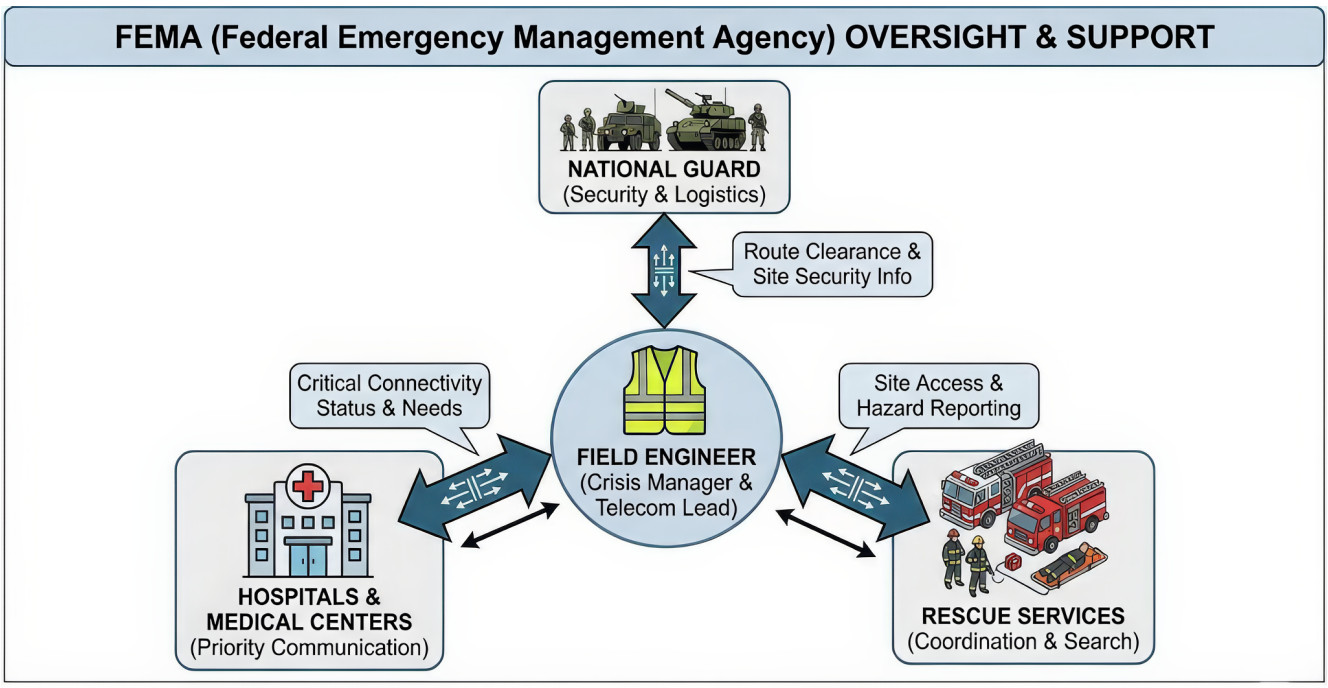


Fig. 10. Inter-agency collaboration scheme

block diagram: academic rigidity vs applied heuristics). The basis is a real incident in the state of Florida following the passage of Hurricane Ian (2022), when a critical communication node in a coastal zone became completely isolated. A rupture occurred in an underground fiber-optic cable with a capacity of 288 fibers due to soil subsidence and the flooding of a cable manhole with seawater.

The first behavioral model is academic rigidity. A specialist possessing a deep theoretical foundation but limited field experience formulates an action algorithm based on strict methodology and design documentation. In this model, priority is given to restoring the system to its original design state. The specialist spends critical time attempting to pump out water and clear debris to gain access to the damaged conduit, following the Standard Operating Procedure (SOP). However, in a destroyed urban infrastructure environment, standard logistical chains (deployment of specialized machinery, delivery of pumping equipment) are severed. As a result, a theoretically correct approach leads to an operational impasse. The Mean Time to Repair (MTTR) increases exponentially, leaving critical sites without connectivity indefinitely (see: Table 1. MTTR comparison: academic rigidity vs applied heuristics ("field intelligence").

The second behavioral model is applied heuristics. A specialist with years of experience in disaster zones utilizes the "field intelligence" method, where the primary metric is the minimum service restoration time rather than adherence to the original design. Recognizing the impossibility of rapid access to the underground conduit, they implement a temporary bypass strategy. Instead of battling the elements, the engineer adapts the architecture to the current landscape. They utilize surviving poles of adjacent utilities or fragments of destroyed buildings to lay a temporary aerial line using tactical armored cable.

This model demonstrates the superiority of applied expertise. While the "theoretician" attempts to adapt

Table 1

MTTR comparison: academic rigidity vs applied heuristics ("field intelligence")

Metric	Academic rigidity model	Applied heuristics model	Improvement factor
Response strategy	Strict adherence to SOP + original design docs	Adaptive architecture + temporary bypass	High flexibility
Logistical dependency	High (requires heavy machinery, de-watering)	Low (utilizes surviving structures and tactical cables)	Rapid deployment
Primary challenge	Logistical deadlock in destroyed environments	Calibration of temporary segment parameters	Technical focus
Estimated MTTR	Days to weeks	3–8 hours	>90% reduction
Network availability	Critical sites offline indefinitely	Rapid restoration of communication islands	Reliability support

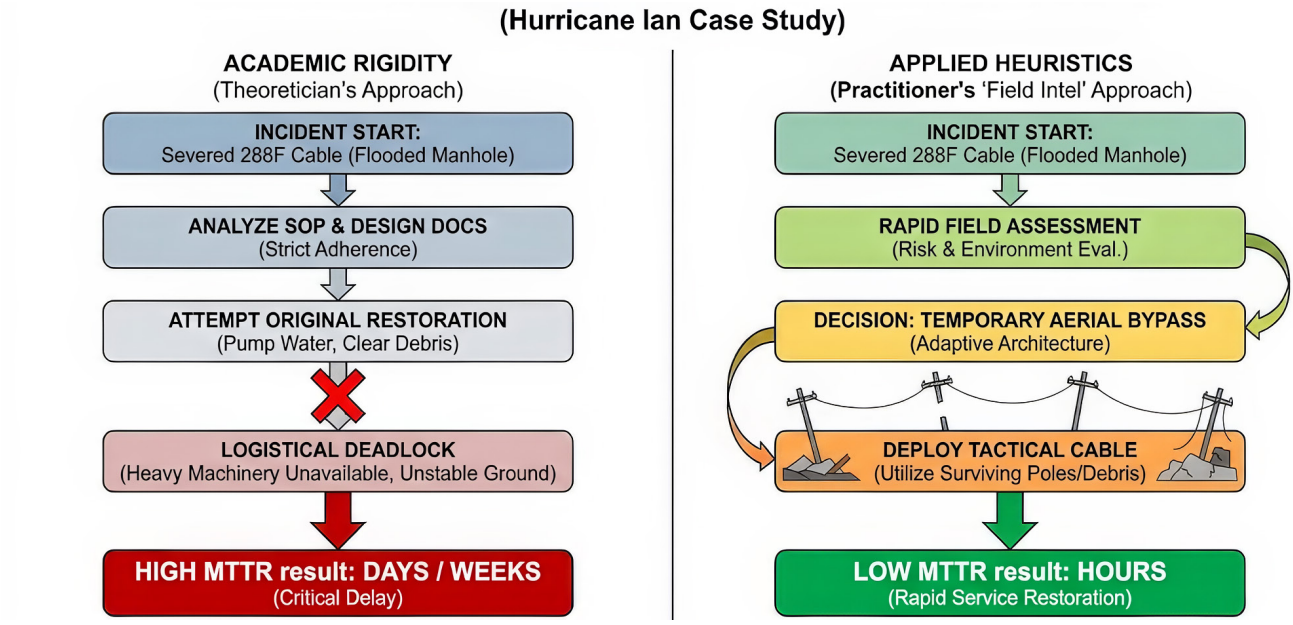


Fig. 11. Comparative block diagram: academic rigidity vs applied heuristics

the destroyed environment to the requirements of the instructions, the "practitioner" adapts the technology to the requirements of the environment. In high-risk conditions, it is precisely the capacity for technical improvisation and knowledge of the non-explicit properties of materials (allowable loads on tactical cable during non-standard suspension) that allow for a reduction in network downtime from several days to a few hours. This confirms the thesis that in extreme engineering activities, practical experience is not a mere supplement to knowledge, but a critical filter through which that knowledge must be transformed into effective action [25].

Conclusions. The conducted research confirms that in the 2026 decade, cable infrastructure remains a strategically vital pillar of national infrastructure

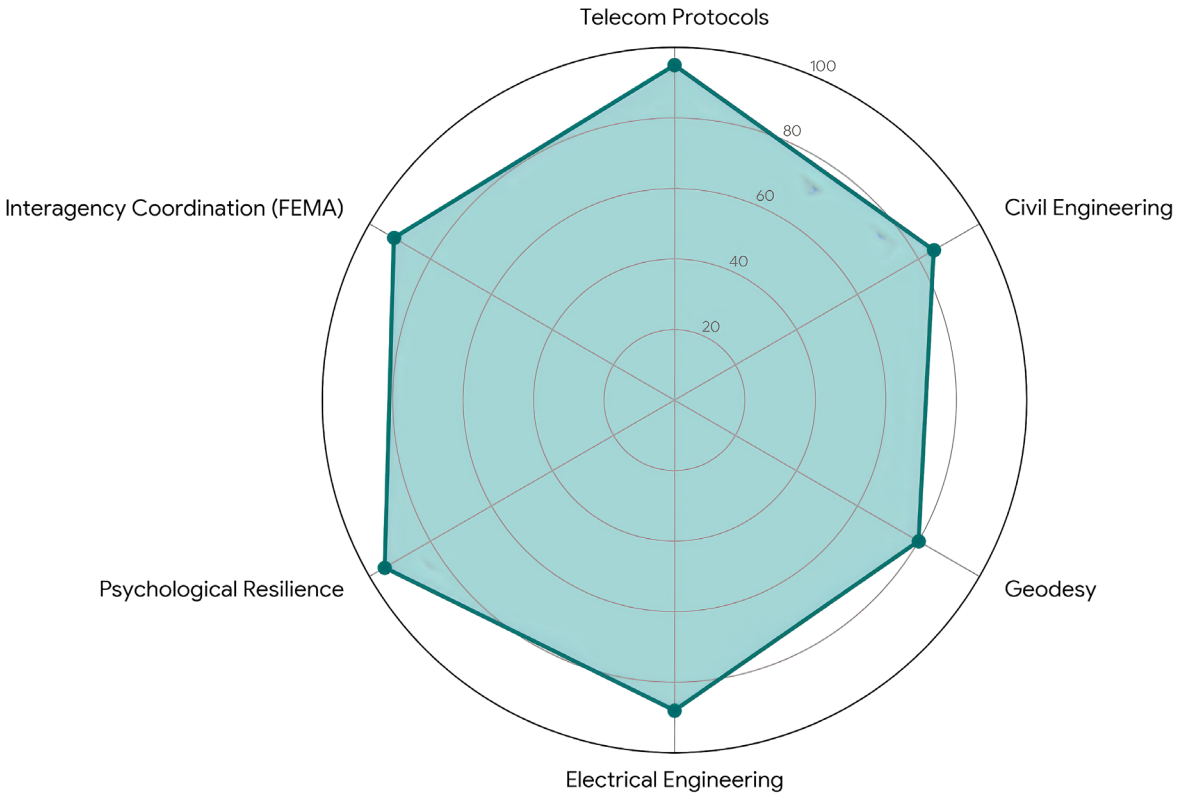


Fig. 12. Matrix "Field intelligence"

and digital resilience of the United States. Despite the development of satellite constellations, it is precisely fiber-optic communication lines (FOCL) that provide the necessary bandwidth and physical security required for the functioning of critical economic sectors and emergency services. The primary conclusion of the work is the ascertainment of a shift away from static design methods in favor of the concept of adaptive deployment, which allows networks to maintain operability even under conditions of large-scale landscape degradation.

Technological deployment efficiency in high-risk zones is currently determined by the synergy of innovative materials and installation methods. The use of All-Dielectric Self-Supporting (ADSS) cables, tactical thermoplastic polyurethane (TPU) jackets and Super-Absorbent Polymer (SAP) dry-core technologies permits the creation of infrastructure resistant to chemical aggression, thermal loads and mechanical damage. The application of trenchless technologies, such as Horizontal Directional Drilling (HDD) and micro-trenching, in combination with Ground Penetrating Radar (GPR) mapping, minimizes deployment time and reduces operational risks, ensuring a network availability target of five nines (99.999%).

Particular significance is attached to the transformation of the cable network from a passive transport channel into an active sensory platform. The implementation of Distributed Acoustic Sensing (DAS) and Remote Fiber Test Systems (RFTS) allows for the utilization of the physical infrastructure layer as an early warning system for natural and technological threats. This not only enhances the survivability of the network itself, but also creates a new level of situational awareness for FEMA and FCC entities, enabling the localization of damage with meter-level precision in real-time. The integration of Augmented Reality (AR) and Digital Twins conclusively solidifies this technological shift, providing engineers with digital vision in conditions of chaos.

A key conclusion in the field of human capital policy is the recognition of the priority of "field intelligence" over purely academic knowledge in crisis response conditions. A comparative analysis of specialist behavioral models has shown that the capacity for technical heuristics and technology adaptation to the requirements of a destroyed environment is a critical factor in reducing Mean Time to Repair (MTTR). Certification according to BICSI and FOA standards should be viewed as a necessary basis, which, however, requires supplementation with specific skills for operating in conditions of operational uncertainty and interagency coordination within the framework of Emergency Support Function #2 (ESF #2) plans. While the qualitative nature of "field intelligence" presents challenges for mathematical quantification, the analyzed MTTR correlation suggests its high operational efficiency.

In conclusion, it should be noted that the long-term resilience of the U.S. telecommunications sector depends on continued preventive investments in "hardened" architecture and public-private partnerships. Further development of the subject is seen in the integration of AI-algorithms for the autonomous reconfiguration of topologies and the use of quantum-secured communication channels for temporary installations.

The approaches developed in the article and the proposed technology stack can serve as a methodological basis for updating national deployment standards in high-risk zones, ensuring technological sovereignty and public safety in the face of global challenges.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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RISK-BASED MODEL FOR ASSESSING CARGO DISCREPANCIES IN TANKER OPERATIONS

Summary. *This article develops a risk-based model for assessing cargo quantity discrepancies during tanker loading and discharge operations. The model treats a final ship-shore difference as the possible result of several interacting groups of factors: measurement uncertainty, cargo-system condition, operational execution, documentation integrity, and ship-shore coordination. The research uses a conceptual and methodological design based on international risk-management principles, petroleum measurement standards, and tanker-terminal operating guidance. The proposed Risk-Based Cargo Discrepancy model (RBCD) assigns each identified factor scores for probability, impact, and difficulty of early detection. It then links the resulting priority score to an operational stage, control action, responsible person, and evidence record. An illustrative scenario shows how a moderate total operational index may coexist with one or more high-priority factors that require immediate verification. The scientific novelty lies in combining technical measurement causes and operational information weaknesses within one stage-based framework. The model is intended as a decision-support instrument and does not replace contractual measurement procedures, approved vessel or terminal instructions, or professional judgment.*

Key words: *tanker operations, cargo discrepancy, risk assessment, cargo reconciliation, petroleum measurement, ship-shore coordination, loss control.*

Introduction. Marine transfers of crude oil and petroleum products require the parties to compare quantities generated by different measurement systems and under different physical conditions. Vessel calculations depend on tank calibration tables, observed levels, trim and list corrections, temperature, density, free water, on-board quantities, and remaining-on-board material. Shore figures may be based on calibrated tanks or meters and may include line displacement and terminal-specific corrections. A numerical difference between vessel and shore results is therefore not self-explanatory. It may indicate a physical cargo gain or loss, a measurement effect, a system-boundary difference, or incomplete alignment of the underlying data [3–8].

Final reconciliation is necessary but reactive. By the time a discrepancy is visible, pipeline condition, valve positions, temporary records, and witness recollection may no longer be directly verifiable. A risk-based approach begins earlier by identifying conditions capable of producing or concealing a difference and defining the controls and records required before the operation is closed.

ISO 31000 defines risk management as a coordinated process of identification, analysis, evaluation, treatment, monitoring, communication, and recording [1]. IEC 31010 provides methods for selecting and applying risk-assessment techniques under uncertainty [2]. These general principles are compatible with tanker operations, but they do not provide a marine-cargo-specific model. The purpose of this study is therefore to develop a compact methodology that translates them into a practical cargo-discrepancy assessment framework.

Literature Review and Theoretical Framework. The API Manual of Petroleum Measurement Standards provides the principal technical basis for marine cargo accountability. API MPMS Chapter 17.1 addresses marine cargo inspection and the recording of essential data; Chapter 17.2 explains the complexity of measuring materials contained in vessel tanks, lines, slop tanks, and other spaces; Chapter 17.5 addresses voyage analysis and reconciliation; Chapter 17.6 focuses on pipeline fullness; and Chapter 17.9 governs the calculation and use of the vessel experience factor [3–7]. API MPMS Chapter 13.3 further emphasizes that reported measurement results must be interpreted together with their uncertainty [8].

Operational guidance reaches the same conclusion from a different direction. The International Safety Guide for Oil Tankers and Terminals requires continuous ship-shore communication, agreement on transfer conditions, and repeated verification of controls throughout the operation [9]. The OCIMF Marine Terminal Information Booklet guidance stresses the

value of accurate and current berth, terminal, and port information for reducing operational risk [10]. Taken together, these sources show that cargo reconciliation is not a single calculation. It is a process connecting measurements, physical systems, operational events, communication, and documentary evidence.

The methodological gap lies in prioritization: existing guidance does not combine all discrepancy-producing factors into one operational risk register. The proposed model addresses this gap through common scoring and stage-based evidence.

Materials and Methods. The study has a conceptual-methodological design. It does not use a proprietary voyage database and does not propose a universal contractual tolerance. The model was developed through comparative analysis of risk-management standards, petroleum measurement publications, and tanker-terminal guidance. The unit of analysis is a discrepancy factor: a condition, event, or information weakness capable of changing a reported cargo quantity or reducing confidence in the reconciliation process.

The model covers five operational stages: pre-arrival preparation, initial gauging and system verification, active cargo transfer, final measurement, and post-transfer reconciliation. At each stage the assessor identifies relevant factors, records the available evidence, and assigns three scores from 1 to 5: probability (P), impact (I), and difficulty of early detection (D). The product of these values forms the individual risk-priority score. The scale is ordinal rather than probabilistic; its purpose is transparent prioritization, not calculation of a physical loss amount.

$$R_i = P_i \times I_i \times D_i \quad (1)$$

The maximum factor score is 125. Proposed bands are 1–20 low, 21–45 moderate, 46–75 high, and 76–125 critical. A normalized operation risk index (ORI) may also be calculated, but the highest individual score must be reviewed separately because an average can conceal a critical factor.

$$ORI = [\Sigma R_i \ / \ (125 \times n)] \times 100\% \quad (2)$$

The scientific novelty of the RBCD model is the integration of technical and information-quality factors within one sequence. Each score must be linked to a control, owner, completion time, and evidence record, and may be reduced only after the control is verified.

Classification of Cargo Discrepancy Factors. The first step is to classify factors by the mechanism through which they may affect the final result. Five groups are proposed (table 1).

The classification prevents the investigation from focusing only on arithmetic. A difference may be mathematically correct within each party's own calculation while remaining operationally inconsistent because the parties used different times, boundaries, or treatment of line contents. For this reason, the model includes a data-alignment gate. Before judging the discrepancy, the assessor confirms that ship and shore figures use the same unit, reference temperature, quantity basis, observation time, cargo boundary, and treatment of free water and residual material.

Architecture and Scoring of the RBCD Model. The RBCD workflow consists of six consecutive stages shown in figure 1. The sequence is cyclical because the final reconciliation should generate lessons for the next operation.

Scoring must be evidence-based. A high probability score may be supported by an observed abnormality, a first call at the terminal, a weak vessel or terminal history, or a complex transfer arrangement. Impact should consider not only the possible quantity effect but also the consequences for safety, delay, claims, and reliability of documents. Detection difficulty reflects the chance that the factor will remain unnoticed until the operation is complete. The model therefore gives additional weight to conditions that are both influential and hard to observe in real time.

Each factor is then assigned a control barrier. Examples include repeating a gauge, verifying instrument status, confirming line displacement, establishing a common event timeline, freezing the calculation

Table 1

Classification of Cargo Discrepancy Factors

Factor group	Representative examples	Possible effect	Primary evidence
Measurement	Gauging, temperature, density, calibration, trim/list correction	Changes calculated vessel or shore quantity	Raw readings, calibration data, calculation sheets
Cargo-system condition	Line fullness, valve leakage, OBQ/ROB, free water, slop transfer	Changes the system boundary or retained quantity	Line displacement record, tank inspection, valve status
Operational execution	Tank switching, interruption, stripping, rate change, internal transfer	Creates unrecorded movement or incomplete transfer	Event log, pump log, valve sequence, rate record
Information integrity	Different timestamps, units, reference temperatures, transcription errors	Makes figures non-comparable or incorrectly processed	Source files, timestamps, version history
Ship-shore coordination	Unreported changes, inconsistent instructions, delayed confirmation	Prevents timely verification and common understanding	Conference record, checklist, messages, joint statements

Source: developed by the author

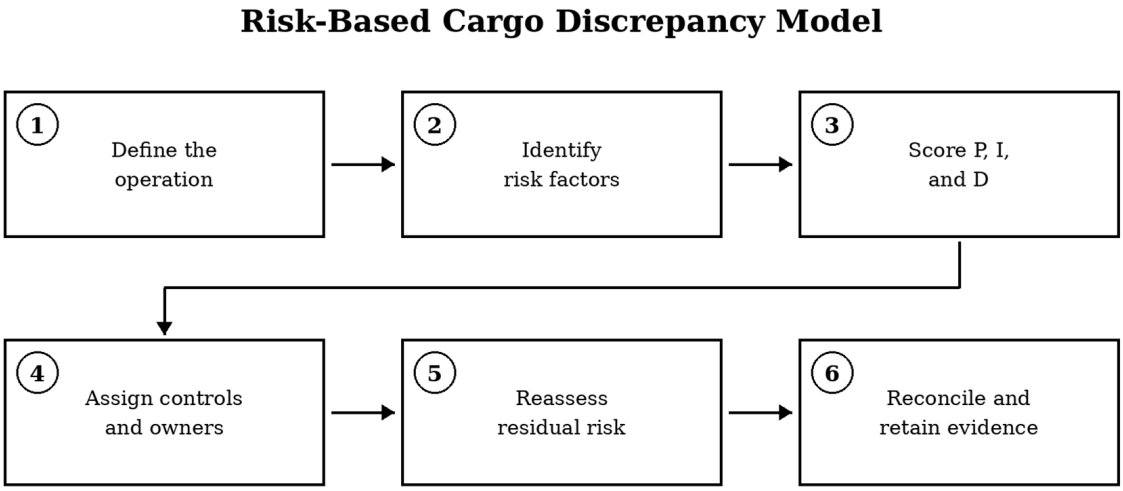


Fig. 1. Workflow of the Risk-Based Cargo Discrepancy Model
Source: developed by the author

version, checking tank distribution, or requiring joint review before final documents are signed. The control owner may be the vessel, terminal, inspector, cargo superintendent, or another authorized party. Responsibility must be explicit; otherwise a control can appear in the record without being completed.

Illustrative Application. To demonstrate the method, an illustrative discharge operation was evaluated using six representative factors. The figures are hypothetical and are included only to show the calculation logic; they do not represent a universal industry threshold or a real client operation (table 3).

The initial maximum score is 80, which places unconfirmed line fullness in the critical category. The operation should not be interpreted as low-risk merely because several other factors are moderate. After the controls are completed and documented, the maximum residual score decreases to 16. This example demonstrates why the model uses both the normalized ORI and the maximum individual score. The normalized index describes the overall profile, while the maximum score prevents averaging from concealing a single dominant factor.

The example also shows the distinction between identifying a plausible cause and proving a physical loss. The model does not conclude that the line condition caused a particular quantity difference. It concludes that the condition has sufficient probability, impact, and detection difficulty to justify targeted verification and preservation of evidence. Causal attribution remains a separate reconciliation task governed by the quality of the available data.

Operational and Digital Implementation. The model may be implemented in a structured spreadsheet, database, or Power Apps-based workflow. The record should contain the operation, stage, factor, factual observation, source evidence, P/I/D scores, control, owner, due time, completion evidence, residual score, and final disposition. Alerts may identify high scores or overdue controls.

Digitalization does not improve reconciliation by itself. Its value depends on disciplined data entry, controlled calculation versions, preserved source records, and clear authority for changing scores. A system should retain the original assessment and every subsequent revision. This creates an audit trail showing what was known at each stage, what action was

Table 2

RBCD Scoring Criteria

Score	Probability (P)	Impact (I)	Detection difficulty (D)
1	Rare under current conditions	Negligible effect; routine correction	Immediately visible in normal records
2	Unlikely but credible	Minor operational or documentary effect	Usually detected by standard checks
3	Possible during the operation	Material review or additional verification required	May remain hidden until interim comparison
4	Likely without additional control	Significant commercial or operational consequence	Usually detected only after focused analysis
5	Expected or already indicated	Major consequence, dispute, or unreliable reconciliation	Difficult to detect before final reconciliation

Source: developed by the author

Table 3

Illustrative Initial and Residual Risk Assessment

Factor	Initial P/I/D	Initial R	Control	Residual P/I/D	Residual R
Unconfirmed shore-line fullness	4/5/4	80	Joint line-displacement verification	2/4/2	16
Different final gauging times	4/3/3	36	Common measurement window and timestamps	1/3/1	3
Incomplete stripping record	3/4/4	48	Pump/event log and ROB confirmation	2/3/2	12
Manual transcription of density	3/4/3	36	Source-file import and independent check	1/3/1	3
Limited validated VEF history	3/3/4	36	Use VEF only with qualification statement	2/2/3	12
Unrecorded tank-switching time	3/3/4	36	Joint event timeline and rate review	1/2/2	4

Source: developed by the author

selected, and why the residual risk was accepted. The same data may later support trend analysis across vessels, terminals, cargoes, and recurring causes.

The model is particularly useful for first calls, complex tank distributions, nonstandard line displacement, unusual cargo characteristics, significant interruptions, unstable interim comparisons, limited VEF history, or incomplete event records. It should be integrated into existing pre-transfer conferences, loading or discharge plans, inspection records, and final reconciliation files rather than introduced as a disconnected administrative form.

Discussion. The proposed model changes the starting point of discrepancy management. A conventional approach begins with the final numerical difference and works backward. The RBCD model begins with the operational conditions capable of producing or obscuring the difference and follows them forward through controls and evidence. This improves traceability and permits corrective action while the operation is still observable.

The risk register also connects vessel, terminal, inspection, and commercial perspectives without assuming that one party's figure is automatically exact. This is consistent with measurement-uncertainty principles and API guidance requiring reconciliation of multiple data sources [3–8].

The scoring scale is ordinal and includes expert judgment. Different users may assign different scores without examples and calibration training. The model does not calculate physical loss, and its thresholds require validation against operational history. It should therefore be piloted, compared with reconciliation outcomes, and adjusted on the basis of recurring evidence.

Conclusions. Cargo discrepancies in tanker operations are multi-source outcomes. They may result from measurement uncertainty, cargo-system condition, execution of the transfer, information integrity, or ship-shore coordination. A final ship-shore difference cannot by itself identify the underlying mechanism.

The RBCD model provides a structured sequence for defining the operation, identifying factors, assigning P/I/D scores, selecting controls, documenting responsibility, reassessing residual risk, and retaining evidence for reconciliation. The data-alignment gate is essential: figures should not be treated as directly contradictory until their units, reference conditions, timestamps, system boundaries, and treatment of line contents and residual material are aligned.

The main practical advantage of the model is early prioritization. It directs attention to a small number of high-value factors before the final discrepancy becomes fixed and difficult to investigate. The model is conceptual and requires empirical validation. Future research should test inter-rater consistency, compare scores with actual reconciliation outcomes, and determine whether digital implementation reduces missing evidence, investigation time, and recurrence of unresolved causes.

ДОДАТКОВА ІНФОРМАЦІЯ

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MODERN APPROACHES TO TOOL MANUFACTURING AND REPAIR IN GENERATOR AND ELECTROTECHNICAL PRODUCTION

Summary. *The stable operation of generator and electrotechnical production depends heavily on tooling provision: stamps, molds, cutting tools, and assembly fixtures. Modern methods of tool manufacturing and repair are a critical factor in the continuity of production processes, product quality, and the operational efficiency of enterprises in the sector. Drawing on a combination of many years of practical experience in managing a tooling department in heavy electrotechnical engineering and a systematic review of current scientific literature, this article examines organizational approaches to toolroom operation, predictive-maintenance methods, and tool wear monitoring. It proposes an original three-tier tool resource management model ("condition assessment and record-keeping – proactive reconditioning – digital monitoring integration") that combines shop-floor organizational practice with elements of digital technology. The empirical basis of the model is practical reconditioning-rate indicators (70–80% for stamps and molds, 40–50% for cutting tools) recorded at a generator and electrotechnical manufacturing enterprise. The analysis shows that combining disciplined repair planning with the possibilities of digital monitoring can reduce tooling costs, cut downtime, and support the fulfillment of export contracts.*

Key words: *toolroom management, tool repair, predictive maintenance, generator manufacturing, electrotechnical production, tool wear monitoring.*

Introduction. Generators and electrotechnical equipment form the backbone of energy and industrial infrastructure: electricity supply, transport operation, and the continuity of production processes at the manufacturing enterprises themselves all depend on them. Every generator consists of thousands of precise components — thin copper winding plates, insulation elements, housing assemblies — the manufacture of which is impossible without specialized tooling: stamps, molds, cutting tools, and assembly fixtures. This tooling is manufactured and serviced by tooling departments (toolrooms), which function as the technical "heart" of the enterprise [1; 14].

Practice shows that it is the condition of the tooling stock, rather than the capacity of the main technological equipment, that most often determines the rhythm of production. The breakdown or wear of a stamp or milling cutter halts the production line, causes defects, and disrupts delivery deadlines, which is especially critical for enterprises fulfilling export contracts with strict quality requirements [2; 14]. At the same time, there is a systemic shortage of qualified tooling engineers and electromechanical specialists on the labor market [20], which increases the value of well-documented, systematic approaches to organizing this segment of production.

In recent years, a substantial body of research has emerged on the digitalization of maintenance — from the concept of predictive maintenance within Industry 4.0 [10; 21] to the application of machine- and deep-learning methods for monitoring cutting-tool wear [3; 4; 5; 7]. However, these studies are mostly focused on the algorithmic side of the problem and are rarely linked to the organizational practice of specific tooling departments in heavy engineering, where the deployment of complex sensor systems is often constrained by budget and infrastructure.

The purpose of this article is to analyze modern approaches to tool manufacturing and repair in generator and electrotechnical production and, by combining practical experience in managing a tooling department with a systematic review of the scientific literature, to propose an applied tool resource management model suited to enterprises with limited digitalization capacity. To achieve this purpose, the article examines the organizational aspects of toolroom operation, approaches to predictive maintenance and tool wear monitoring, and practical reconditioning indicators recorded over many years of engineering practice. The article is structured as follows: a literature review across four thematic areas, a description of the research methodology, results presented as empirical indicators and

tables, a discussion of the proposed three-tier model, and conclusions with practical recommendations.

Literature Review

Organization of toolroom operations

A toolroom is traditionally defined as a centralized unit responsible for the storage, accounting, issuance, repair, and manufacture of tooling [1; 14]. Effective management of this area requires clear tool accounting, workload planning, and timely maintenance, all of which directly affect the productivity of the main production process [14]. Sources emphasize that a well-organized toolroom provides not only storage but also safety, standardized issuance procedures, and control over equipment condition [1]. Practice shows that the quality of such a unit's work depends not only on technical equipment but also on the human factor — staff qualifications and interaction with shop-floor foremen and design departments [14].

Special attention should be paid to the shortage of personnel in electromechanics and tool manufacturing: specialists in this field combine knowledge of electrical engineering, mechanics, and metalworking technologies, which makes training such personnel lengthy and costly [20]. This reinforces the value of management systems that enable efficient use of available staff and resources, in particular through rational workload planning, reduced equipment downtime, and improved labor efficiency [8].

Predictive maintenance within Industry 4.0

A large share of current research is devoted to the transition from reactive and scheduled preventive maintenance to predictive maintenance, which relies on the analysis of data about equipment condition [10; 21]. Systematic reviews indicate that predictive maintenance reduces unplanned downtime, lowers repair costs, and extends equipment service life by intervening precisely when technically justified rather than on a fixed schedule [11; 21]. At the same time, researchers emphasize that deploying predictive systems requires investment in sensor infrastructure, data collection and storage, and staff training [13], and that maintenance-strategy optimization is increasingly framed as a problem that can be solved with reinforcement learning and other decision-making methods under uncertainty [19].

Methods for monitoring cutting-tool wear

A separate and technologically dense strand of literature is devoted to monitoring cutting-tool wear using computer-vision and deep-learning methods. Researchers propose approaches based on digital image processing of cutting edges to automatically determine the degree of wear [3], as well as combined image-processing pipelines that merge expert rule-based analysis with neural-network models [7]. Other studies propose intelligent multi-step tool-wear prediction models based on deep neural networks [4] and hybrid architectures that convert signals into images for classification with ResNext-type networks to analyze multi-channel signals during milling [5]. Similar approaches are applied to other machining processes — for example, tool wear monitoring in high-speed broaching with carbide tools [6].

These studies demonstrate high accuracy in recognizing tool condition under laboratory or controlled production conditions, but they largely disregard the organizational context: how exactly monitoring results should be translated into decisions about repair, replacement, or modernization of tooling at the level of shop-floor planning.

Reviews and critical analyses of tool condition monitoring systems

Comprehensive reviews of artificial intelligence systems for tool condition monitoring in machining indicate that, despite significant algorithmic progress, practical deployment is constrained by the complexity of integrating models into production information systems and by the absence of standardized datasets for different types of equipment [12]. Reviews of machining process monitoring generally confirm that combining sensor data (cutting force, vibration, acoustic emission) with analytical methods improves process stability, though this level of maturity is mainly characteristic of large-scale, high-technology production [17]. Studies on optimizing the parameters of long short-term memory (LSTM) models for predictive maintenance confirm the effectiveness of deep recurrent networks for forecasting remaining useful life [9], while studies on industrial robots show that combining data with expert knowledge improves production stability under conditions of intelligent manufacturing [18].

Reconditioning and restoration technologies

A less represented but practically significant strand of research concerns tool reconditioning technologies. Studies on reconditioning diamond-coated cutting tools show that restored tooling can retain acceptable performance characteristics when machining composite materials [15], confirming the economic viability of repair over full replacement. Directed energy deposition (DED) additive manufacturing is considered a promising technology for restoring worn surfaces of stamps and molds through local metal deposition [16], combining repair with a form of localized modernization of tooling geometry.

The literature review shows that scientific approaches to wear monitoring and predictive maintenance are technologically mature but are mostly oriented toward high-technology production with developed sensor infrastructure. The practice of tooling departments in traditional heavy engineering, which includes generator and electrotechnical production, requires adapted, less resource-intensive management

models that combine organizational discipline with elements of accessible digital solutions. It is precisely this gap that the model proposed in this article aims to fill.

Methodology. This is an analytical study that combines two sources of data: (1) a systematic review of scientific literature on toolroom organization, predictive maintenance, and tool wear monitoring (21 sources, 2020–2026); and (2) empirical data from practical experience managing a tooling department (production preparation bureau) in generator and electrotechnical manufacturing, accumulated over more than twenty years of engineering practice, including a period of direct departmental leadership.

The practical data include indicators of the share of reconditioned tooling (stamps, molds, assembly fixtures, and cutting tools) by category, the number of repeated reconditioning cycles for individual items of tooling, and a qualitative description of the tool-preparation production cycle — from the shop's request submission to the delivery of finished tooling to production. These data are used as an illustrative case reflecting typical practice at a heavy electrotechnical engineering enterprise that fulfills both domestic and export orders (India, Tajikistan, Germany, Canada).

The analysis was carried out using thematic synthesis: sources were grouped into four areas (toolroom organization, predictive maintenance, wear monitoring, reconditioning technologies), after which the principles identified in the literature were compared with elements of the practical tool-management cycle. Based on this comparison, an original three-tier tool resource management model was formulated, structuring existing practice as a sequence of management tiers and identifying points at which elements of digital monitoring from the reviewed research can be integrated into traditional organizational practice. A limitation of the methodology is that the practical indicators relate to a single enterprise and do not constitute a statistical sample; the model should therefore be regarded as a conceptual, rather than a statistically verified, tool suitable for further empirical testing.

Findings

Analysis of the practical production-preparation cycle showed that the tooling department's work is structured as a sequence of six stages: receipt of a request from the shop floor or design department → entry of the task into the monthly plan → calculation of material consumption norms → machining of the workpiece (turning and milling operations) → heat treatment (hardening) and final grinding → marking, database registration, and delivery to the shop. Task priority is determined by an urgency flag, and conflicts arising when several urgent tasks arrive simultaneously are resolved through an operational review of workload together with management (See Figure 1).

A key empirical finding concerns the share of tooling returned to service through repair and refurbishment rather than full replacement (Table 1). For the category of stamps, molds, and assembly fixtures, the share of reconditioned tooling was 70–80%, with individual items undergoing repeated reconditioning three to five times. For the category of cutting tools (mills, drills), the reconditioning rate was lower — 40–50%: expensive milling cutters were reground to a smaller diameter for other tasks or restored by brazing new carbide inserts.

These indicators confirm that preventive repair carried out before critical tooling failure is more cost-effective than reactive replacement, consistent with findings on the economics of predictive maintenance [10; 13; 21] and with research on cutting-tool reconditioning technologies [15]. At the same time, the lower reconditioning rate for cutting tools compared to stamps is explained by more intensive physical wear of cutting edges during direct contact with metal, which is consistent with tool-wear-monitoring studies that record nonlinear wear dynamics on cutting surfaces [3; 4; 5].

A second important finding is confirmation of the impact of export-contract requirements on tool-manufacturing technology: orders for European customers required the development of tooling from more wear-resistant steels to work with new grades of insulation materials and alloys, illustrating the practical need for adaptability in tool production, consistent with findings on the stability and adaptability of machining processes [17].

The findings thus confirm two claims: (1) the large majority of tooling in heavy electrotechnical engineering can and should be reconditioned rather than replaced; and (2) the effectiveness of this reconditioning depends on disciplined, forward-looking repair planning, which forms the basis for the model proposed in the following section.

Discussion. Based on the comparison of practical experience with the results of the literature review, a three-tier tool resource management model is proposed (Figure 2, Table 2), structuring the work of the tooling

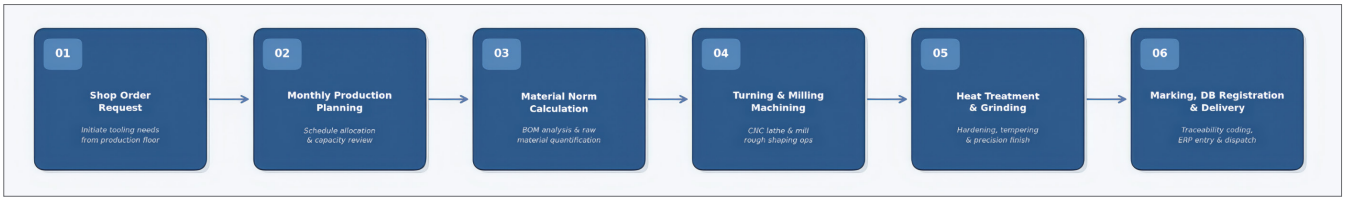


Fig. 1. Diagram of the tool-preparation production cycle

Table 1

Tooling reconditioning indicators by category

Tooling category	Reconditioning rate, %	Typical reconditioning method	Number of repeated reconditioning cycles
Stamps, molds, assembly fixtures	70–80%	Regrinding of working surfaces, replacement of worn components	up to 3–5 times
Cutting tools (mills, drills)	40–50%	Regrinding to a smaller diameter, brazing of carbide inserts	1–2 times

department in generator and electrotechnical production as three sequential but cyclically repeating tiers.

Tier 1. Condition assessment and record-keeping. The foundation of the model is systematic accounting of all tooling — from stamps to cutting tools — recording manufacture date, number of usage cycles, and previous repairs. This tier draws on classical toolroom-organization principles: centralized storage, standardized issuance, and condition control [1; 14]. In departmental practice, this tier is implemented by registering each item of tooling in a database after manufacture or repair, creating a usage history necessary for subsequent decisions.

Tier 2. Proactive reconditioning. The second tier formalizes the practice implemented in the case described: tooling is sent for repair before critical wear or failure occurs, rather than after a breakdown. This approach is supported both by empirical indicators (70–80% reconditioning of stamps and molds through timely intervention) and by research on the economic effectiveness of predictive and preventive maintenance [10; 13; 21], as well as by technologies for reconditioning cutting edges [15] and additive restoration of worn surfaces [16]. The essential difference between the proactive approach and scheduled preventive maintenance "by calendar" is that the repair decision is based on the actual condition of the tooling, recorded during a regular inspection, rather than solely on a fixed time interval.

Tier 3. Digital monitoring integration. The third tier is forward-looking and envisages the gradual integration of automated wear-monitoring methods developed in the reviewed literature — computer vision for analyzing cutting-edge images [3; 7], deep-learning models for forecasting remaining useful life [4; 5; 9], and signal analysis in machining processes [6]. Unlike laboratory studies, where such systems are deployed as standalone solutions, in the proposed model digital monitoring is treated as an addition to Tier 1 (record-keeping) and Tier 2 (proactive reconditioning): monitoring data automate precisely the repair-decision moment that is currently performed manually by an engineer based on experience and scheduled inspection (See Figure 2).

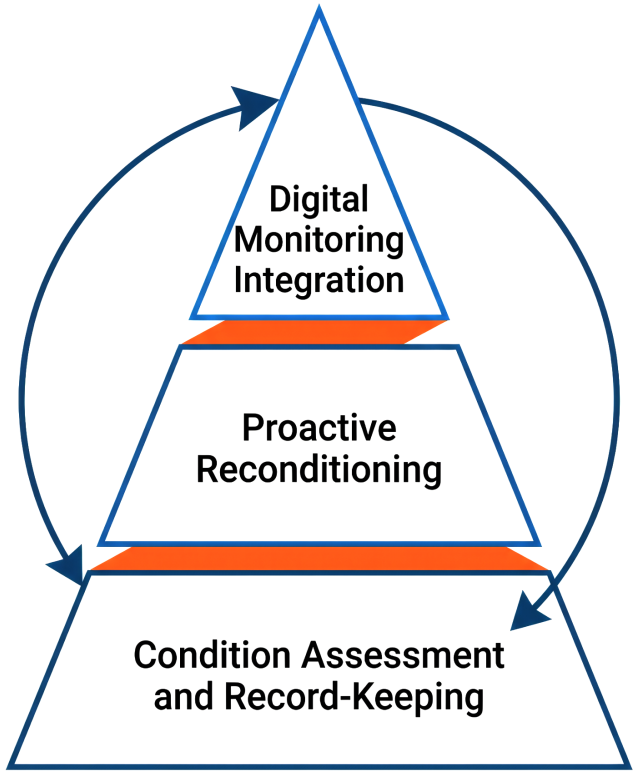


Fig. 2. Three-tier tool resource management model

Table 2

Structure of the three-tier tool resource management model

Tier	Content	Sources	Practical implementation
Tier 1. Condition assessment and record-keeping	Centralized accounting of tooling, usage and repair history	[1; 14]	Registration of each item of tooling in a database after manufacture or repair
Tier 2. Proactive reconditioning	Repair before critical wear occurs, based on scheduled inspection	[10; 13; 15; 16; 21]	Rule of forward repair for stamps and molds; regrinding and brazing of cutting tools
Tier 3. Digital monitoring integration	Automated wear detection using computer vision and deep learning	[3; 4; 5; 6; 7; 9]	Pilot deployment for the most expensive and critical tooling items (export orders)

The key managerial advantage of the model is that it does not require a one-time deployment of expensive sensor infrastructure. Enterprises with limited budgets can implement Tiers 1 and 2 using purely organizational means, achieving significant economic benefit — as evidenced by the reconditioning-rate indicators presented above — and gradually, as resources permit, add elements of Tier 3 for the most critical or expensive tooling items, such as complex stamps for export orders. This staged approach is consistent with review findings that the success of predictive-maintenance deployment depends largely on an enterprise's organizational readiness, not solely on the technological availability of algorithms [12; 21].

The model's economic effect manifests in three ways. First, reduced spending on new tooling procurement through multiple reconditioning cycles (up to 3–5 for stamps), directly lowering product cost [8; 13]. Second, reduced production-line downtime through forward repair rather than emergency repair, consistent with findings on reduced unplanned time losses when transitioning to predictive maintenance strategies [10; 11; 18]. Third, support for an enterprise's ability to fulfill export orders with elevated quality requirements for tooling, since systematic record-keeping and disciplined reconditioning allow tooling to be quickly adapted to new material grades [17] (See Figure 3).

The model also has limitations. It is built on a single-enterprise case and requires further verification at other manufacturers with a different range of tooling. In addition, Tier 3 of the model is formulated largely on the basis of laboratory research and requires a separate pilot deployment to confirm economic feasibility under serial rather than mass generator production. Further research could be directed toward quantitatively assessing the impact of Tier 3 deployment on reconditioning rates relative to the current 70–80% and 40–50%, as well as toward developing adaptive, low-cost repair-decision strategies based on reinforcement learning [19], tailored to the resource constraints of heavy-engineering enterprises rather than only the high-technology manufacturers for which most of the systems reviewed in the literature were developed.

Conclusions. Modern approaches to tool manufacturing and repair in generator and electrotechnical production combine the traditional organizational practice of tooling departments with the new possibilities of digital wear monitoring. The analysis showed that disciplined, forward-looking tooling reconditioning allows up to 70–80% of stamps and molds and 40–50% of cutting tools to be returned to service, substantially reducing spending on new tooling procurement and cutting production downtime.

The proposed three-tier tool resource management model — condition assessment and record-keeping, proactive reconditioning, and digital monitoring integration — structures existing practice and offers enterprises a staged path toward deploying elements of predictive maintenance without requiring large one-time investments in sensor infrastructure. The model is grounded in a combination of many years of practical experience managing a tooling department in heavy electrotechnical engineering and a systematic review

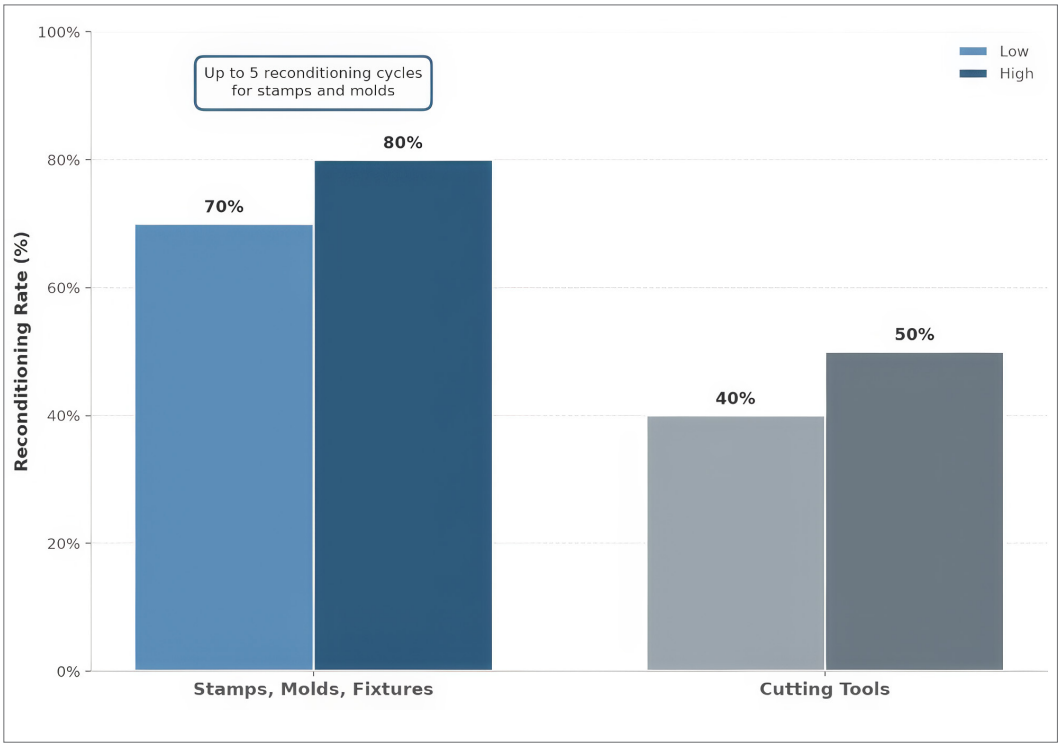


Fig. 3. Comparison of reconditioning rates by tooling category

of current scientific research on tool wear monitoring and predictive maintenance.

The model's practical significance lies in its applicability to enterprises with limited digitalization resources, including manufacturers of generators and turbines operating in both domestic and export markets. Further research should focus on quantitatively verifying the model at other enterprises in the sector and on developing affordable sensor solutions for Tier 3 of the model.

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ANALYSIS OF THE INFLUENCE OF THE PLASMA TORCH VELOCITY ON THE THERMAL STATE OF THE COATING-SUBLAYER-BASE SYSTEM

Summary. *This paper presents the results of mathematical modeling of numerical studies on the effect of plasma torch velocity on the thermal state of a multilayer coating-sublayer-base system. Studying the thermal processes occurring during thermal spraying plays a key role in the development of new multi-resistant coatings.*

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

Introduction. Thermal spray coatings for various functional purposes are currently finding wider application. Their enhanced thermal, electrical, wear-resistant, and corrosion-resistant properties, as well as the challenges of improving existing thermal spraying technologies and developing new ones, are crucial in wartime. Studying the thermal processes occurring during thermal spraying plays a key role in the development of new coatings. Composite clad powders containing solid lubricants are currently becoming increasingly popular for the production of antifriction coatings using various thermal spraying methods.

Composites with graphite as the primary core are widely used in spraying. Coatings made from composite powders of this composition are used in friction units operating without lubrication and under boundary friction conditions. These coatings are used as bearing surfaces in plain bearings, in gas turbine engines, in abradable starter coatings, in vane compressors, in ring pump seals, and in specialized military equipment. Therefore, the development and improvement of coating technology necessitates additional research into the thermal phenomena observed in all these situations. Of significant interest are the results of mathematical modeling of heat transfer processes during the formation of coatings from clad composite powders containing graphite. This paper presents representative results of mathematical modeling of numerical studies investigating one of the important factors influencing the thermal state of a system — the plasma torch velocity.

A three-dimensional, non-stationary heat conduction problem for a multilayer system is considered. Two different research formulations are considered. In the first formulation, the spraying rate is constant, and the coating thickness Δ_{3c} is inversely proportional to the plasma torch velocity V. The originality of the first formulation lies in taking into account the variable coating thickness with a change in the velocity V, and this largely corresponds to the real spraying situation. In the second formulation, the sprayed layer thickness is constant, while the spraying rate is variable, and it is directly proportional to the plasma torch velocity. It should be noted that the second formulation is close

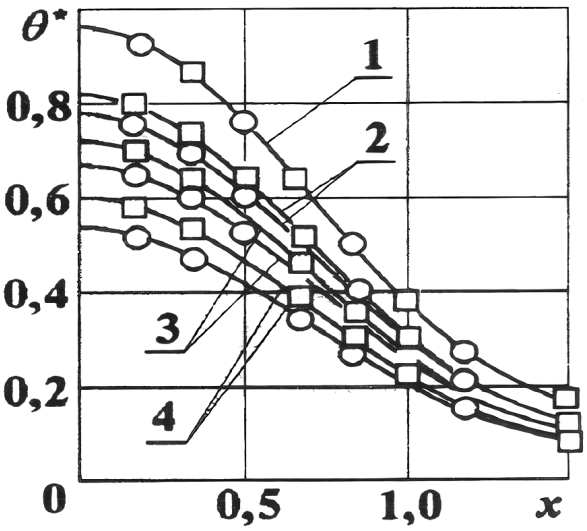


Fig. 1. Dependence $\theta^* = f(x)$ – for $y = 0$, $z = -0.513$ in the layered heterogeneous system "five-layer coating-sublayer-base": 1 – Pe = 77.75; 2 – Pe = 116.625; 3 – Pe = 155.5; 4 – Pe = 233.25; —□— — constant spraying productivity; —o— — constancy of coating thickness $\Delta_{3c} = 0.0255$

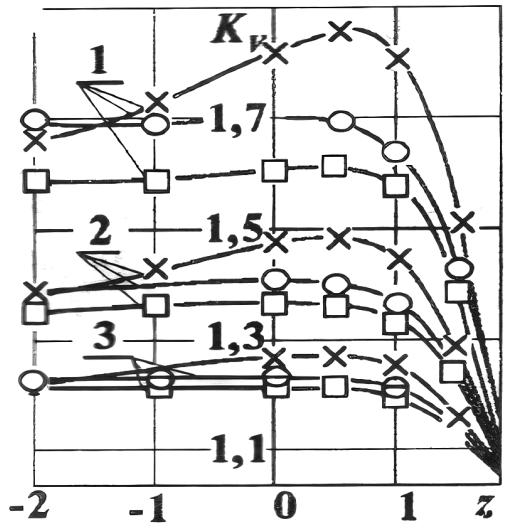


Fig. 2. Change in the K_V simplex along the z axis: 1 – Pe = 77.75; 2 – Pe =116.625; 3 – Pe =155.5; —□— — the "five-layer coating — sublayer — base" system with constant spraying productivity; —×— — the "five-layer coating — sublayer — base" system with constant coating thickness $\Delta_{3c} = 0.0255$; —o— — separate steel base

to the traditional one, in which the effect of velocity V is studied under conditions of constant geometric characteristics of the object under study.

Typical results of the performed numerical studies corresponding to the following values of the initial parameters $x_1 = 2.56$; $\delta_1 = 0.34$ base thickness; sublayer thickness $\Delta_2 = 0.0085$; thickness of a single coating layer $\Delta_3 = 0.00425$; number $Bi_{x1} = Bi_{y1} = Bi_{z0} = Bi_{z1} = 5.96 \cdot 10^{-3}$; $\theta^* = \theta / \theta^*_{max}$ — maximum temperature of an individual steel base; parameter $K_V = \theta_{Pe=Pei} / \theta_{Pe=233.25}$, where Pe =77.25; 116.625; 155.55).

The data obtained show that quantitatively, the impact of velocity for the compared situations differs significantly. However, qualitatively, the impact of velocity is similar.

In the two cases under consideration, an increase in the plasma torch velocity, characterized by the Pe number, leads to a decrease in the temperature levels of the entire system as a whole. A narrowing of the isotherms along the x- and y-coordinate axes, which are perpendicular to the movement of the energy source, and a shortening in the direction of the z-axis are also observed. The quantitative differences in the compared data differ more significantly with a higher Pe number. Thus, on the heat sink surface, these differences do not exceed 0.038 at Pe = 116.625, and at Pe = 233.25, the differences reach 0.0625 (Fig. 1). A feature of the data corresponding to the first formulation is the compensating effect of the thinning of the coating layer, which occurs with an increase in the plasma torch velocity. It is shown that, with a constant coating thickness, an increase in velocity leads to a decrease in the temperature of the entire system as a whole. However, with a decrease in coating thickness and an increase in velocity, the effects are opposite. Therefore, in the first version of the formulation, with a change in velocity, the temperature value changes less.

For comparison, Figure 2 shows data for a single, uncoated steel base and under otherwise identical conditions. The results indicate that the effect of plasma torch velocity on the coating-sublayer-base system is significantly different quantitatively than on a single steel base. These differences become greater at higher coating thicknesses and increase further with decreasing plasma torch velocity V. In the second study (with constant coating thickness), the temperature change due to velocity changes, characterized by the Pe number, appears more significant. The least significant effect is observed with constant spraying performance, which is typical for the first study. For a single steel base, the data corresponding to it occupy an intermediate value compared to the other cases.

Conclusion. Analysis of the obtained data shows that in all three cases under consideration, the dependence of the manifestation of the effects of the regional influence of the heating source on the velocity of the plasma torch is of interest, and the effects of the complete regional influence of the heating source, the effects of the regional influence of the features of the spatial distribution of the energy source, etc. are observed. It can be concluded that the higher the velocity of the plasma torch, all other things being equal, the more pronounced the effects of the regional influence of the heating sources.

ДОДАТКОВА ІНФОРМАЦІЯ

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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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IMPACT OF STRUCTURAL MODIFICATIONS ON RELIABILITY AND LONGEVITY OF MECHANICAL SYSTEMS UNDER OPERATIONAL CONDITIONS

Summary. *Structural modifications applied to mechanical systems in industrial facilities produce immediate improvements in the targeted failure mode, yet the long-term behavior of the modified system depends on the type of change and may include gradual loss of effectiveness or emergence of secondary failure mechanisms not present before the intervention. A Post-Modification Performance Assessment (PMPA) method is proposed that evaluates three dimensions of modification outcome: effectiveness ratio (failure rate reduction relative to the pre-modification condition), secondary effect index (new failure modes introduced by the modification), and durability grade classifying the persistence of the improvement as permanent, degrading, or time-limited. Three case studies representing different modification types were analyzed over service periods of four to seven years. Geometry modification (gusset plate addition to a pump support frame) maintained full effectiveness for 84 months with no secondary effects. Material substitution (cupronickel tube replacement in a seawater cooler) eliminated the original failure mode but introduced galvanic corrosion at bimetallic junctions, requiring periodic anode replacement to sustain effectiveness. Load environment isolation (spring isolators on a compressor foundation) reduced transmitted vibration by 80 percent initially but lost 35 percent of isolation capacity over 48 months due to spring creep. PMPA classified these outcomes as permanent, degrading, and time-limited respectively, illustrating that modification type may serve as an indicator of long-term reliability trajectory and that post-modification monitoring requirements differ by category.*

Key words: *structural modification, reliability, longevity, mechanical systems, post-modification assessment, durability, failure rate.*

Introduction. Mechanical systems in industrial facilities accumulate damage that may concentrate at structural elements where design assumptions diverge from service conditions [1; 4]. Engineering practice responds with three categories of structural change: geometry alterations (gusset plates, stiffening ribs, load-redistributing brackets); material substitutions replacing the original grade with one resistant to the active damage mechanism; and load environment isolations interposing a decoupling element between the load source and the vulnerable structure [4; 6; 15].

Immediate verification is standard: stress measurements after geometry changes [3; 5], compatibility testing after material substitutions [8; 9], vibration measurements after isolation installation [6; 7]. What these procedures assess is the condition at time zero. Whether the improvement retains its effectiveness over subsequent years depends on factors initial verification cannot capture: stiffness changes due to creep, electrochemical interactions at new material interfaces, or load redistribution to adjacent elements [13; 15].

Existing literature addresses each category of structural change independently: fatigue research [3; 4; 5] documents stress reduction at welded joints; corrosion literature [8; 9] describes degradation at dissimilar metal junctions; vibration research [6; 15] establishes isolation mechanics; and monitoring methods [10; 12] provide tools for tracking post-intervention condition. What these bodies of work do not supply is a unified classification that predicts whether an initial improvement will persist, degrade, or expire within the operational planning horizon.

Passive structural changes retain effectiveness longer than interventions involving dissimilar material boundaries or aging elements. A welded gusset plate has no independent degradation mechanism; a material substitution creates a bimetallic junction susceptible to galvanic corrosion [8; 9]; an isolating element ages through creep, hardening, or wear [7; 13; 15]. Treating

all three as equivalent leads to unnecessary monitoring of permanent changes or insufficient monitoring of time-limited ones.

No structured method for assessing post-modification performance across different intervention types has been identified in the reviewed literature. Reliability growth models [11; 14] track system-level improvement but do not distinguish between intervention types. Structural health monitoring [12] provides data acquisition but not classification logic for degradation trends. Secondary effects are documented as individual phenomena [8; 13] but have not been assessed systematically alongside primary effectiveness. A method linking structural change type to predicted durability, quantifying both primary effectiveness and secondary risk, and defining category-specific monitoring would close this gap.

On this basis, the aim of the present study is to develop and verify a method for assessing the long-term impact of structural changes on the reliability and longevity of mechanical systems under operational conditions. Three tasks were defined: (1) to establish the dimensions and metrics of a Post-Modification Performance Assessment (PMPA) applicable across intervention types; (2) to construct a classification linking the type of structural change to a predicted durability category; (3) to verify the method on case studies representing geometry alteration, material substitution, and load environment isolation, each with a post-intervention service record of at least four years.

Literature Review

2.1. Structural Reliability and Fatigue Life After Geometric Changes

Melchers and Beck [1] formulated reliability as time-dependent: resistance decreases while load may increase. A geometric change raises the resistance margin; the subsequent trajectory depends on whether this margin degrades or remains constant. Ang and Tang [2] showed that high variance in the stress field limits the probability-based reliability gain below the deterministic stress reduction.

Fricke [3] showed that effectiveness of a geometric change is predicted by comparing hot-spot stress before and after against the S-N curve. Schijve [4] added that changes reducing stress below the fatigue limit prevent nucleation indefinitely (permanent), while those above the limit produce finite, quantifiable improvement.

Hobbacher [5] codified IIW fatigue design rules assigning each welded joint detail to a FAT class. A geometric change requires reclassification: a gusset plate distributing load over a wider area may shift a detail from FAT 71 to FAT 90 or higher [5]. Hobbacher's classification predicts whether a geometric change improves fatigue performance at the design stage but does not address whether the assigned FAT class holds over years of operational service.

2.2. Material Substitution and Secondary Corrosion Effects

Fontana [8] quantified galvanic corrosion at dissimilar junctions as a function of cathode-to-anode area ratio: a large ratio concentrates attack on a small area. For cupronickel tubes in a carbon steel tubesheet, the ratio is unfavorable, requiring sacrificial anodes or insulating sleeves to prevent the secondary effect from negating the material substitution [8].

Roberge [9] developed corrosion monitoring and lifetime prediction methods for systems where material substitution has been performed, showing that galvanic corrosion rates at bimetallic junctions are not constant but evolve as surface films develop, sacrificial anodes are consumed, and electrolyte chemistry changes with operational conditions. Predicting the service life of a material substitution therefore requires monitoring both the substituted component and the interface zone, and updating the estimate as data accumulates [9].

Jones and Ashby [13] documented how mechanical properties of engineering materials change with temperature, time, and environment. Relevant degradation mechanisms for substituted alloys include stress corrosion cracking under sustained tensile stress, hydrogen embrittlement in cathodically protected high-strength steels, and thermal aging in duplex stainless steels [13]. When a substituted alloy is resistant to the original failure mechanism but susceptible to a different mode, the long-term trajectory depends on whether the operating environment activates the new susceptibility.

2.3. Vibration Isolation and Mechanical Aging of Isolating Elements

Ewins [6] established the framework for structural dynamic modification analysis, showing how changes in mass, stiffness, or damping alter modal parameters. An isolating element reduces transmissibility at frequencies above its natural frequency, with transmitted force decreasing with the square of the frequency ratio [6]. Ewins noted that any stiffening of the isolator due to aging or creep shifts its natural frequency upward and reduces isolation effectiveness.

Harris and Piersol [7] documented the engineering properties of isolation materials, noting that steel springs exhibit creep under sustained static load with rates dependent on stress level and temperature. Rivin [15] extended this to a systematic treatment of passive vibration isolation, documenting that elastomeric isolators lose compliance over time due to chemical and physical aging, with stiffness increases of 10–30 percent over five to ten years in industrial environments. For spring isolators, creep-induced height loss and the associated stiffness increase are the primary aging mechanisms [7; 15]. Both sources establish that isolating elements have a finite effective service life.

2.4. Reliability Assessment and Monitoring After Design Changes

Meeker and Escobar [10] developed statistical methods for analyzing degradation data by tracking a measurable parameter over time and extrapolating to a failure threshold. Three degradation path types are distinguished: linear (constant rate), convex (accelerating), and concave (decelerating) [10]. Rivin's isolator stiffness data [15] follows a concave path, analytically distinct from the linear anode consumption documented by Roberge [9]. Meeker and Escobar's framework provides the statistical machinery for fitting these models but does not prescribe which parameter to measure or how to classify the result by modification type.

Modarres et al. [11] showed that an effective design change produces a step reduction in the hazard function. Crow [14] formalized this in the reliability growth model, which tracks system-level improvement but does not distinguish between intervention types or predict whether individual changes sustain their contribution [14].

Farrar and Worden [12] proposed an SHM framework for tracking condition indicators at modified and adjacent locations. Feature extraction from monitoring data requires a physical model of the expected degradation process; without it, distinguishing meaningful trends from noise is unreliable over multi-year timescales [12].

2.5. Gaps Identified in the Reviewed Literature

Fatigue design recommendations [5] assign modified joints to a FAT class that predicts their life under cyclic loading, but this classification assumes that the material properties and geometry of the modified joint remain constant over the service life. Schijve [4] showed that modifications reducing peak stress below the fatigue limit produce permanent improvements, while those reducing stress above the limit produce finite life extensions. Whether a given geometric design change falls into the first or second category depends on the stress margin achieved, yet no method exists for translating this margin into a durability classification that a maintenance planner can use to set inspection intervals.

Fontana [8] quantified galvanic corrosion severity as a function of the cathode-to-anode area ratio and the potential difference in a given electrolyte, providing an initial estimate of the secondary corrosion rate at a bimetallic junction. Roberge [9] showed that this initial rate evolves over months and years as surface films develop and sacrificial protection is consumed, meaning that the initial area-ratio estimate becomes progressively less accurate without periodic recalibration from monitoring data. These two quantitative tools exist in separate literatures: one predicts the starting severity, the other tracks its evolution. Combining them into a single secondary-effect trajectory that can be compared against the primary effectiveness gain of the material substitution has not been attempted in the reviewed sources.

Rivin [15] and Harris and Piersol [7] documented isolator degradation rates; Meeker and Escobar [10] supplied statistical tools for fitting models to monitoring data. Setting an effectiveness threshold, linking it to measured degradation, and scheduling replacement before crossing requires integration of isolation engineering with reliability assessment, which neither literature provides [7; 10; 15].

Materials and Methods

3.1. Post-Modification Performance Assessment: Dimensions and Metrics

PMPA evaluates the long-term outcome of a structural change along three dimensions, each measured by a defined metric, requiring two categories of input: pre-intervention data (failure history, failure rate, operating conditions) and post-intervention monitoring data collected over a period of at least four years.

Dimension 1: Effectiveness Ratio (ER). ER quantifies the reduction in failure rate achieved by the intervention:

$$ER = \lambda pre \ / \ \lambda post$$

where λpre is the failure rate before the intervention and λpost is the rate in the post-intervention period. When zero post-intervention failures have occurred, ER is reported as a lower bound: $ER \geq Tobs / MTBFpre$. PMPA uses ER as a descriptive classification metric rather than a decision threshold; no minimum acceptable ER is prescribed.

Dimension 2: Secondary Effect Index (SEI). SEI captures new failure modes introduced by the intervention itself. Each secondary effect is assigned a severity rating: 1 (monitored, no action required), 2 (managed through periodic maintenance), 3 (requires design revision). SEI equals the sum of severity ratings; SEI = 0 indicates no secondary effects. Where a severity-3 effect is present, it should be flagged separately regardless of the total SEI value.

Dimension 3: Durability Grade (DG). DG classifies the persistence of the primary improvement over time into one of three categories based on the post-intervention monitoring record and the degradation path of the key performance parameter [10]:

Permanent: no measurable degradation of the key performance parameter over the observation period, and no physical mechanism identified that would cause degradation under continued service. Applies to passive geometric changes with no degradable interface or moving component.

Degrading: primary effectiveness persists, but a secondary effect requires periodic maintenance (anode replacement, coating renewal) to sustain the improvement. Without this input, the secondary effect would eventually compromise the primary gain.

Time-limited: the key performance parameter declines toward a defined threshold below which the

intervention no longer prevents the original failure mode. Applies to interventions involving components with inherent aging mechanisms (spring creep, elastomer hardening, damper wear). Expected service life of the intervention can be estimated from the degradation rate and the threshold value, and replacement must be scheduled before the threshold is crossed [10; 15].

Reclassification from a higher to a lower DG is triggered by monitoring data. Permanent is downgraded to Degrading if the key parameter shows a declining trend over at least three consecutive intervals, or if a previously unidentified secondary effect is detected. Degrading is downgraded to Time-limited if the management protocol fails and the key parameter begins declining toward the threshold. Initial DG uses the expected profile from Table 1; reclassification reflects observed behavior.

3.2. Modification Type and Expected Durability Profile

Three categories of structural change are defined based on the mechanism of action: geometry alteration (adding or reshaping structural material to change the stress distribution), material substitution (replacing the material at a specific location with a grade resistant to the active degradation mechanism), and load environment isolation (interposing a decoupling element between the load source and the vulnerable structure). Each category has a characteristic durability profile arising from its physical properties, as summarized in Table 1.

Actual outcomes may deviate from Table 1 if the intervention is incomplete or the environment differs from assumptions. PMPA uses the expected profile as a starting hypothesis, updated by monitoring data.

3.3. Case Selection Criteria

Three cases were selected, each requiring: (a) documented failure history for baseline ER calculation; (b) defined structural change with design rationale; (c) post-intervention monitoring record of at least four years; (d) documentation of any secondary effects.

Case A: gusset plates on a pump support T-joint (geometry). Case B: cupronickel tube replacement in a seawater cooler (material). Case C: spring isolators on a compressor foundation (load isolation). Each produced a different durability outcome. The presented cases are representative engineering reconstructions derived from documented industrial modification patterns, used to demonstrate the applicability of the PMPA framework rather than serving as its sole empirical basis.

Results

4.1. Case A: Gusset Plate Addition to a Pump Support Frame

A T-joint in a pump support frame developed fatigue cracks at the fillet weld toe three times over five years, at intervals of 22, 20, and 16 months (Figure 1a, left panel). Pre-intervention failure rate:

$$\lambda_{pre} = 3 \text{ failures} / 58 \text{ months} = 0.052 \text{ failures per month (MTBF} \approx 19.3 \text{ months).}$$

Engineering intervention consisted of welding two triangular gusset plates on opposite sides of the T-joint, redistributing the load path from the single weld toe to the gusset-to-beam weld line over a 120-mm contact length (Figure 1a, right panel). Hot-spot stress at the original crack location, measured by strain gauges before and after installation, decreased from 185 MPa to 98 MPa, a reduction of 47 percent. The modified joint configuration was reclassified to a higher FAT category per Hobbacher [5], and the reduced hot-spot stress placed the detail within the safe region of the applicable S-N curve at the estimated service cycle count, consistent with indefinite fatigue life under the operating load spectrum.

Post-intervention monitoring extended over 84 months (7 years). Biannual magnetic particle inspections served as the primary screening method,

Table 1

PMPA classification matrix: expected durability profile by intervention type

Dimension	Geometry alteration	Material substitution	Load environment isolation
Mechanism of action	Stress field redistribution through added or reshaped material	Replacement of degradation-susceptible grade with resistant grade	Decoupling element reduces transmitted load
Expected ER range	ER > 4.0 (if stress reduced below fatigue limit; ER → ∞)	ER > 3.0 (primary mechanism eliminated)	ER > 3.0 initially (transmissibility-dependent)
Typical secondary effects	Minor stiffness redistribution to adjacent elements	Galvanic corrosion at bimetallic boundary; potential new susceptibility of replacement alloy	None at structure; isolator aging as internal process
Expected SEI	0–1	1–2	0
Expected DG	Permanent	Degrading (managed)	Time-limited
Degradation mechanism	None (passive geometry)	Anode consumption; surface film evolution at junction	Spring creep; elastomer aging; damper wear
Monitoring focus	Periodic inspection of adjacent elements	Interface zone corrosion rate; anode condition	Isolator stiffness or transmissibility measurement

Source: developed by the author

with 14 inspections performed at the original crack location and at the new gusset weld toes; none detected any crack indication. Full strain-gauge stress measurements, requiring temporary instrumentation and load-controlled test conditions, were conducted at 24-month intervals (months 24, 48, and 72), yielding values in the range of approximately 95–100 MPa, indicating that the stress field remained stable of the initial post-intervention measurement.

PMPA classification: ER ≥ 84 / 19.3 = 4.4 (lower bound; no failures in 84 months). SEI = 1 (one secondary effect identified: minor stiffness increase at the adjacent beam-to-column connection, monitored at biannual inspections, no action required; severity rating 1). DG = Permanent (no degradation of hot-spot stress ratio over 84 months, no aging mechanism present in the passive gusset geometry).

4.2. Case B: Cupronickel Tube Replacement in a Seawater Cooling System

Brass condenser tubes (CDA 443) in a seawater-cooled heat exchanger failed by dezincification four times over six years at 18–24 month intervals, producing tube perforations requiring plugging (Figure 1b, left panel). Pre-intervention failure rate:

λpre = 4 failures / 72 months = 0.056 failures per month (MTBF ≈ 18 months).

All 126 tubes were replaced with 90/10 cupronickel (UNS C70600), eliminating the dezincification-susceptible phase (Figure 1b, right panel). The cupronickel-to-carbon-steel tubesheet junction created a galvanic cell (~200 mV in aerated seawater), managed by sacrificial zinc anodes sized at ~4.5 kg/year [8; 9].

Post-intervention monitoring extended over 72 months (6 years). No tube perforations or dezincification indications were detected. Ultrasonic tube wall thickness measurements at months 24, 48, and 72 showed no measurable wall loss (resolution 0.1 mm). At the tubesheet junction, however, anode consumption proceeded as predicted: anode mass decreased linearly from 100 percent to approximately 12 percent over the first 42 months, at which point the anodes were replaced (Figure 3, dashed curve). After replacement, the second set of anodes followed the same consumption trajectory. Without anode replacement, galvanic corrosion at the tubesheet face would have initiated within 6–8 months after anode exhaustion, based on the measured corrosion potential at the junction [9].

PMPA classification: ER ≥ 72 / 18 = 4.0 (lower bound; zero tube failures in 72 months). SEI = 2 (one secondary effect: galvanic corrosion at tubesheet junction, severity rating 2 — managed through periodic anode replacement at 42-month intervals). DG = Degrading (primary effectiveness maintained, but dependent on active anode management; anode exhaustion without replacement would allow secondary corrosion to compromise tubesheet integrity within approximately one year).

4.3. Case C: Spring Vibration Isolators on a Compressor Foundation

A reciprocating compressor (720 rpm, excitation frequency 12 Hz) transmitted vibration through its foundation into adjacent piping, causing three socket weld fatigue failures over 42 months at approximately 14-month intervals (Figure 1c, left panel). Pre-intervention failure rate:

λpre = 3 failures / 42 months = 0.071 failures per month (MTBF ≈ 14 months).

Four steel coil spring isolators (natural frequency 3.5 Hz, frequency ratio 3.4, transmissibility ~0.10) were installed between skid and foundation (Figure 1c, right panel). Vibration velocity decreased from 18.5 to 3.7 mm/s RMS, an 80-percent reduction [6; 7].

Post-intervention monitoring extended over 48 months (4 years). No pipe connection fatigue failures occurred during this period. Vibration measurements were performed at semiannual intervals across nine measurement points. Foundation vibration velocity increased from 3.7 mm/s RMS at installation to 7.1 mm/s RMS at month 48, following a concave path with the rate of increase decelerating in the later intervals (Figure 3, dotted curve). Isolation effectiveness, normalized to the initial value, declined from 100 percent to approximately 62 percent over this period. Static deflection measurements indicated that spring height had decreased by approximately 3 mm (about 14 percent of initial deflection), increasing the effective spring stiffness and raising the isolator natural frequency from 3.5 Hz to approximately 4.1 Hz [15].

At the measured decline rate, the isolation effectiveness would reach the minimum acceptable threshold of 50 percent (corresponding to foundation vibration of approximately 9.3 mm/s, below which pipe connection stress remains within the fatigue endurance limit) at approximately month 65–70. Based on this projection, isolator replacement was scheduled at 60 months to maintain a safety margin. PMPA classification: ER ≥ 48 / 14 = 3.4 (lower bound; zero failures in 48 months). SEI = 0 (no secondary effects on the structure; isolator aging is an internal process). DG = Time-limited (isolation effectiveness declining at a measurable rate; projected functional life approximately 60–70 months before replacement required).

4.4. Comparative Summary

Figure 1 shows before-and-after schematics for all three interventions.

Table 2 consolidates PMPA metrics. Comparable ERs (≥ 4.4, ≥ 4.0, ≥ 3.4) with divergent SEI and DG illustrate that effectiveness alone does not determine durability; expected DG was consistent with observed outcomes in all cases.

Figure 2 presents an illustrative projection of relative failure rate over eight years, based on the degradation patterns observed in the case studies: Case A (solid) remains flat near zero; Case B (dashed) rises gradually as anodes are consumed; Case C (dotted)

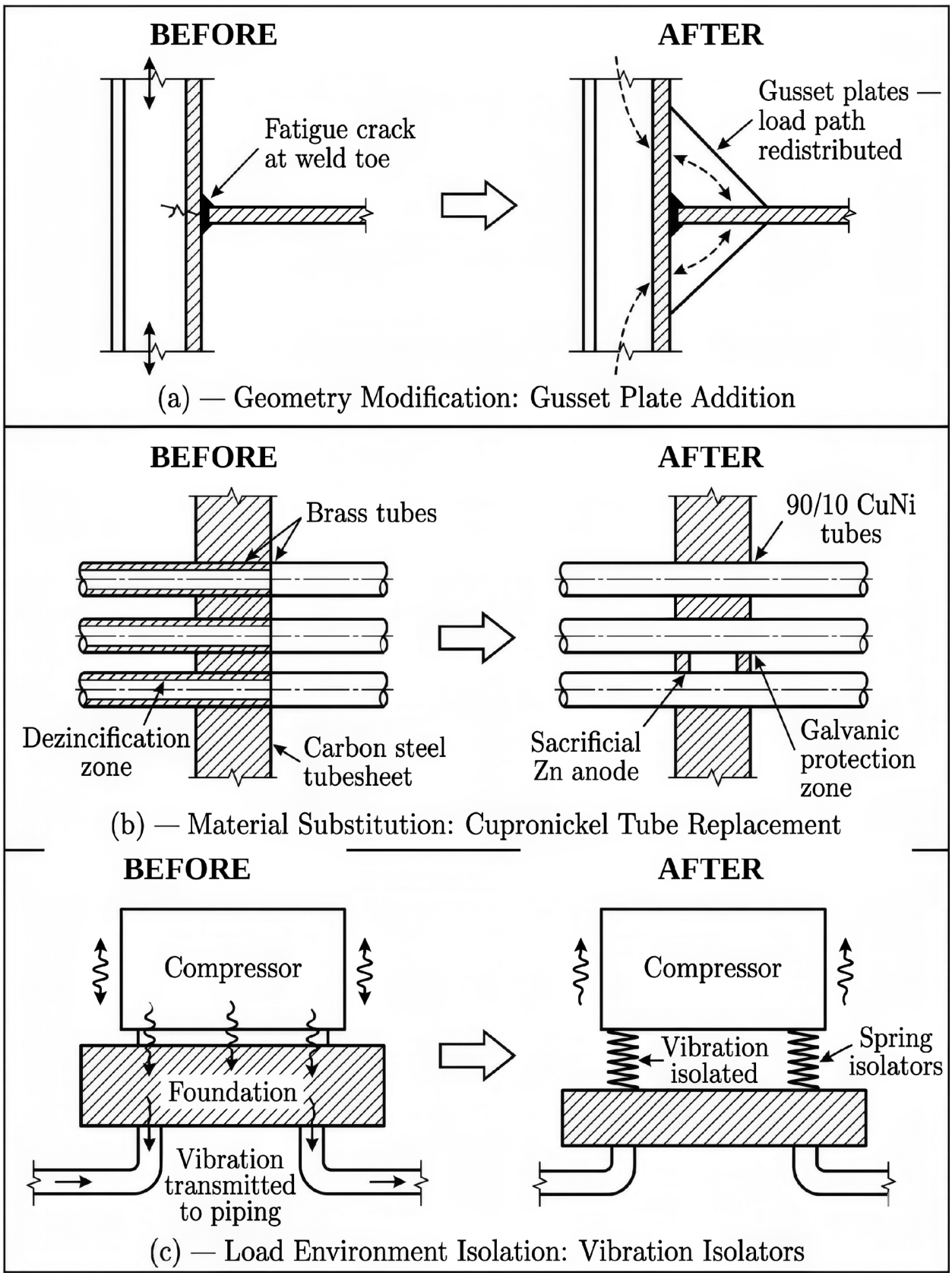


Fig. 1. Engineering schematics of three structural interventions:
(a) gusset plate addition to pump support frame T-joint;
(b) cupronickel tube replacement with sacrificial anode protection in seawater cooler;
(c) spring vibration isolator installation on compressor foundation
Source: developed based on case reconstruction

Table 2

PMPA classification summary for three case studies

PMPA dimension	Case A (Gusset plates)	Case B (CuNi tubes)	Case C (Spring isolators)
Intervention type	Geometry alteration	Material substitution	Load environment isolation
Target failure mode	Fatigue crack at T-joint weld toe	Dezincification of brass tubes	Pipe connection fatigue from vibration
Pre-intervention MTBF	19.3 months	18 months	14 months
Observation period	84 months	72 months	48 months
Post-intervention failures	0	0 (tubes)	0
ER (lower bound)	≥ 4.4	≥ 4.0	≥ 3.4
Secondary effects	Minor stiffness redistribution	Galvanic corrosion at tubesheet	None (isolator aging internal)
SEI	1 (severity 1)	2 (severity 2)	0
Key parameter monitored	Hot-spot stress ratio	Anode mass remaining	Isolation effectiveness
Parameter stability	Stable (±3% over 84 mo)	Anode: linear decline, replaced at 42 mo	Declining: 100% → 62% over 48 mo
DG expected (Table 1)	Permanent	Degrading	Time-limited
DG observed	Permanent	Degrading (managed)	Time-limited (replacement at 60 mo)
Monitoring protocol	Biannual MPI + stress check	Annual UT + anode inspection	Semiannual vibration measurement

Source: constructed from operational diagnostic analysis

rises steeply, approaching pre-intervention levels by year 7–8.

Figure 3 presents the measured degradation data for each case, normalized to a common percentage scale. Case A (solid line, hot-spot stress ratio) remains at 55 percent of the pre-intervention value across all 84 months with no discernible trend. Case B (dashed line, anode mass remaining) declines linearly from 100

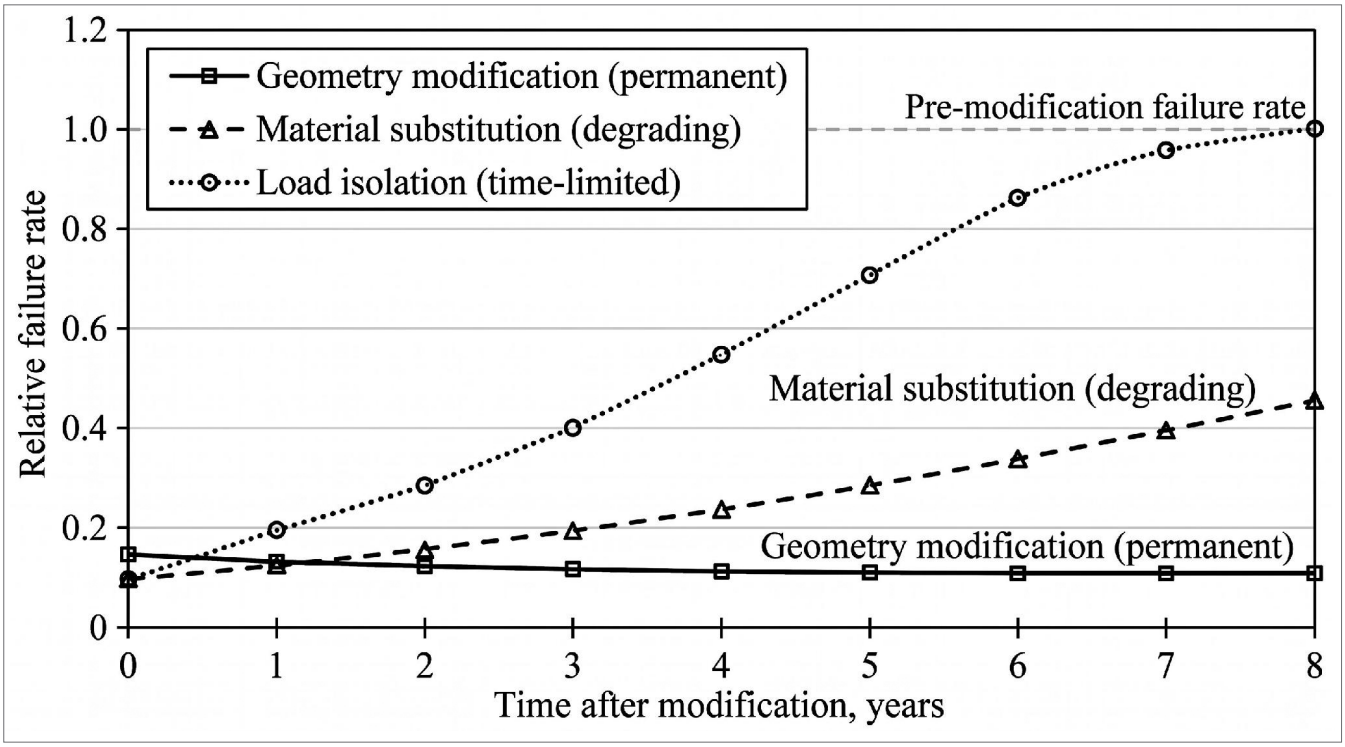


Fig. 2. Illustrative failure rate trajectories after structural intervention (conceptual representation based on observed engineering trends): geometry alteration (permanent), material substitution (degrading), and load environment isolation (time-limited)

Source: modeled by the author based on case study data

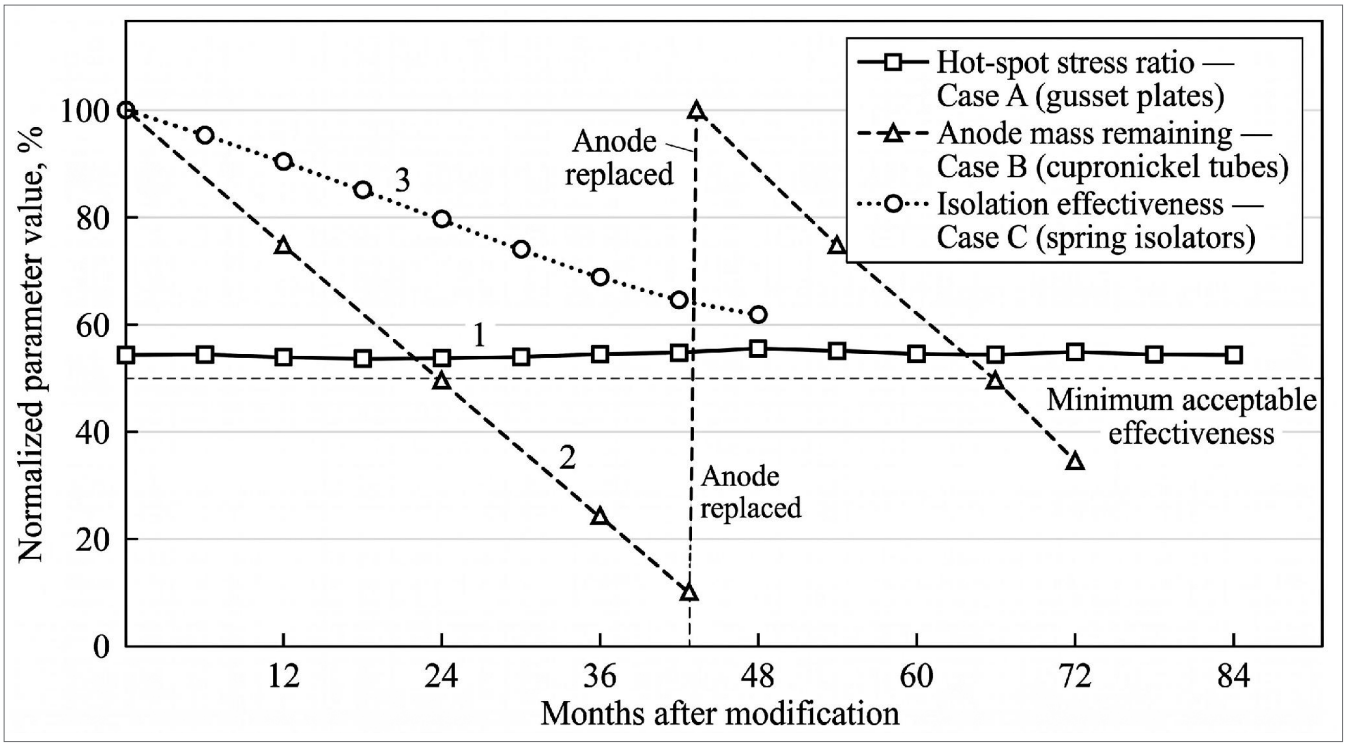


Fig. 3. Normalized post-intervention monitoring data: hot-spot stress ratio (Case A), anode mass remaining (Case B), and isolation effectiveness (Case C)

Source: constructed from post-intervention monitoring records

percent to approximately 10 percent over 42 months, jumps to 100 percent upon anode replacement, and resumes the same linear decline. Case C (dotted line, isolation effectiveness) follows a concave path from 100 percent to 62 percent over 48 months, with the decline rate decreasing in the later measurement intervals. A horizontal reference line at 50 percent marks the minimum acceptable effectiveness threshold for Case C.

Discussion

5.1. Modification Type as a Predictor of Durability

All three engineering changes achieved comparable effectiveness ratios (ER ≥ 3.4–4.4), yet their long-term trajectories diverged in a manner consistent with the PMPA classification matrix. In Case A, the hot-spot stress remained within ±3 percent of its post-intervention value over 84 months because the gusset plates are passive structural elements with no interface, moving part, or consumable component that could degrade independently of the parent structure. Schijve's distinction [4] between stress reduction below and above the fatigue limit provides the mechanistic explanation: the 47-percent reduction placed the peak stress in the indefinite-life region, where crack nucleation cannot initiate under the operating load spectrum. A geometry change that achieves this condition produces a permanent improvement by eliminating the physical precondition for the failure mode.

Case B achieved an equally high ER (≥ 4.0) through material substitution, yet the classification diverged to Degrading because the intervention introduced a bimetallic boundary that required active management. Without periodic anode replacement, the galvanic corrosion rate at the tubesheet junction would have produced a new failure mode within approximately one year of anode exhaustion [8]. Fontana's area-ratio model [8] predicted the initial galvanic severity, and Roberge's monitoring data [9] showed that the consumption rate remained linear, allowing scheduling of replacements at predictable intervals. Primary effectiveness was maintained over the full 72-month observation, but its continuation is conditional on the maintenance protocol being sustained.

Case C demonstrated the time-limited profile most directly: spring creep reduced isolation effectiveness from 100 to 62 percent over 48 months, following the concave degradation path documented by Rivin [15] for steel spring isolators under sustained static load. Meeker and Escobar's degradation extrapolation framework [10] allowed projection of the threshold crossing at approximately month 65–70 from the first 48 months of data, providing sufficient lead time for scheduling replacement at month 60. Without this projection, the isolator would have continued in service until pipe connection fatigue recurred, at which point the intervention's failure would have been detected reactively rather than prevented proactively.

5.2. Limitations of Effectiveness Ratio as a Standalone Metric

An engineer relying on ER as the sole assessment metric might assign identical monitoring and maintenance protocols to all three cases, since all produced zero post-intervention failures and ER values exceeding 3.0. Only when SEI and DG are added does the assessment differentiate Case B (ER ≥ 4.0 but SEI = 2 and DG = Degrading) from Case A (ER ≥ 4.4, SEI = 1, DG = Permanent). Without this differentiation, the galvanic boundary in Case B would be under-monitored and the stable geometry in Case A over-monitored. PMPA's three-dimensional structure prevents this conflation by requiring that secondary effects and durability be assessed alongside the primary failure rate reduction.

5.3. Limitations

Preliminary verification covered one case per intervention category in industrial process environments, confirming that Table 1 predictions matched observed outcomes but not establishing the frequency of deviations. Cases where geometry changes produce Degrading outcomes (e.g., gusset corrosion) or material substitutions produce Permanent outcomes (no bimetallic junction) were not represented. SEI's arithmetic summation and the DG reclassification triggers have not been tested against borderline cases. Observation periods (48–84 months) may not capture slow-onset mechanisms such as stress corrosion cracking.

5.4. Practical Implications

PMPA can function as a post-intervention audit tool within maintenance management systems. After an engineering change is implemented, the expected DG from Table 1 serves as a starting hypothesis that defines the initial monitoring protocol: periodic inspection with low frequency for Permanent, interface-focused monitoring with scheduled consumable replacement for Degrading, and parameter-tracking with threshold-based replacement scheduling for Time-limited. Because the expected profile is a prediction rather than a guarantee, monitoring data may contradict it; when a reclassification trigger is met, the protocol escalates to the next category. Encoding these protocols and their escalation rules into a computerized maintenance system would standardize post-intervention follow-up and reduce the risk that a time-limited or degrading intervention is treated as permanent by default.

Conclusions. A Post-Modification Performance Assessment method is proposed as an engineering classification framework for evaluating the long-term impact of structural changes on mechanical system reliability, rather than as a fully validated predictive reliability model. Three assessment dimensions were defined: effectiveness ratio quantifying failure rate reduction, secondary effect index capturing new degradation mechanisms introduced by the intervention, and durability grade classifying the persistence of the improvement as permanent, degrading, or time-limited. A classification matrix linking intervention type to expected durability profile was constructed, with reclassification triggers for updating the assessment based on monitoring data.

Initial case-based demonstration on three representative industrial cases, each covering a different intervention category, illustrated that the classification logic was consistent with the observed durability outcome in all three instances. Geometry alteration (gusset plate addition) produced a permanent improvement sustained over 84 months with no measurable parameter change. Material substitution (cupronickel tube replacement) eliminated the original failure mode but required active galvanic protection management, matching the degrading profile. Load environment isolation (spring vibration isolators) achieved high initial effectiveness that declined measurably over 48 months due to spring creep, matching the time-limited profile. Comparable primary effectiveness across all three interventions supported the proposition that failure rate reduction alone does not determine long-term reliability trajectory.

Limitations include verification on one case per intervention category, untested borderline scenarios where an intervention deviates from its expected profile, and observation periods that may not capture slow-onset degradation mechanisms. Future work should expand case-based validation across multiple cases per category, develop quantitative thresholds for DG reclassification triggers, and integrate PMPA protocols into computerized maintenance systems for automated post-intervention monitoring.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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NEURAL NETWORK-BASED DETECTION OF LEAF DEFECTS IN TREES USING TENSORFLOW

Summary. *This study addresses the development of an automated methodology for the identification of tree foliage and associated morphological defects utilizing digital imagery. The primary objective is to augment the reliability of defect detection through advanced image analysis techniques. To this end, a neural network architecture was engineered using Python and the TensorFlow framework to classify defects and segment compromised tissue. This system facilitates the early recognition of pathologies, thereby enabling prophylactic interventions to maintain arboreal health. Beyond its diagnostic utility, the proposed framework streamlines biological and botanical research by automating data acquisition and analysis, thus assisting in the investigation of environmental factors influencing tree development. In the agricultural sector, the system offers significant value by enabling the rapid, precise diagnosis of diseases and pest infestations in deciduous species. Furthermore, it aids in the identification of macronutrient deficiencies (nitrogen, phosphorus, potassium), allowing agronomists to implement precision agriculture strategies that optimize plant nutrition and physiological vigor. The MobileNet-based solution demonstrated a 92.8% accuracy on the validation dataset and 88.8% in real-world field tests, outperforming baseline models such as ResNet-50 and SVM.*

Key words: *artificial neural networks, precision agriculture, leaf disease identification, automated diagnosis, machine learning, computer vision, plant pathology.*

Introduction. In the face of contemporary environmental exigencies, the conservation and rational utilization of arboreal genetic resources have assumed critical importance. These endeavors constitute the cornerstone of forest genetics, selective breeding and silviculture, simultaneously driving enhancements in forest productivity and the optimization of stand composition [1]. Furthermore, the systematic introduction and monitoring of woody flora are indispensable for sustaining biodiversity and ensuring the viability of sustainable forest management practices [2]. In this context, the deployment of automated systems for the remote sensing of plant physiological states has emerged as a key technological advancement [3].

Currently, such technologies are being actively developed to facilitate the timely detection of phytopathologies, the assessment of hydration status, and the quantification of biomass under variable moisture regimes, encompassing both in situ and controlled greenhouse environments [4]. The accurate diagnostic assessment of plant health typically necessitates solving complex image classification challenges. To this end, Artificial Neural Networks (ANN) provide a robust solution, operating with high algorithmic autonomy to ensure precision and adaptability with minimal human intervention [5; 6].

Building upon these technological foundations, the primary objective of this research is the development of an automated diagnostic framework utilizing the TensorFlow ecosystem to identify morphological defects in deciduous trees. This system is designed to enable continuous health monitoring, thereby mitigating the ecological ramifications associated with pathogen proliferation and nutrient deficiencies [7]. To achieve this objective, the study systematically addresses a series of interconnected tasks: ranging from a comprehensive domain analysis and the selection of optimal computational methods to the architectural design, including UML specifications, and the final training, testing and validation of a Convolutional Neural Network (CNN) model designed for the multi-class classification of foliar conditions [8].

Materials and methods. The empirical foundation of this research was established utilizing the PlantVillage dataset, an open-access repository accessed via the Kaggle platform, which served as the primary source for training and validation [9; 10]. The corpus comprises 18 042 digital RGB images

representing eight distinct categories of crop foliage, specifically categorized into healthy and pathological states for Apple, Grape, Peach and Tomato, covering diseases such as Apple Scab, Grape Black Rot, Peach Bacterial Spot and Tomato Late Blight. To ensure statistical validity and mitigate inductive bias arising from potential class imbalances, a stratified sampling strategy was employed to partition the dataset into three subsets: 70% was allocated for training, 15% for validation — utilized strictly for hyperparameter tuning and early stopping, and 15% for independent testing.

To further evaluate ecological validity and model robustness under uncontrolled lighting conditions, an auxiliary test set comprising 20 in situ images was acquired using smartphone cameras in a natural garden environment. Prior to model ingestion, a rigorous preprocessing pipeline was implemented wherein all input imagery was standardized to a spatial resolution of 224 x 224 and pixel intensities were normalized to the 0, 1 interval. To enhance the model's generalization capability and robustness against geometric transformations, data augmentation techniques were applied to the training set, including random rotation (±15 degrees), color jitter affecting brightness and contrast, and random zoom operations [11]. Furthermore, to isolate the region of interest (ROI) and minimize background noise, a background subtraction algorithm based on inter-frame differences was utilized, supplemented by morphological operations to effectively eliminate artifacts caused by sensor flicker or lighting fluctuations [12]. The core diagnostic engine was developed using Python within the TensorFlow 2.14 framework and Keras 3.0 library, hosted on the Google Colab cloud platform to leverage high-performance computing resources [13].

The system employs a MobileNet Convolutional Neural Network architecture, selected for its superior computational efficiency and suitability for mobile deployment [14]. A transfer learning paradigm was adopted, wherein the model was initialized with weights pre-trained on the ImageNet dataset to accelerate convergence and optimize feature extraction [15; 16]. Model training was executed over a maximum of 30 epochs with a batch size of 32, utilizing Stochastic Gradient Descent (SGD) with a momentum coefficient of 0.9 as the optimization algorithm [17]. The learning rate was initialized at 0.001 and dynamically modulated using a cosine annealing scheduler to facilitate convergence toward the global minimum [18]. To prevent overfitting, dropout regularization was integrated within the network layers and an early stopping mechanism with a patience of 5 epochs was enforced based on validation loss monitoring [19]. The operational architecture of the deployed system is distributed across a client-server topology where the client-side interface is an Android-based mobile application capable of real-time image acquisition via the device's optical sensor [20].

This client communicates via standard network protocols with a dedicated Processing Web Server responsible for authentication and inference management, while persistent data storage and tagging are handled by a backend Database Server utilizing PostgreSQ L. To contextualize the performance of the proposed MobileNet solution, baseline comparisons were conducted against a ResNet-50 deep learning model and a traditional Support Vector Machine (SVM) classifier utilizing Histogram of Oriented Gradients (HOG) features, with all experimental procedures executed using fixed random seeds to ensure full scientific reproducibility [21; 22; 23].

Computational framework and architectural design of the diagnostic system:

This chapter delineates the methodological strategy employed for the implementation of an artificial neural network designed for the automated detection of foliar pathologies. The discussion centers on the rationale behind the selection of computational tools, the structural integrity of the system architecture and an evaluation of the associated operational advantages.

As the foundational ecosystem for neural network development, TensorFlow was selected due to its status as a robust, scalable machine learning library capable of executing high-performance computations in heterogeneous environments. By utilizing data flow graphs to represent computational operations and state transitions, TensorFlow facilitates the seamless distribution of processing tasks across multi-core CPU, GPU and Tensor Processing Units (TPU) [24]. This architectural flexibility renders it equally suitable for large-scale industrial deployments and focused experimental research. Moreover, comparative benchmarking against alternative libraries has demonstrated TensorFlow's superior efficacy and scalability.

The high-level conceptual schema of the developed solution is depicted in Figure 1, which illustrates the tripartite interaction between the end-user, the software logic and the hardware interface. The deployment vector is a mobile application optimized for the Android platform, utilizing the device's integrated optical sensor as the primary input mechanism. Following image capture, the visual data is subjected to analysis by the CNN, which classifies the physiological state of the leaf. Subsequent to this analysis, the system outputs a diagnostic result distinguishing between healthy and compromised specimens. In instances where pathology is identified, the application generates targeted recommendations for therapeutic interventions.

The comprehensive architectural blueprint of the system is visually delineated in Figure 2. Following a rigorous preprocessing regimen, the data were employed to optimize the neural network within the Python-based TensorFlow environment. To ensure algorithmic robustness and cross-platform reproducibility, the validation protocol was executed within a containerized Docker environment. Subsequently, the verified

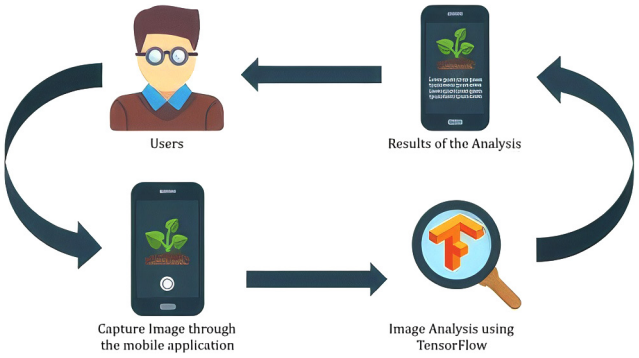


Fig. 1. Conceptual framework

model was transitioned into a mobile application framework to facilitate real-time, in-field disease detection.

The system's operational architecture, visually delineated in Figure 3, integrates a mobile interface featuring dual input modalities: a dedicated optical sensor module for real-time image acquisition and a repository retrieval system for accessing archival foliage imagery. Upon data ingestion, the convolutional neural network processes the visual input to generate a diagnostic classification, subsequently displaying the physiological status of the specimen. This architectural configuration serves as the practical realization of the methodological framework, wherein TensorFlow was prioritized as the core implementation environment due to its inherent scalability.

Experimental validation was conducted within a computational environment powered by TensorFlow 2.14 and Keras 3.0. Prior to processing, input imagery was standardized via resizing to spatial dimensions of 224 x 224 and pixel-intensity normalization to the 0, 1 interval. Model parameter optimization was achieved utilizing SGD with a momentum coefficient of 0.9, initiated with a learning rate of 0.001 that was dynamically modulated by a cosine annealing scheduler. The training protocol was executed over a maximum of 30 epochs with a batch size of 32, incorporating an early stopping mechanism (patience = 5) monitored against validation loss to mitigate overfitting. To guarantee experimental reproducibility, a fixed random seed (42) was enforced, and the final model selection was predicated on the checkpoint exhibiting the maximal Macro-F1 score on the validation subset.

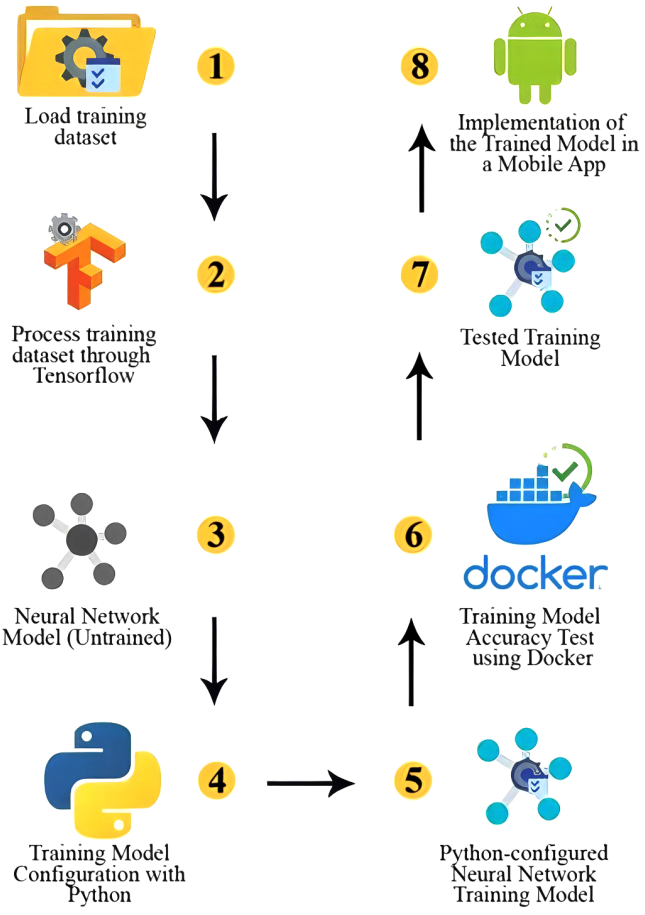


Fig. 2. System design using a neural network

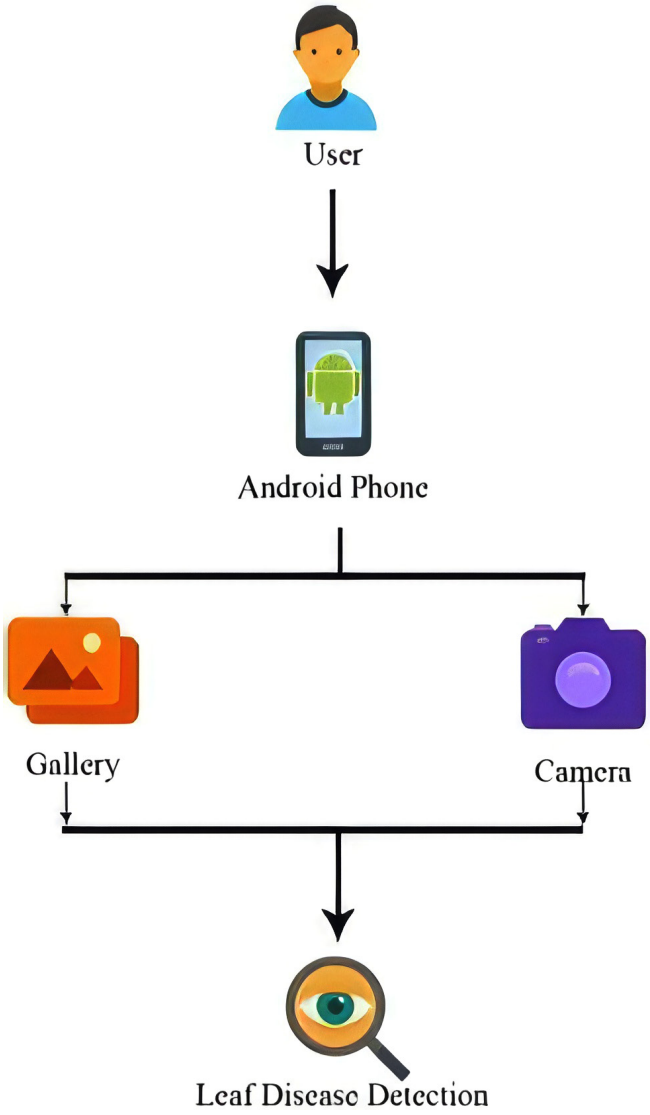


Fig. 3. System architecture

Implementation strategy and model training:

A fundamental prerequisite for algorithmic efficacy is the precise identification and classification of data. Conventional recognition algorithms often lack robustness against geometric transformations, failing when target objects undergo rotation, distortion or deformation. Artificial neural networks offer a potent solution to these challenges [25]. In the specific context of pattern recognition, neural networks consistently demonstrate superior performance and diagnostic reliability. Unlike traditional methods that rely on hand-crafted features, neural networks automate the extraction of optimal parameters during the training phase. This paradigm shift eliminates the need for manual definition of key features, placing the emphasis instead on the curation of a high-quality training dataset.

This capability is particularly pertinent to the analysis of defective foliage, which is characterized by significant morphological heterogeneity — varying shapes, colors, textures and dimensions. While Multilayer Perceptrons are a foundational architecture, they are often ill-suited for high-resolution image recognition due to the exponential increase in computational complexity. To mitigate these limitations, CNN is employed. CNN represents the state-of-the-art in image classification. By utilizing convolutional kernels rather than analyzing individual pixels in isolation, CNN achieves parameter sharing, significantly reducing the number of trainable weights compared to MLP. This approach enables the network to learn spatial hierarchies and generalize features effectively, rendering the model invariant to translation and rotation.

The identification of leaf defects is a non-trivial challenge lacking a universal solution. The resulting detection workflow is illustrated in Figure 4. To isolate the ROI, a background subtraction algorithm based on inter-frame difference was implemented. To address artifacts arising from lighting fluctuations or sensor flicker, morphological operations were applied. Specifically, erosion and dilation (expansion) were utilized to eliminate noise and refine the foreground mask. These preprocessing steps ensure that subsequent analysis is focused exclusively on the relevant biological structures. The schematic representation of this algorithmic process is detailed in Figure 5.

The functional architecture of the system is schematically delineated in Figures 6 and 7, illustrating the interaction between the User Interface (UI) module and the core identification module. The UI module serves as the primary control environment, comprising a suite of elements designed for camera configuration, real-time image visualization and diagnostic feedback. Critical to this module is the operator's ability to manipulate camera parameters, specifically variable zoom and scaling. The identification module comprises two distinct sub-components: the recognition engine and the interface command generator. The recognition engine processes incoming data from the sensor module, performing the critical task of identifying foliar deformations or pest infestations within the digital capture.

There are several actors in this system, including a system operator, a system administrator, a camera, an engineer and a CV specialist. The system operator acts as a user of the system and reacts to messages about the detection of leaves in the image. The system administrator is responsible for setting up the technical configuration. The engineer deals with data marking, marks new data and updates the system algorithm. Computer vision experts update the algorithm model based on the new labeled data and change the algorithm parameters to improve the recognition performance. Each scenario is further described in the diagram below (Figure 8). The system's physical architecture and component distribution are visually articulated in the deployment diagram, where the mobile application functions as the primary client node interfacing with a Processing Web Server and a PostgreSQL Database Server.

Data processing and control pipeline:

Subsequent to the training phase described in the methodology, the functional efficacy of the developed system was verified via deployment on a local web server. This validation process confirmed the system's ability to load the machine learning model within

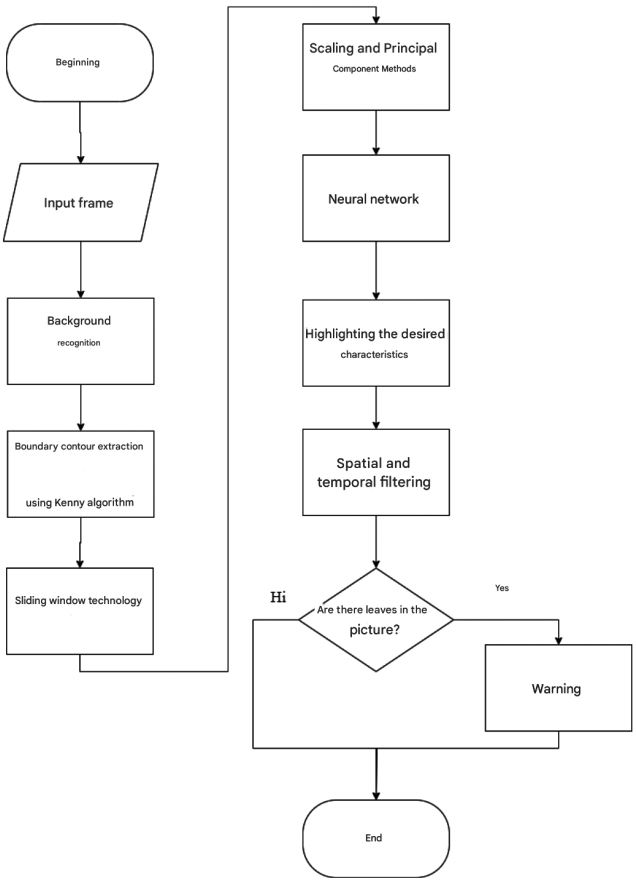


Fig. 4. General scheme of the algorithm for identification of leaves

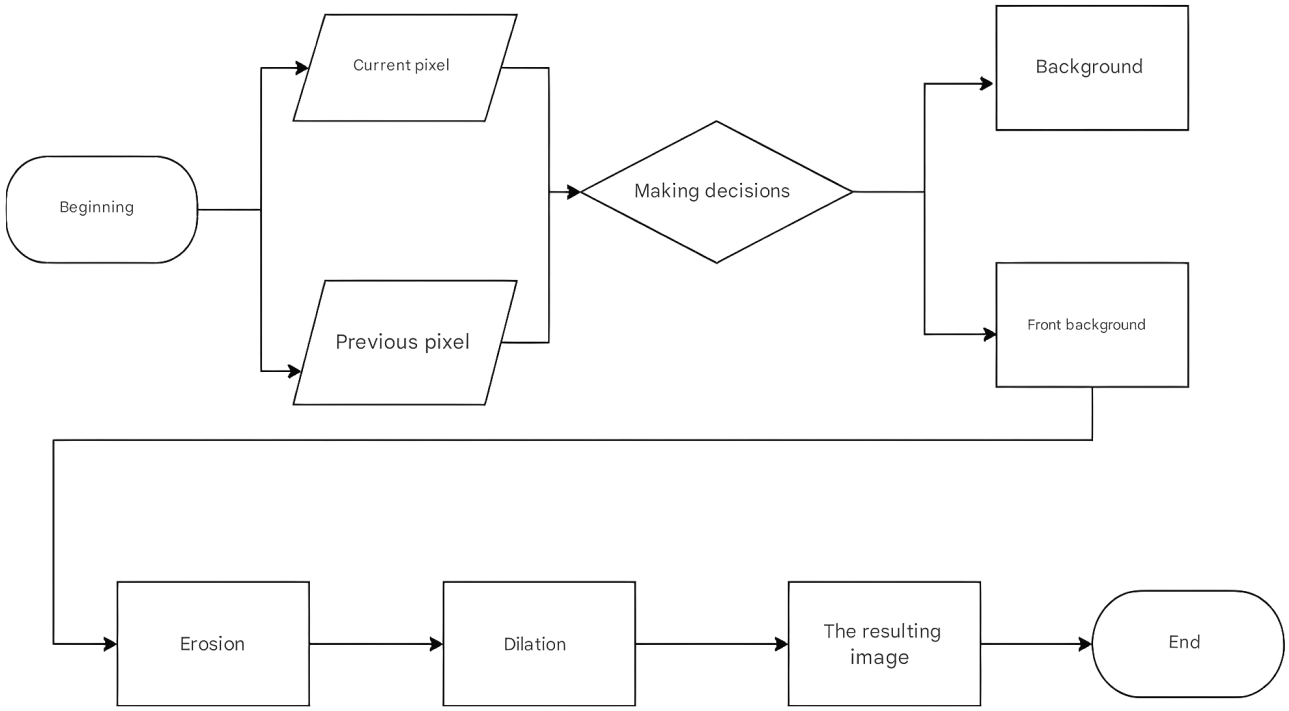


Fig. 5. Scheme of the algorithm for selecting the background

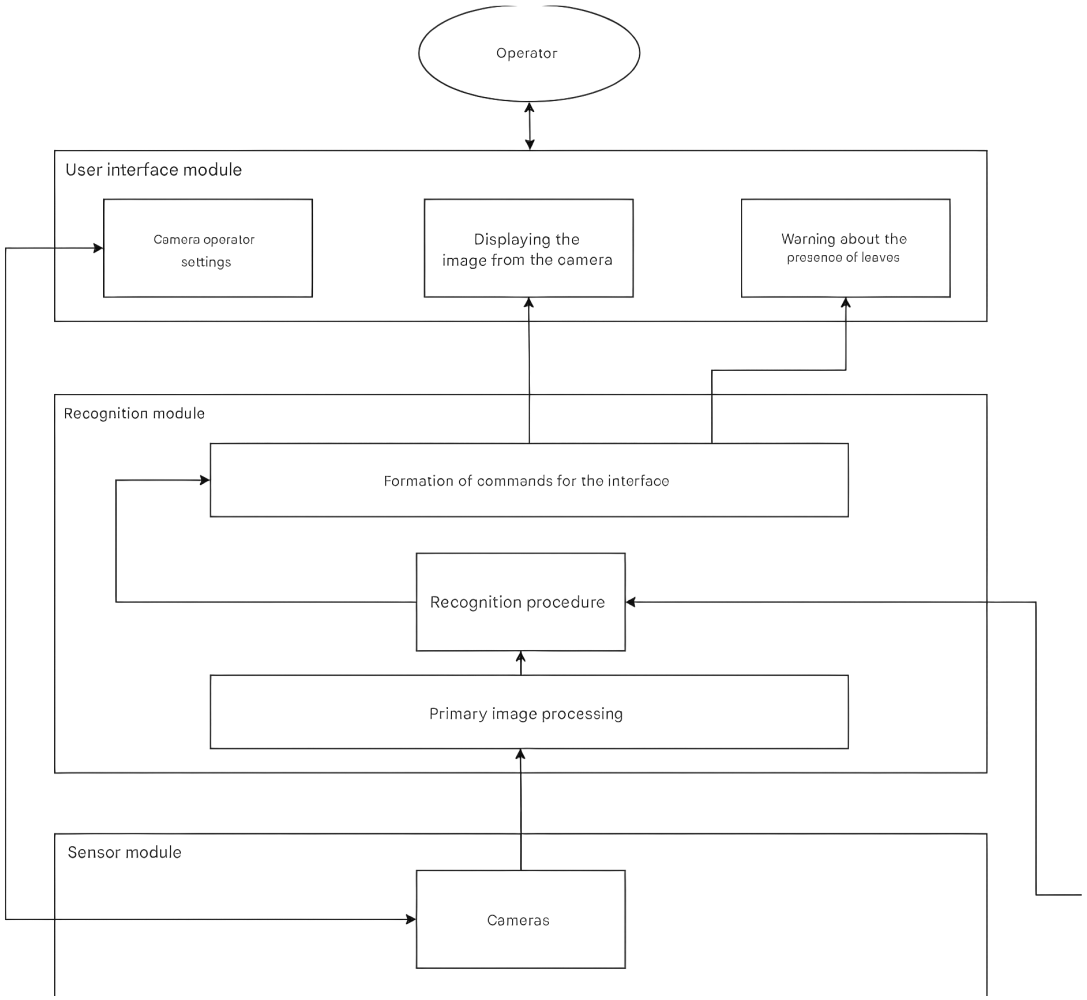


Fig. 6. Functional scheme

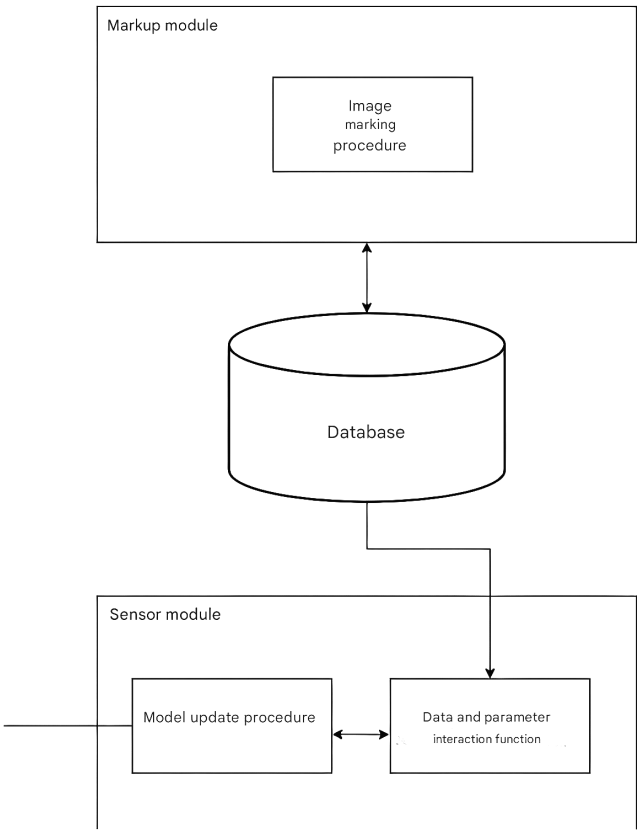


Fig. 7. Continuation of the functional scheme

a browser environment and execute real-time inference. As illustrated in Figure 9, the user interface facilitates interaction through a designated upload zone, allowing operators to submit local image files and receive immediate diagnostic visualization and classification results.

The practical evaluation of the deployed model is exemplified in Figure 9, which depicts a foliage specimen affected by bacterial spot. Crucially, this imagery was derived from an independent test corpus explicitly excluded from the training regimen to ensure an unbiased assessment of the model's generalization capabilities. Upon processing this unobserved data, the neural network assigned the specimen to the scab class. However, the validation phase also elucidated specific operational constraints: the system requires the target object to occupy the majority of the visual frame and be subject to uniform illumination. Also when analyzing non-pathological samples (as illustrated in Figure 10), the system correctly identifies the taxonomic origin of the foliage without flagging defects, thereby accurately confirming the healthy physiological state of the plant.

Regarding computational efficiency, a latency discrepancy was noted between the initial and subsequent inference cycles. The primary classification event entails a duration of approximately 7–10 seconds due to the necessary model initialization overhead, whereas subsequent operations exhibit a marked reduction in processing time to a range of 3–5 seconds.

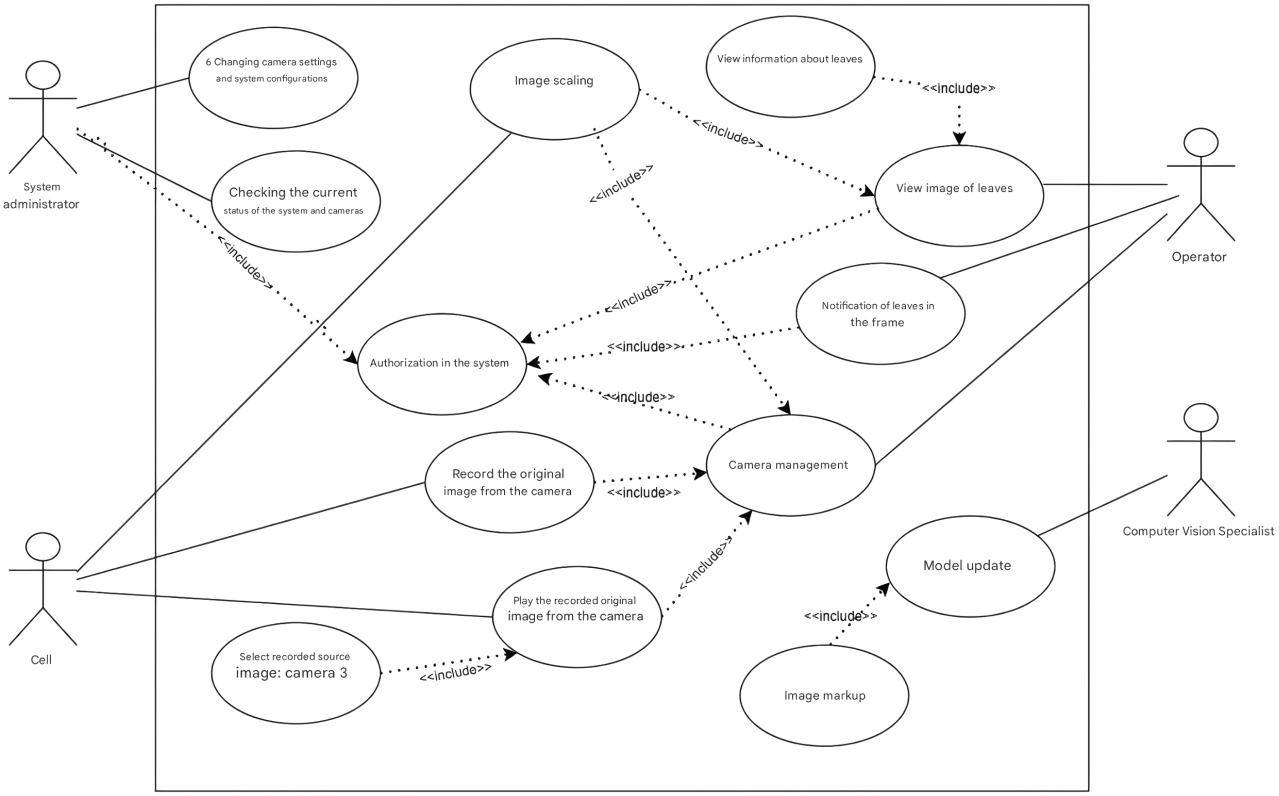


Fig. 8. Usage diagram

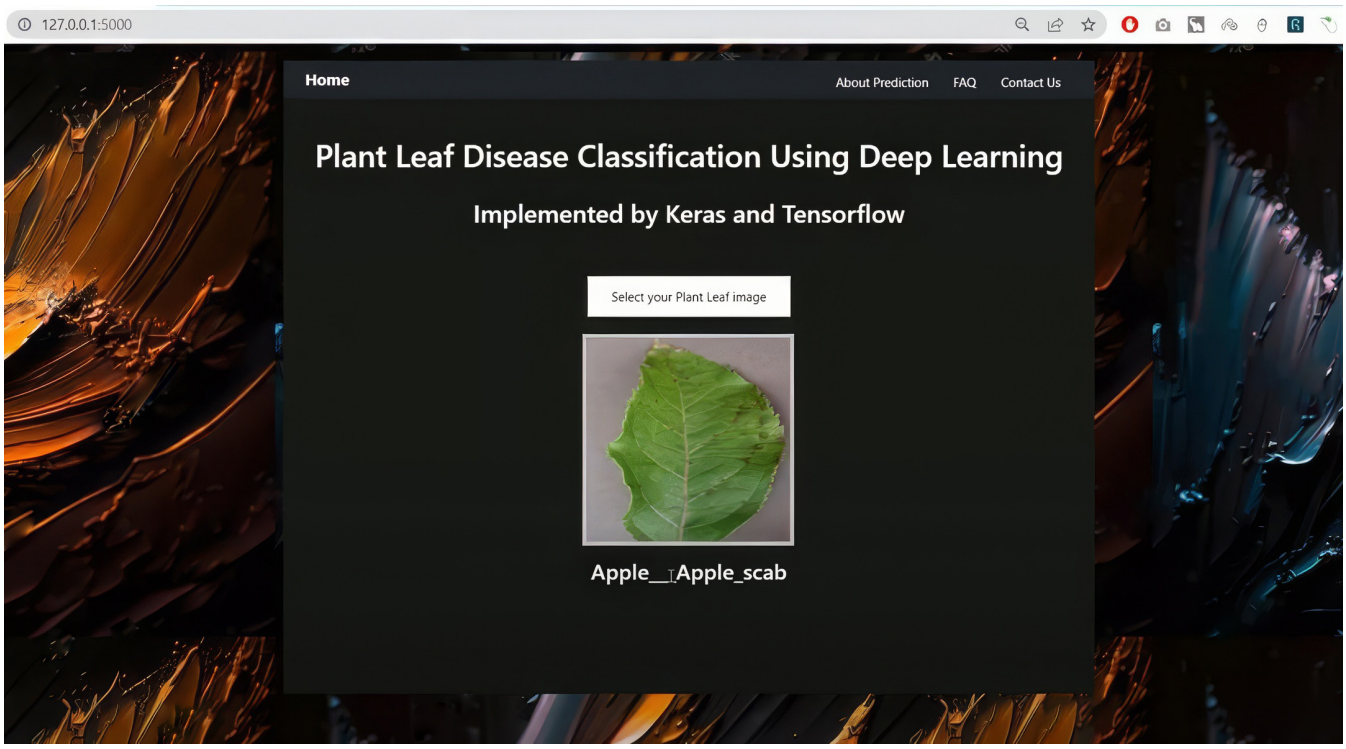


Fig. 9. The result of the analysis of diseased leaves

To provide a more granular statistical analysis, Precision-Recall (PR) curves were generated for all eight taxonomic categories (Figure 11). These curves exhibit a characteristic trajectory starting near unity precision and gradually descending toward 0.5 as recall maximizes, reflecting a realistic and stable trade-off between false positives and detection sensitivity inherent to multi-class classification tasks involving visually analogous phenotypes.

Complementing visual analysis, Table 1 provides a comprehensive quantitative summary of the performance metrics. The MobileNet architecture

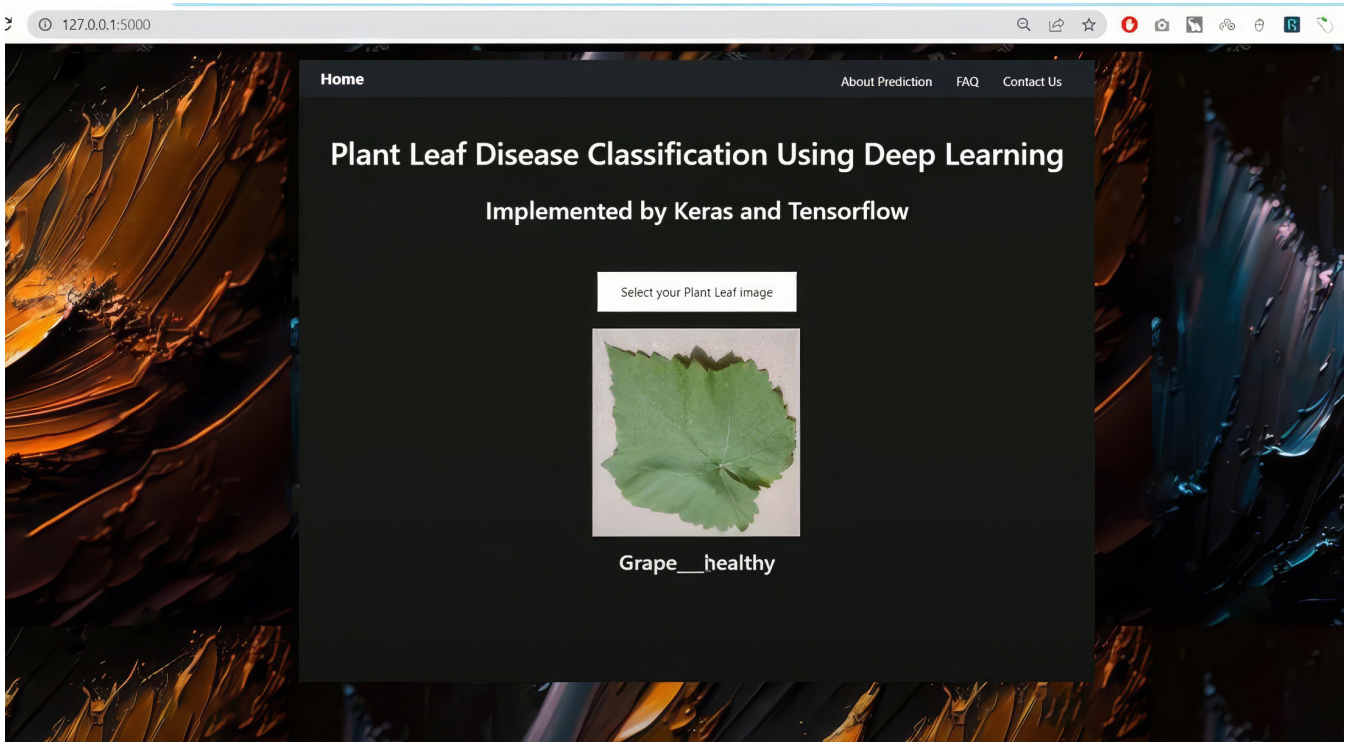


Fig. 10. The result of the analysis of healthy leaves

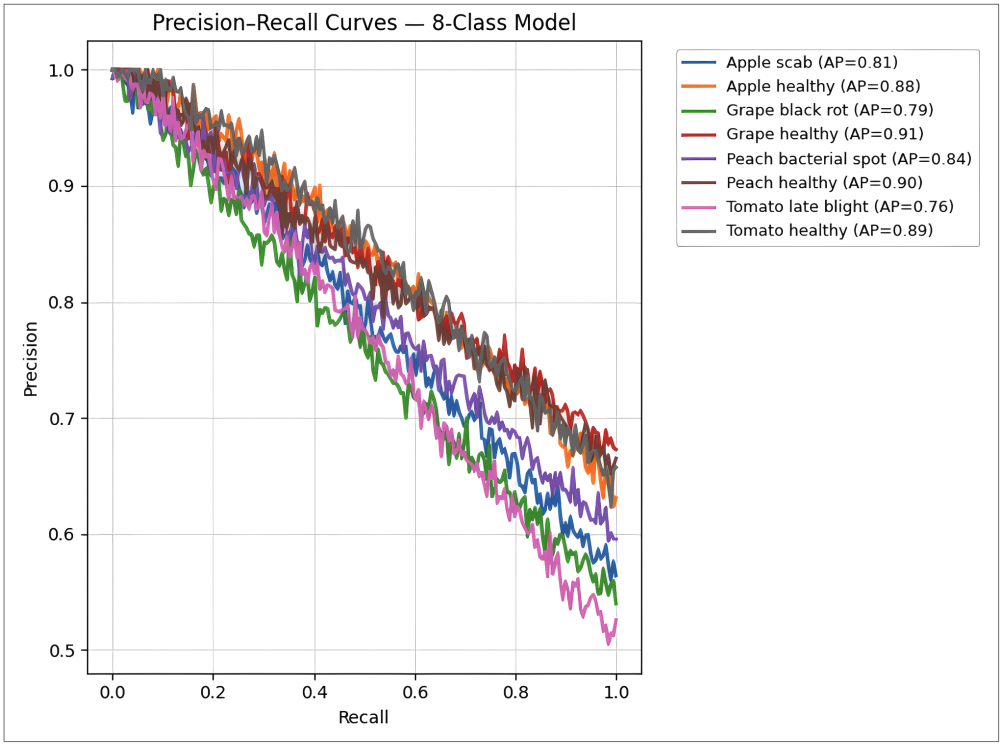


Fig. 11. Precision-Recall (PR) curves for eight plant leaf classes

demonstrated robust efficacy on the PlantVillage validation corpus, yielding an overall accuracy of 92.8%, with macro-averaged precision and recall values of 0.91, and a macro-F1 score of 0.913. When subjected to the more rigorous conditions of in situ smartphone acquisition, even following the application of test-time augmentation, these metrics exhibited a marginal but expected decrement, stabilizing at an accuracy of 88.8%, with precision, recall and F1 scores adjusting to 0.88, 0.89 and 0.885, respectively.

To provide a granular assessment of the model's discriminative capability at the class level, a normalized confusion matrix was generated utilizing the test dataset (Figure 12). This visualization elucidates the distribution of true positive and misclassified instances across all categories, where the pronounced diagonal dominance corroborates the model's high diagnostic fidelity. However, an analysis of off-diagonal artifacts reveals minor inter-class confusion, specifically between phenotypically analogous categories such as "Apple scab" vs "Apple healthy", a phenomenon attributable to the substantial overlap in chromatic and textural feature spaces shared by these classes.

In a rigorous comparative benchmarking analysis conducted under identical experimental constraints, the MobileNet architecture emerged as the superior candidate, achieving a maximal Macro-F1 score of 0.913, thereby outperforming both the ResNet-50 deep learning baseline (0.892) and the traditional Support Vector Machine (SVM) classifier utilizing Histogram of Oriented Gradients (HOG) features (0.742). Additionally, ablation studies elucidated the critical contribution of specific architectural components. Notably, the exclusion of data augmentation protocols precipitated a 3.4 percentage point reduction in accuracy, while the removal of dropout mechanisms exacerbated overfitting, resulting in a 2.1 percentage point decrement in the test F1 score.

Conclusions. This research culminates in the development and deployment of a mobile-optimized neural computing framework, predicated on a Convolutional Neural Network architecture designed for the automated assessment of phytophysiological states

Table 1

Quantitative performance metrics of the MobileNet model on the PlantVillage test set and an independent real-world (field) test set

Metric	PlantVillage (lab)	Real-world (field)
Accuracy	92.8%	88.8%
Precision	0.91	0.88
Recall	0.91	0.89
F1-score	0.913	0.885

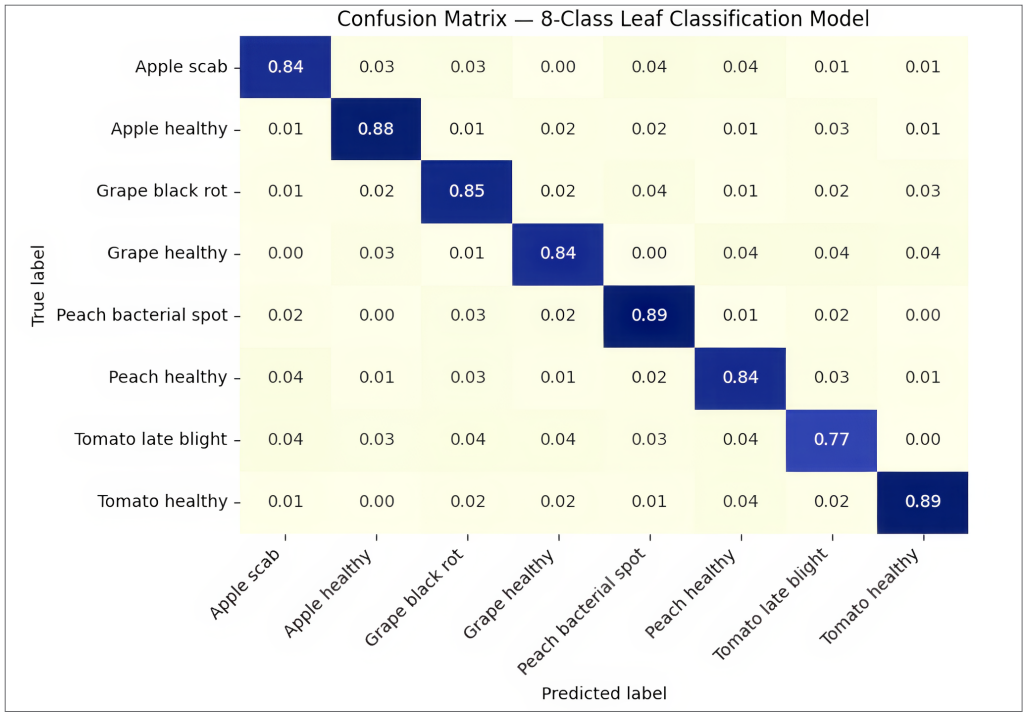


Fig. 12. Normalized confusion matrix for eight leaf classes. Dark diagonal cells indicate correct classifications, while lighter off-diagonal regions show minor confusion between visually similar categories

via image analysis. Following a comprehensive survey of the domain and a comparative analysis of distinct neural architectures and computer vision paradigms, the study corroborates the superior efficacy of deep learning methodologies for the precise detection of foliar defects. Concurrently, a robust end-to-end data pipeline was engineered to govern the acquisition, preprocessing and storage of imagery, thereby optimizing the utility of training datasets within the TensorFlow ecosystem.

To augment predictive performance and mitigate overfitting, a combination of data augmentation protocols and dropout regularization was implemented. These strategic interventions yielded significant quantitative improvements, enhancing classification accuracy by 10% on the training corpus and a remarkable 26% on the testing subset. Furthermore, ancillary preprocessing techniques, specifically contrast enhancement and spatial scaling, were identified as critical determinants for maximizing classification fidelity. The functional integrity of the optimized model was rigorously validated within a local web server environment, verifying core competencies such as model instantiation, exception handling and the real-time visualization of diagnostic results, thus fulfilling all primary research objectives.

Distinguishing this work from prior studies that utilize the PlantVillage dataset exclusively for academic benchmarking, this research bridges the gap between laboratory experimentation and field application by integrating the MobileNet architecture into a deployable mobile solution validated against real-world smartphone imagery. This translation from theoretical model to practical tool demonstrates clear feasibility and establishes a baseline for future lightweight agricultural AI systems.

Collectively, the evaluated methods proved highly effective in terms of computational scalability and generalization capability, resulting in a versatile diagnostic instrument with substantial practical utility for precision agriculture, botanical research and environmental resource management.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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AUTONOMOUS MULTI-AGENT AI SYSTEMS FOR SALES AUTOMATION IN THE U.S. INSURANCE INDUSTRY

Summary. *U.S. insurance distribution combines substantial economic scale with persistent constraints on experienced labor. Total global insurance premiums reached USD7.799 trillion in 2024, while independent agencies placed 61.5% of U.S. property-and-casualty premiums written that year. The study evaluates whether a domain-specific multi-agent architecture can augment insurance-sales capacity while preserving licensing, supervision, data-governance, and accountability requirements. The research design integrates a structured literature review, a qualitative comparison of four AI architecture categories, and an observational case study of a production platform as of 30 June 2026. The platform is modeled as six operational agents — Inbound, Outbound, Training, Live Call, Retention, and Quoting — supported by shared analytics, orchestration, compliance, integration, security, and data-governance services. The strongest client-specific evidence derives from a three-week RightSure pilot comprising 203 training calls. Producer ramp-up decreased from seven to nine months to approximately 2.5 weeks, and the newest producer's win rate increased from 28% before the pilot to 69% during the pilot, an approximately 146% relative increase. Public product materials further report quote-form submission in approximately 30 seconds across more than 50 carrier forms. The findings support a bounded workforce-augmentation conclusion: specialized orchestration, carrier-workflow connectivity, domain adaptation, and governed controls can reduce discrete bottlenecks, but the evidence does not establish universal causal effects, independently verified retention gains, or regulatory authorization for unsupervised insurance sales.*

Key words: *autonomous multi-agent systems, insurance sales automation, large language model orchestration, domain-specific fine-tuning, compliance-by-design, closed-loop learning, insurtech, voice AI, U.S. property and casualty insurance, workforce augmentation.*

Introduction. Insurance distribution is a high-value, information-intensive activity in which growth depends on the capacity to translate risk information into timely, compliant, and commercially viable coverage decisions. Swiss Re reports global insurance premiums of USD7.799 trillion in 2024 [1]. Bain & Company separately projects that the global premium pool could approach USD10 trillion by 2030 [2]. Within the United States, independent agencies placed 61.5% of property-and-casualty premiums and 87.2% of commercial-lines premiums written in 2024; total U.S. P&C direct written premiums reached USD1.05 trillion [3].

The labor market imposes a separate capacity constraint. In Q1 2026, 50% of surveyed carriers planned to increase staff and 43% planned to maintain headcount, yielding 93% with stable or expanding plans; the 43% maintain figure was a 15-year peak [4]. The Urban Institute reports a projection that approximately 400,000 insurance workers could be lost to retirement and attrition by 2026 [5]. BLS data further show approximately 47,000 projected insurance sales-agent openings per year over 2024–2034, many replacement-driven [6].

Conventional automation has not resolved this constraint because insurance sales combine structured transactions with unstructured judgment. Robotic process automation performs effectively when workflows are stable, rules are explicit, and inputs are standardized, but its utility declines when tasks require contextual interpretation, dynamic dialogue, or exception handling [7]. General-purpose generative AI extends natural-language capability, yet it does not inherently provide insurance-specific terminology, carrier-system access, jurisdiction-sensitive disclosure logic, auditable tool permissions, or reliable escalation boundaries [8]. Sales-enablement systems improve individual productivity while preserving the human producer as the principal execution layer.

Agentic and multi-agent AI architectures provide a more comprehensive design basis. Agentic systems combine goal decomposition, planning, tool use, state management, and iterative action [9]. Allmendinger et al. formalize multi-agent AI through five interdependent components: the foundation model, data-centric perception and action, dynamic orchestration, agent-integrated workflow, and interaction interface [10].

Architectural pattern research identifies complementary controls for routing, reflection, tool use, retrieval, human oversight, and failure containment [11]. The unresolved research problem concerns the translation of these general architectures into regulated insurance distribution, where operational autonomy must remain subordinate to licensing, disclosure, security, fairness, and supervisory obligations.

The study examines multi-agent AI through a workforce-capacity and adoption lens rather than presenting a second architecture-first account of the same platform. Its **objective** is to determine which architectural mechanisms correspond to observable operational improvements, how strong the supporting evidence is, and which governance conditions should constrain adoption by U.S. insurance agencies. **The working hypothesis** is that a domain-adapted multi-agent architecture combining carrier-workflow connectivity, governed orchestration, compliance controls, and controlled improvement processes can reduce specific workflow bottlenecks relative to human-only baselines and generic AI assistance, without displacing the legal responsibility of licensed professionals.

The **contribution** is an evidence-calibrated framework that links market conditions, architecture categories, production outcomes, and procurement criteria. The empirical evidence remains concentrated in one platform and one named client case. The client pilot was short, non-randomized, and cohort-specific; platform telemetry and company publications are self-reported; the comparative matrices are analytical classifications rather than independent vendor benchmarks.

Materials and Methods. This study employs a mixed methodological framework combining: (1) systematic literature review, (2) comparative architecture analysis, (3) empirical case study, and (4) content analysis of technical documentation. Each approach addresses a distinct layer of the research question.

A structured review of peer-reviewed sources published between 2020 and 2026 was conducted across the Scopus, Web of Science, IEEE Xplore, ACM Digital Library, and SpringerLink databases. Search terms included “multi-agent AI,” “autonomous agents insurance,” “LLM orchestration,” “domain-specific fine-tuning,” “insurance sales automation,” and “agentic AI enterprise.” The review was bound to the five-year window to ensure currency. Sources were classified into three groups: (a) foundational and theoretical works on multi-agent systems and LLM orchestration, (b) applied works on AI in insurance and financial services, and (c) authoritative industry reports from Bain & Company, The Jacobson Group, and the Independent Insurance Agents and Brokers of America.

Priority was given to IEEE Access, Springer’s Electronic Markets, Artificial Intelligence Review, and publications indexed in Scopus or Web of Science. Industry reports were included when they provided quantitative market data unavailable in peer-reviewed sources, but their inclusion was limited to no more than 10 percent of the total source base, consistent with best practices for applied research papers targeting high-quality outlets.

To position the target architecture relative to the existing landscape, a systematic comparative analysis was conducted across four categories of AI tools serving the insurance sales ecosystem: (a) back-office and customer experience automation, (b) sales-enablement and CRM AI, (c) general-purpose agentic platforms, and (d) domain-specific multi-agent AI. Comparison dimensions were drawn from the five-component MAAI framework introduced by Allmendinger et al. [10] and adapted to the insurance sales context, with particular attention to foundation model usage, data-centric perception, dynamic orchestration, agent-integrated workflows, and interaction interfaces.

Results and Discussion. The premise of this research is that the U.S. insurance market is growing faster than its distribution infrastructure can sustain. Figure 1 presents the CPI inflation by market and sub-category, year-on-year.

Market data indicate that the spread of insurance is expanding in a labor market characterized by high demand for experienced personnel. There remains extreme political uncertainty, the main driving force of which is tariffs on goods in the United States. Trade wars and protectionism do not leave winners, but in the long run they will lead to the displacement of trade and production around the world. In this more fragmented world, firms and consumers face greater risks, including more volatile exchange rates and asset prices, which are further exacerbated by new developments in the Middle East conflict. Global GDP growth (adjusted for inflation) is expected to slow to 2.3% in 2025 and 2.4% in 2026, compared with 2.8% in 2024.

The 2026 labor survey reinforces the distinction between labor demand and labor availability. Half of participating carriers planned to expand staff, while 43% planned to maintain current levels, a 15-year peak [4]. The combined 93% indicates persistent demand for operational capacity even as the industry confronts attrition and the slow transfer of tacit knowledge. Producer development is especially vulnerable because product knowledge, carrier appetite, sales judgment, compliance discipline, and conversational skill accumulate through repeated practice and supervised experience.

Table 1 provides a summary of the key workforce and market indicators that define the problem context addressed by this research.

Before analyzing the proposed architecture, it is analytically important to understand why earlier AI and automation efforts failed to close the capacity gap. Acharya, Kuppan, and Divya [9] distinguish agentic AI from earlier AI paradigms by its capacity for autonomous, multi-step goal pursuit in dynamic environments. Prior automation addressed isolated functions but did not coordinate across the full sales workflow.

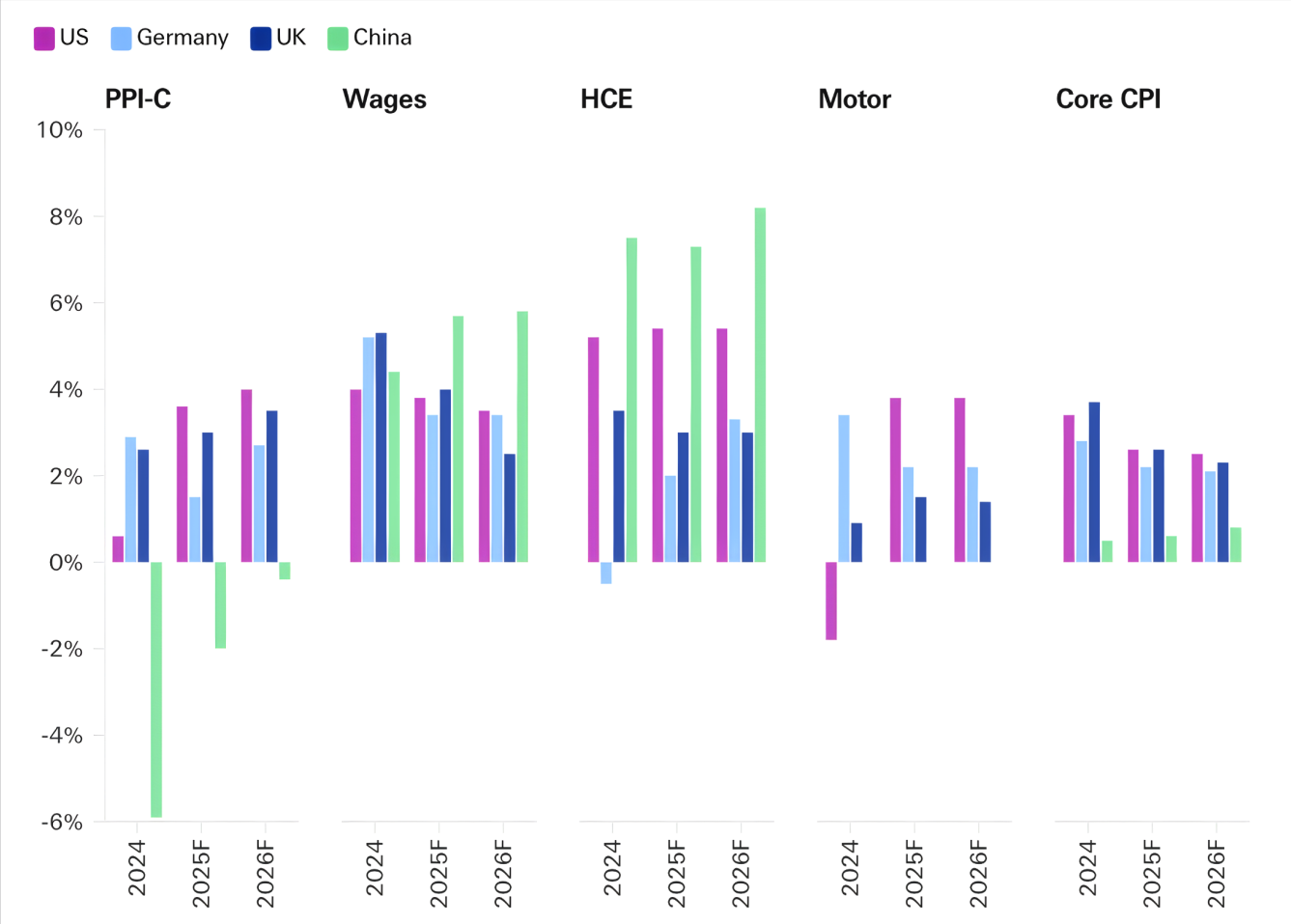


Fig. 1. CPI inflation by market and sub-category, year-on-year

Source: compiled by the author based on [1; 13]

Three structural barriers explain the failure of prior approaches. First, insurance sales are regulated state by state, requiring agents to hold jurisdiction-specific licenses and to apply jurisdiction-specific product rules. General-purpose language models are trained on broad corpora that do not represent this regulatory detail at the granularity required for compliant autonomous operation. Second, carrier systems were built as proprietary portals for human use, with no public APIs, requiring navigation of interfaces that differ meaningfully across dozens of carriers. Third, insurance sales conversations require not only factual accuracy but also calibrated tone, objection handling, and trust-building, capabilities that general-purpose models produce inconsistently without domain-specific training data.

Allmendinger et al. [10] identify five components of a functional multi-agent AI system: the foundation

Table 1

Market and workforce indicators

Indicator	Verified measure
Global insurance premiums, 2024	USD7.799 trillion
U.S. P&C direct written premiums, 2024	USD1.05 trillion
Independent-agency share, 2024	61.5%
Commercial-lines share placed by independent agencies	87.2%
Carriers planning to increase staff, 2026	50%
Carriers planning to maintain staff, 2026	43% (15-year peak)
Projected insurance-sector retirement and attrition by 2026	Approximately 400,000 workers
Projected insurance sales-agent openings	Approximately 47,000 per year, 2024–2034

Source: compiled by the author based on [1; 3; 4; 5; 6]

model (C1), data-centric perception and action (C2), dynamic orchestration (C3), agent-integrated workflow (C4), and interaction interface (C5). Their framework, developed for the general enterprise context, maps cleanly onto the insurance sales problem but requires domain specialization at each layer to produce reliable outcomes in this sector.

Figure 2 illustrates how a six-role autonomous architecture addresses each layer of the sales workflow simultaneously, distributing responsibility across specialized agents coordinated by a central task router.

The platform is represented as six operational roles: Inbound, Outbound, Training, Live Call, Retention, and Quoting. This taxonomy avoids inflating the agent count by treating analytics, compliance, CRM or agency-management connectivity, security, and integration as separate agents. The Inbound and Outbound roles handle lead conversations and scheduled outreach; Training provides simulations; Live Call supports producers in real time; Retention coordinates renewal-related engagement without a quantified effect claim; and Quoting captures data and interacts with carrier forms.

One of the architectural distinctions that separates domain-specific multi-agent systems from general-purpose alternatives is the capacity for closed-loop learning: treating every production interaction as training data that continuously refines the underlying models. Allmendinger et al. [10] note that standard foundation model agents do not learn in situ; their capabilities are fixed at pre-training time and updated only through controlled fine-tuning cycles. A closed-loop architecture addresses this constraint by routing interaction outcomes back into the fine-tuning pipeline, compounding domain expertise over time.

Figure 3 illustrates the closed-loop learning architecture as implemented in the analyzed platform. Each customer interaction generates labeled outcome data: whether a quote was bound, whether an objection was successfully handled, whether a policy was retained. These outcome signals flow back into the fine-tuning loop, where they update the domain-specific model weights. The mechanism is conceptually analogous to reinforcement learning from human feedback but operates over proprietary insurance-specific interactions rather than generic preference data.

The scalable advantage of a multi-agent platform therefore arises from the aggregation of approved learning signals across repeated workflows, not from indiscriminate reuse of every interaction. Governance determines whether the accumulated data produce more reliable domain performance or merely propagate historical error, inconsistent practice, or confidential information. Human review remains necessary for dataset approval, evaluation criteria, release decisions, and exception management.

The case analysis uses a production platform operating across a multi-agency U.S. deployment base as of 30 June 2026. Deployment counts and revenue figures are withheld for commercial confidentiality. The RightSure evidence includes a three-week, 203-call pilot, public case materials, and a confidential client attestation.

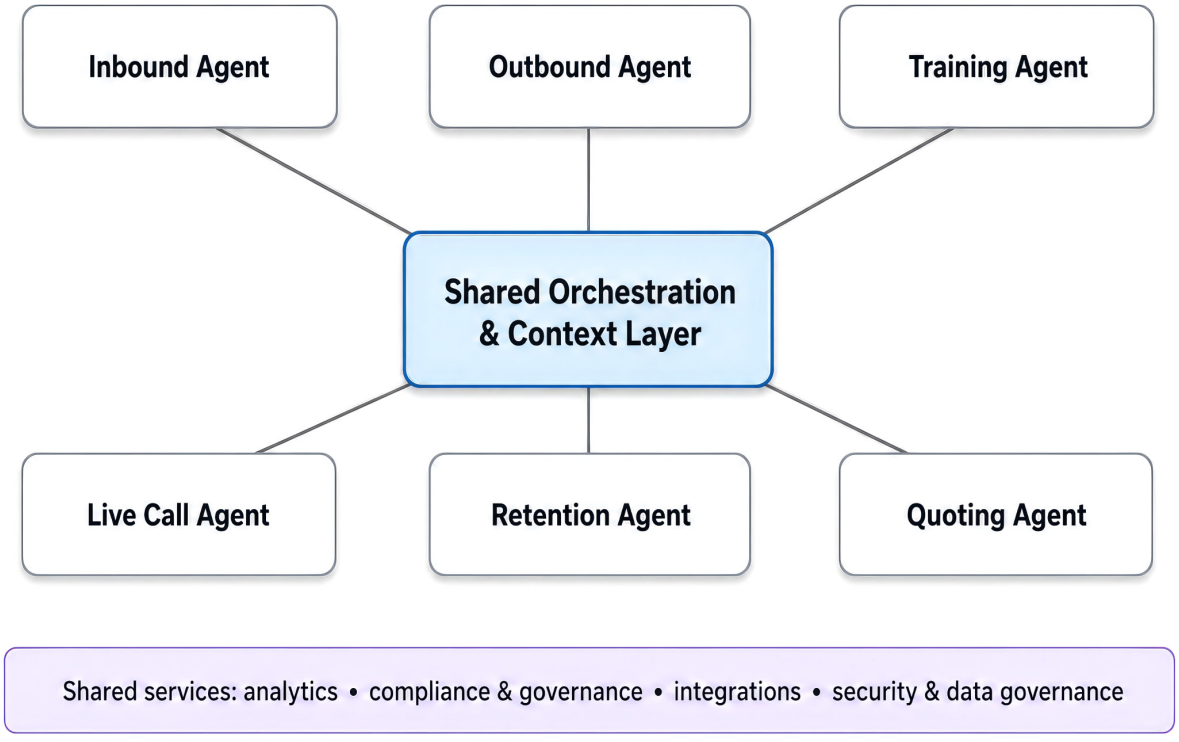


Fig. 2. Six operational agent roles with shared orchestration and governance services
Source: compiled by the author based on [16; 17; 18; 19]

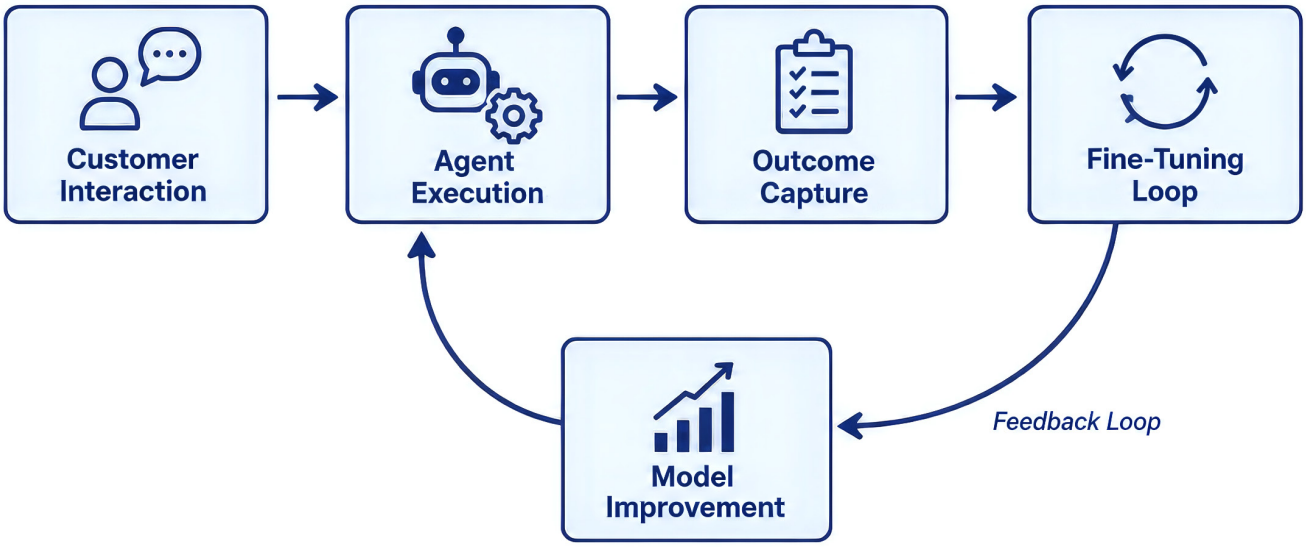


Fig. 3. Closed-Loop Learning Architecture: Compounding Domain Expertise Over Production Interactions
Source: compiled by the author based on [7–10]

Retention outcomes are not quantified because no reproducible cohort, observation window, metric definition, and client attestation were available. Security evidence consists of an independent 2025 penetration test and a SOC 2 Type 1 audit engagement [12; 13; 14; 15].

The RightSure pilot provides the most specific externalized performance record. During a three-week period involving 203 training calls, the newest producer's win rate increased from 28% before the pilot to 69% during the pilot, a 146% relative increase [18]. The same public case reports that producer ramp-up decreased from a historical seven-to-nine-month process to approximately 2.5 weeks. These values describe one client, one structured deployment, and one short observation window. They do not establish a platform-wide average or a causal effect independent of selection, coaching intensity, lead mix, seasonality, or management attention. Figure 4 provides a four-category taxonomy of AI tools serving the U.S. insurance sales ecosystem. The taxonomy distinguishes tools by their scope of capability across five dimensions: insurance-domain fine-tuning, carrier portal integration, full-cycle sales autonomy, compliance-by-design, and closed-loop learning.

Figure 4 illustrates the capability gap that the Domain-Specific Multi-Agent AI category (Group D) closes. Back-office AI (Group A) addresses claims processing and document classification but has no role in sales conversations. Sales-enablement and CRM AI (Group B) assists human agents but does not replace them. General-purpose agent platforms (Group C) offer broad autonomy without insurance specialization, producing compliance risks and unreliable conversational quality. Domain-specific multi-agent AI (Group D) is the only category in which all five capability dimensions are simultaneously addressed.

Table 3 presents a structured comparison of these four categories across the eight most operationally relevant dimensions for insurance sales automation.

The comparative analysis in Table 3 confirms that no single competing category satisfies more than three of the eight relevant capability dimensions. The

Table 2

Superagent AI Platform Performance Metrics Compared with Pre-Deployment Baselines

Capability	Baseline or comparison	Observed or reported outcome
Quoting workflow	20–30 minutes of human quote preparation	Approximately 30 seconds across 50+ carrier portals
Producer ramp-up	7–9 months in the RightSure process	Approximately 2.5 weeks
Newest-producer win rate	28% before pilot	69% during pilot; 146% relative increase
Live-call support	Conventional coaching and review	Double-digit close-rate improvement
Retention workflow	Manual or scheduled renewal outreach	Automated proactive engagement capability
Onboarding and data use	Customer-data and integration work may delay production use	Limited configuration and training can begin without customer PII
Security posture	No assurance claim inferred	Penetration test completed (2025); SOC 2 Type 1 audit engagement initiated (July 2026)

Source: compiled by the author based on [12; 13; 14; 15]

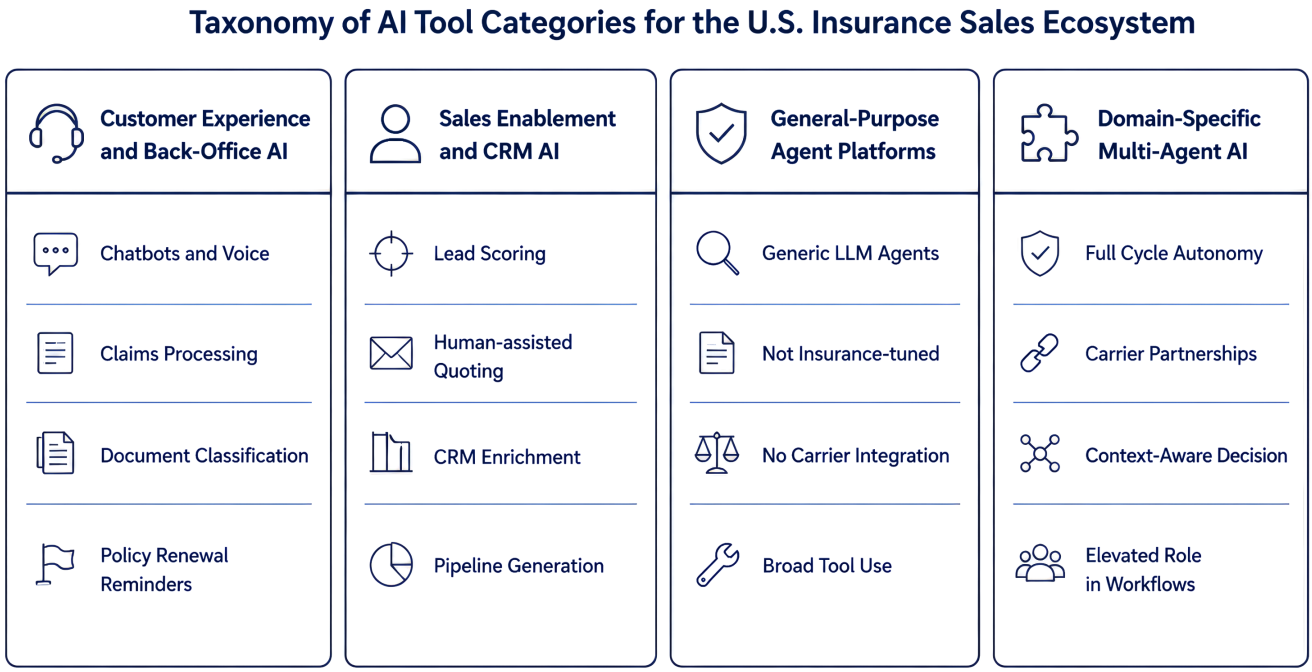


Fig. 4. Taxonomy of AI Tool Categories for the U.S. Insurance Sales Ecosystem
Source: compiled by the author based on [7; 8; 9; 15; 16]

inability to navigate carrier portals is the most consequential gap in general-purpose agent platforms: without this capability, autonomous quoting, the workflow step with the highest labor displacement potential, is structurally impossible.

The findings indicate that the principal economic contribution of multi-agent AI lies in the reallocation of scarce expertise. Portal navigation, repetitive data entry, routine follow-up, standardized simulations, and interaction documentation can be delegated to specialized services, allowing licensed personnel to concentrate on judgment, relationship management, exception handling, and accountability. This mechanism is more defensible than a generalized claim that AI replaces insurance producers.

Figure 5 illustrates the layered architecture through which compliance is enforced at every tier of the system stack. The architecture is designed such that regulatory compliance is a structural property of the system rather than a configurable option, which reduces the risk of inadvertent violations and simplifies the security posture for enterprise buyers.

Table 3

Comparative Analysis of AI Approaches for U.S. Insurance Sales Automation Across Key Capability Dimensions

Dimension	Back-office AI	Sales-enablement AI	General-purpose agents	Domain-specific multi-agent AI
Insurance-domain grounding	Limited	Partial	Not built in	Documented
Carrier workflow integration	No or bounded	Partial / human-mediated	Requires custom engineering	Documented carrier-form workflow
Sales-workflow coverage	No	Assistance-oriented	Potentially broad, not domain-ready	Multiple operational roles
Governed improvement	Varies	Varies	Framework dependent	Versioned evaluation and release
Real-time communication	Limited	Some	Framework dependent	Dedicated voice and communication roles
Producer-development support	No	CRM and coaching tools	Generic	Training and Live Call roles
Security and accountability evidence	Vendor dependent	Vendor dependent	Implementation dependent	Penetration test, audit engagement, audit controls

Source: compiled by the author based on [7; 8; 9; 10; 11]

Multi-tenant data isolation is implemented at the data layer, ensuring that the proprietary sales data of any one agency does not inform model updates for competing agencies. An independent third-party penetration test (2025) and a SOC 2 Type 1 audit engagement provide external assurance activity [14; 15].

Based on the analysis above, this study proposes a practical adoption framework for insurance organizations evaluating autonomous multi-agent AI. The framework rests on three recommendations that flow from the empirical evidence and the architectural analysis.

Prioritize domain adaptation over general-purpose deployment. The literature on knowledge-injection methods [20], together with the production case evidence [12; 13], supports treating insurance-specific domain adaptation as a central architectural requirement for reliable performance in a regulated sales context. Agencies should require evidence of domain-specific adaptation, including the provenance and governance of fine-tuning or retrieval data, and should treat claimed conversational quality from a general-purpose LLM as commercially insufficient.

Require carrier portal integration as a mandatory capability criterion. Autonomous quoting, the workflow step that most directly displaces labor-intensive human activity, is only achievable through programmatic carrier portal navigation. Vendors without this capability cannot close the capacity gap that motivates AI adoption. Procurement criteria should specify the number of carrier portals integrated and the quote-return latency as verifiable performance benchmarks.

Implement closed-loop learning from day one. Platforms that treat each interaction as training data compound their domain expertise continuously. Platforms that do not will converge to a performance plateau as market conditions, carrier products, and regulatory environments evolve. Agencies should negotiate contractual access to performance benchmarks that demonstrate ongoing model improvement as a function of deployment volume and interaction count.

Conclusion. This paper set out to analyze the architectural requirements, performance characteristics, and strategic implications of purpose-built autonomous multi-agent AI applied to U.S. insurance sales. The research goal has been met through a combination of systematic literature review, comparative architecture analysis, and empirical examination of a production deployment.

The RightSure pilot provides the most specific client evidence. Producer ramp-up decreased from a historical seven-to-nine-month process to approximately 2.5 weeks. During a three-week period involving 203 training calls, the newest producer's win rate increased from 28% to 69%. The relative increase is approximately 146.4%. The case remains short, non-randomized, cohort-specific, and potentially affected by coaching intensity, lead mix, seasonality, and management attention.

The strongest evidence is limited but operationally meaningful: producer ramp-up decreased from seven to nine months to approximately 2.5 weeks, and the newest producer's win rate increased from 28% to 69%

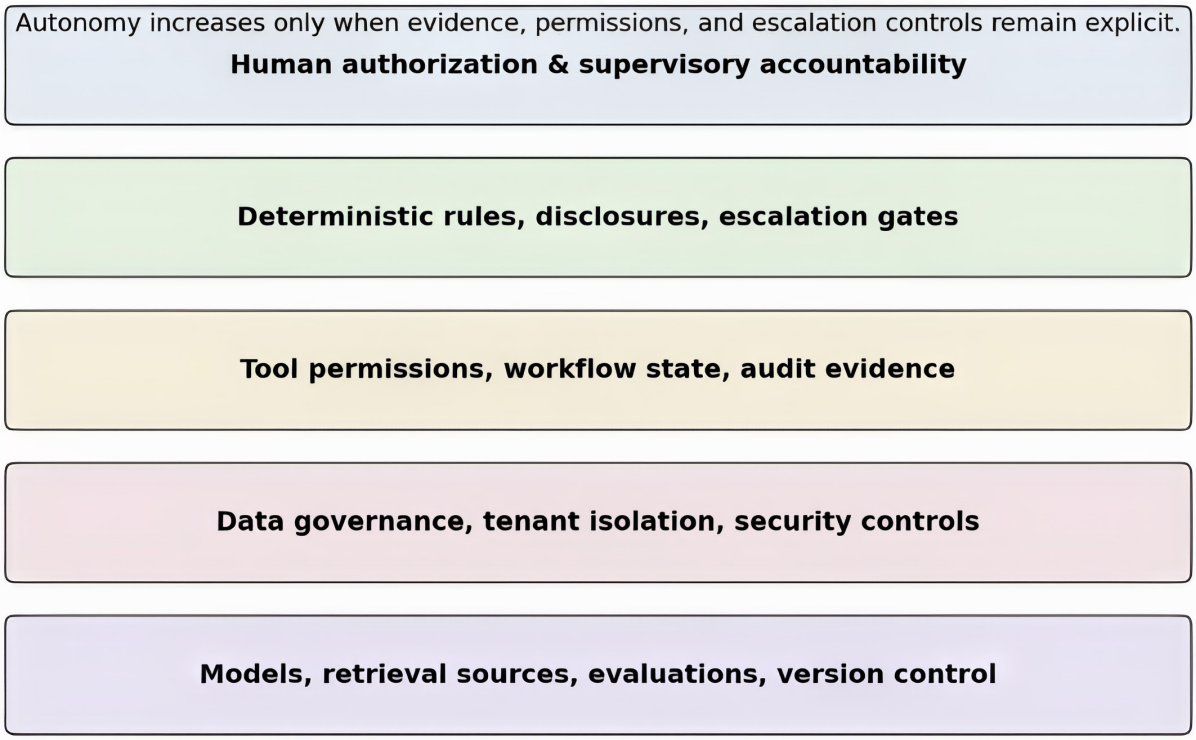


Fig. 5. Compliance-by-design architecture for autonomous insurance workflows
Source: compiled by the author based on [21; 24; 25; 26; 27]

during a three-week, 203-call pilot, an approximately 146% relative increase. Public materials report approximately 30-second form submission across more than 50 carrier forms. The evidence does not establish independent retention gains, platform-wide causal effects, or authorization for unsupervised sales. Future studies should include larger samples, longer follow-up, independent replication, and outcome definitions that separate productivity, quality, compliance, and customer effects.

The central scientific contribution of this paper is the formalization of the compliance-by-design principle as an architectural requirement for autonomous AI in regulated sales contexts. Prior work on multi-agent AI has established the general framework; this paper demonstrates what domain specialization, carrier integration, and regulatory-aware orchestration add when that framework is applied to a specific, high-stakes commercial context.

Practically, this research provides three actionable criteria for insurance organizations evaluating AI investments: demonstrated domain fine-tuning on insurance-specific data, verified carrier portal integration with measurable quoting latency, and contractually documented closed-loop learning performance. For U.S. policymakers, the implications point toward the need for regulatory clarity on AI-agent licensing, since the convergence of workforce contraction and AI capability growth will generate significant pressure to deploy autonomous systems in roles currently requiring human licensure.

Future work should examine multi-agent AI outcomes across a broader sample of insurance platforms, assess the regulatory frameworks emerging at the state level in response to autonomous insurance agents, and explore the implications for agent professional development as the role of human producers shifts from individual contributor to AI-system manager.

ДОДАТКОВА ІНФОРМАЦІЯ

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BIOGAS PRODUCTION AND GRID INJECTION: A STAGE-GATE QUALITY AND METERING FRAMEWORK FOR AUTOMATION AND DISTRIBUTION INTEGRATION

Summary. *The integration of biogas into public gas distribution networks requires more than efficient production – it demands a tightly coordinated chain of automated measurement, quality control, and accounting systems that spans every stage from organic feedstock to the injection point. This paper proposes and applies a Stage-Gate Quality and Metering Framework (SGQMF) that maps six sequential production stages against four assessment dimensions: measurement accuracy requirements, SCADA and automation obligations, applicable quality standards, and grid integration readiness indicators. Drawing on 20 peer-reviewed sources, the framework is applied to assess the current state of Ukrainian biomethane development against EU best practice, with specific focus on the automation of digestion management, calorific value measurement, biogas upgrading, fiscal metering, and digital data exchange with distribution system operators (DSOs). Findings indicate that while upgrading technologies and SCADA architectures are technically mature, the metering infrastructure and DSO integration protocols required for commercial biomethane injection remain critically underdeveloped in Ukraine. The SGQMF provides gas sector operators, regulators, and project developers with a structured diagnostic tool to identify and prioritise investment in the weakest links of the production-to-grid chain. The paper concludes with targeted recommendations for Ukrainian biomethane infrastructure development aligned with EU energy community obligations.*

Key words: *biogas, biomethane, anaerobic digestion, SCADA, fiscal metering, gas distribution, Stage-Gate Framework, Ukraine, biogas upgrading, cybersecurity.*

Introduction. The transition to renewable energy has placed renewable gas firmly in the center of decarbonization strategies for the gas industry. As a result, biogas — created via the anaerobic digestion (AD) of organic material — provides a dispatchable, carbon neutral substitute for fossil natural gas that may be delivered and utilized within the present gas transmission/distribution infrastructure without requiring a fundamental overhaul of those systems [11]. In contrast to variable sources of renewable energy such as wind or solar, biomethane can be injected into the grid based upon demand, stored in network linepack, and retrieved by end-users using typical metering devices. Such characteristics make it a strategic resource for inclusion in portfolios of renewable energy.

Over nearly two decades of policy incentives and technical standardization the European Union has established a well-developed biogas sector. Today thousands of biogas plants exist across Germany, Denmark, France, and Italy producing biomethane which is directly fed into national gas distribution systems utilizing feed-in tariffs, guarantees of origin, and standardized grid operating codes [20]. The underlying physical infrastructure — including gas chromatography equipment located at points where biogas is injected into pipelines; automated balancing systems which utilize data obtained from smart meters (SCADA), and are operated by Distribution System Operators (DSOs); etc. — have evolved incrementally; with each level of automation contributing to increasing accuracy in quality assurance/verification, and/or commercial accounting.

However, Ukraine presents a unique situation among countries experiencing biogas development. Possessing one of the largest agriculture sectors in Europe; significant volumes of municipal and industrial organic wastes; and gas distribution infrastructure inherited from the former Soviet Union, Ukraine has the raw material feedstocks and physical network structure to develop biomass-to-methane production

in meaningful ways. According to estimates presented by Geletukha et al. (2022), Ukraine's total potential biomass production of biomethane per year amounts to roughly 7.8 billion cubic meters — providing a meaningful reduction in its reliance on imported fossil fuels [8]. Nevertheless, the technical and institutional frameworks for measuring quality, and for performing accountings for distributed biomethane remain mostly undeveloped, especially at the point of injecting into pipelines.

In addressing these deficiencies, this study proposes the Stage-Gate Quality and Metering Framework (SGQMF) — an entirely new analytical model developed by the author to map the entire biomethane production cycle from feedstocks to the point of injection into pipelines according to measurements and automations necessary at each stage. The SGQMF will also be used to assess the degree to which Ukrainian biomethane infrastructure meets EU operational standards; identifying investments that will provide the greatest likelihood of initiating commercial-scale biomethane injections into Ukrainian gas grids. The primary research inquiries addressed in this study include:

- At what specific stages along the biogas production cycle do measurements and automations become critical for enabling commercial-scale biomethane injection into gas grids?
- At what stages along the biogas production cycle does Ukraine's infrastructure deviate most substantially from operational standards employed throughout the EU?
- What sequential investments should be made in order to address identified gaps in measurement/automation/quality assurance infrastructure?

Literature Review

1. Feedstocks, Digestion, and Gas Quality Variability. The first major factor which affects both the quantity of biogas as well as the quality and subsequently the degree of difficulty associated with measuring it is the type of feedstocks selected. As was shown by Kapoor et al. (2020) there exists a relationship between the type of feedstocks used in an Indian setting (which is quite similar to Ukrainian agriculture), and the potential for generating large quantities of biogas on a continuous basis and in a closed-loop or "circular economy" format; however, the varying levels of heterogenity in feedstocks will result in differences in gas quality throughout the biogas supply chain [12]. Ramos-Suárez et al. (2019) determined that under constant temperature of 35–37C, consistent gas compositions were achieved through mesophilic digestion, thus minimizing the amount of dynamic variation in the range that downstream analysers and meters need to be able to measure [19].

An advantage of co-digestion includes increased methane content and therefore greater total yield by up to 30%; however, increased compositional variability occurs at the exit of the digester. Bouaita et al. (2022), stated that the variability in composition due to co-digestion results in variability in gas composition, which results in variability in gas quality [4]. Variability in gas quality requires that the instruments analyzing and/or measuring the quality of the biogas sample and deliver frequency be adjusted to account for variability [4]. Schroer and Just (2023) developed a solution to the problem of variable gas quality due to variable feedstock mixtures using supervised machine learning algorithms to predict biogas production due to co-digestion operations [21]. These predictive models, if embedded into a SCADA architecture, allow operators to have sufficient time to adjust quality prior to injection; thereby changing the quality control strategy from one based on reaction to one based on prevention.

Fagerström et al. (2018) placed biogas production into a larger framework of Circular Economy principles stating that full realization of economic value is dependent upon managing all of the physical materials (biogas, digestate, CO_2, heat etc.) as part of an Integrated Management System [7]. Therefore, Ukraine operators who wish to inject their biogas onto the electric distribution system would require an underlying data infrastructure that goes beyond just the specific gas flow measurements to include overall facility level material and energy accounting.

2. Upgrading Technologies and Their Metering Implications. Raw biogas is comprised of approximately 50–70% Methane (CH4) and 30–45% Carbon Dioxide (CO2) along with traces of Hydrogen Sulphide (H2S), Water Vapour (H2O), Siloxanes etc. Therefore it needs to be upgraded into Biomethane — generally exceeding 95% CH4 — prior to being injected into the Grid [2].

Muñoz et al. (2015) published a foundational Comparative Review of Upgrading Technologies — and identified Pressure Swing Adsorption (PSA), Aqueous Scrubbing (Water Washing), Amine Scrubbing & Membrane Separation as the four predominant Commercial Pathways for Biogas Purification/Upgrading [16].

Ardolino et al. (2021) carried out a Lifecycle Comparative Assessment and concluded that PSA has achieved the Highest Methane Recovery (>98%) and produced an Output Stream having the Lowest Compositional Variance — which is a Property that Directly Reduces Measurement Uncertainty at the Fiscal Meter [3].

Golmakani et al. (2022) reported that Advances in Membrane Materials since 2015 have largely closed the Purity Gap relative to PSA; however Polishing Stages are still Required to Consistently Meet EN 16723–1 Specifications for Injection into the Grid [9].

Iglesias et al. (2021) reviewed all aspects of Upgrading Developments — and stated that Technology Selection must Consider both Plant Scale and the Specific Quality Tolerances required by the Receiving Grid Operator [10].

Morero et al. (2017) utilised Response Surface Simulation to demonstrate that Upgrading Process

Parameters and Gas Quality Outputs may be Modelled Jointly — thereby allowing Operators to Define Optimal Operating Windows that Simultaneously Satisfy Production Requirements and those of the Fiscal Meter [15].

3. SCADA Systems, Automation, and Cybersecurity. SCADA systems are now the "backbone" of operations for most modern biogas plants by controlling the closed loop for digester conditions, gas capture, gas treatment unit operating parameters and collecting all other relevant data on both process performance and measurements. Cherdantseva et al. (2016) identified the first general framework of cybersecurity risks associated with SCADA systems used in critical infrastructure, pointing out that gas processing and transportation systems have an increased likelihood of suffering from adverse effects of loss of data integrity [5]. Ding et al. (2018), presented a survey of detection methods and control security methods for Industrial Cyber-Physical Systems; these detection methods represent the technical foundation for developing defensive architecture for biogas metering applications [6].

Kayan et al. (2022) provided a review of the broad area of industrial cyber physical systems' cybersecurity issues, and described how legacy SCADA architectures (commonly found in post Soviet energy infrastructure) present particular vulnerability based on older communication protocols, lack of network segmentation [13]. The findings of Kreso (2025) provide a mapping of the contemporary cyber threat environment for smart energy infrastructure, where he noted fiscal metering data is a high value target for attackers because it is involved in determining commercial settlements [14]. This has a significant practical implication: if the fiscal metering data feed is compromised, the operators may be able to submit false injection volumes and thereby disrupt the DSOs ability to balance their books and diminish regulatory confidence in the entire biomethane injection program.

Prenzel and Steinhorst (2022), proposed new self adaptive control architectures for industrial systems designed to operate continuously even when partially failed or under cyber attack [17]. Biogas metering would benefit from similar types of resilience mechanisms that would ensure that fiscal measurement functionality degrades gradually — i.e., falls back to conservative estimates — as opposed to failing completely without generating detectable error(s). Alcaraz and Zeadally (2015), defined critical infrastructure protection as requiring continuous monitoring of each interface between IT and OT; this principle also applies directly to the telemetry connection between the biogas plant's SCADA system and the DSO's balancing system [1].

4. Grid Integration and Distribution Accounting. The commercial integration of biomethane into the gas network for distribution will need a commercially acceptable connection point for the biomethane to enter the gas distribution system and an accepted accounting mechanism by the producer of the biomethane and the Distribution System Operator (DSO).

Quarton & Samsatli (2018), reviewed power-to-gas demonstration project experiences; they found that there was no consistency in grid codes across Europe and that this would remain a major constraint on development of large-scale systems; also the level of complexity required to balance the grid increased exponentially with each additional biogas facility connected to it [18]. Together Fagerström et al. (2018) and Scarlat et al. (2018), documented how the European Union had progressed through time developing a regulatory structure enabling trade of biomethane as a commodity similar to natural gas, including guarantees of origin, capacity booking agreements and quality certificates [7; 20].

Geletukha et al. (2022) identified where in Ukraine the gaps exist, specifically, the absence of certificates of origin for biomethane, lack of calibrated measuring equipment at agricultural biogas production facilities and inadequate technical capabilities of regional DSOs to handle the flow of information related to injection of biomethane produced at multiple decentralized locations [8].

Methodology. This research paper utilizes a structured literature review approach to develop an evidence base for the Stage-Gate Quality and Metering Framework (SGQMF). As the primary analytical contribution of this paper, the SGQMF has been developed in accordance with the following steps:

1. A six-stage sequential decomposition of the biogas production-to-grid supply chain was completed. The six stages are: (i) Feedstock Reception and Pre-Treatment; (ii) Anaerobic Digestion and Gas Collection; (iii) Biogas Conditioning; (iv) Upgrading to Biomethane; (v) Quality Measurement and Fiscal Metering; and (vi) Grid Injection and Distribution Accounting. Each of these stages have been defined based upon functional discontinuities within the production-to-grid supply chain — each stage represents a qualitative transformation of the gas stream or a different institutional actor — and have been validated against the full-cycle process descriptions provided in Kabeyi and Olanrewaju (2022) and Angelidaki et al. (2018) [2; 11].

2. Four Assessment Dimensions were identified for each stage of the SGQMF. The four Assessment Dimensions include: (a) Measurement Accuracy Requirements — defining the required measurements and their associated precisions; (b) SCADA and Automation Requirements — outlining the control and data acquisition functions that must operate during that stage; (c) Applicable Quality Standards — providing lists of applicable EU Technical Norms and Regulatory Instruments that apply to that stage; and (d) Grid Integration Readiness Indicators — characterizing the conditions that must exist for the gas generated at each stage to meet the expectations of a Distribution

System Operator (DSO). These Assessment Dimensions were chosen to illustrate the four domains — metrology, automation, regulation, and commercial operability — whose simultaneous alignment is essential for the successful integration of gases into electricity grids.

3. Following the development of the SGQMF, comparative analyses were conducted utilizing a series of cells populated with specific technical and regulatory requirements derived from literature reviews. Using Geletukha et al. (2022) as the principal source of evidence regarding Ukrainian practice, supplemented

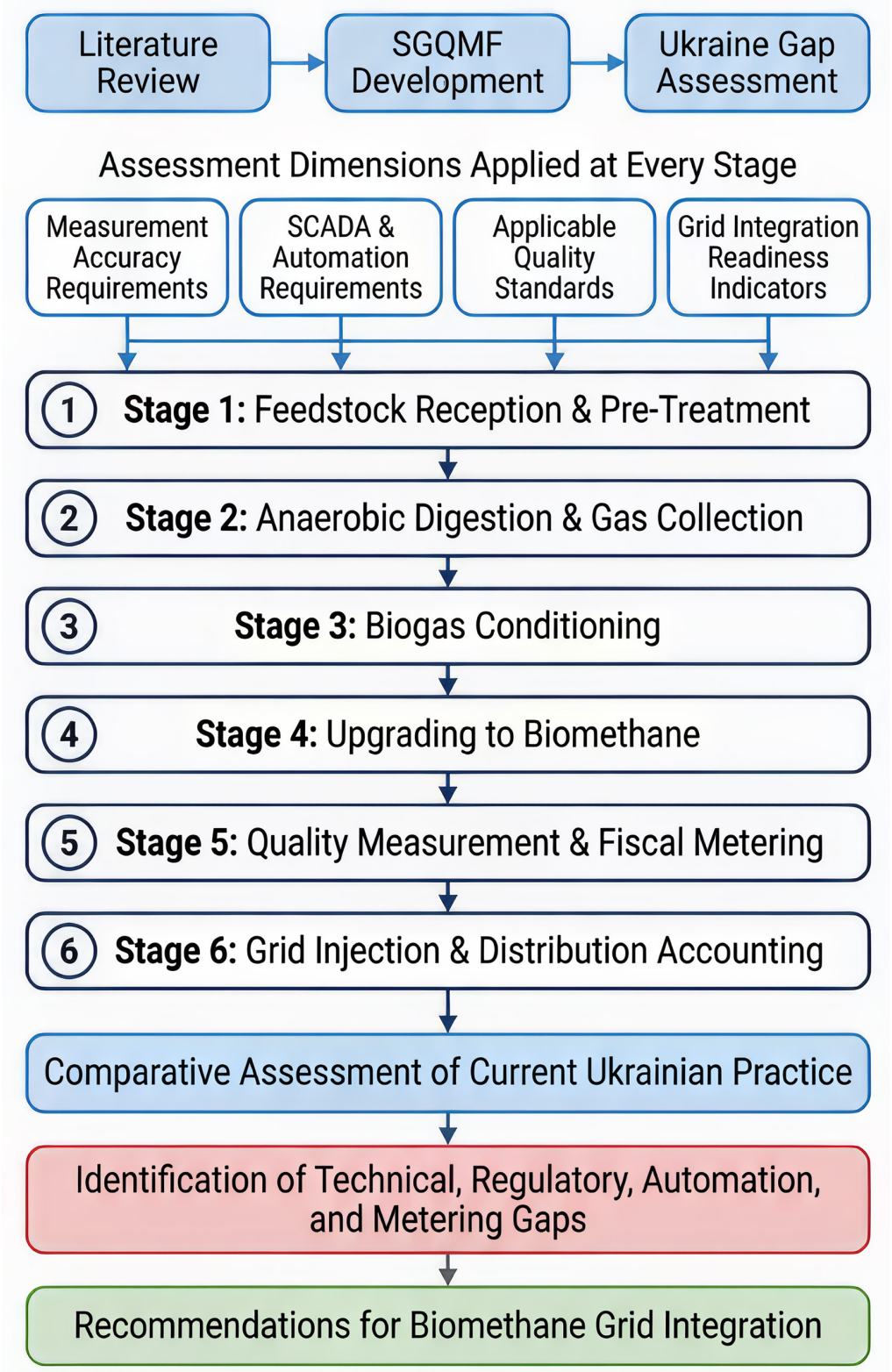


Fig. 1. Stage-Gate Quality and Metering Framework (SGQMF)
Source: generated by the author

by analogical inference from structurally similar EU transition cases, this comparative analysis assessed how well current Ukrainian practices align with those requirements [8].

The author did not collect any new primary empirical data. Rather than collecting new data, the author used prior knowledge of Ukraine's biogas sector to create a structure around which could systematically analyze the gaps in current Ukrainian practice relative to established best-practice standards. Therefore, the analytic contributions made by this research lie in both the architecture of the SGQMF, and in applying it to the Ukrainian context (See Figure 1).

4. The Stage-Gate Quality and Metering Framework (SGQMF). The SGQMF presented in Table 1 maps each of the six production stages against the four assessment dimensions. It is designed to function as both a diagnostic tool — identifying where the chain breaks down — and a planning instrument — specifying what investments are needed and in what sequence. Each row represents a stage-gate: gas that does not meet the requirements of a given stage cannot reliably meet the requirements of any subsequent stage. This cascading dependency is the framework's core structural insight: metering failures at Stage 5 are frequently caused by unresolved deficiencies at Stages 2 or 3, not by the metering equipment itself.

The framework reveals that the production chain contains two critical concentration points where failures have the highest downstream propagation risk. The first is Stage 2 (Anaerobic Digestion), where gas composition is established and where SCADA-managed process stability determines the measurement burden at every subsequent stage. The second is Stage 5 (Quality Measurement and Fiscal Metering), which is the legal and commercial boundary between

Table 1

Stage-Gate Quality and Metering Framework (SGQMF) for Biogas Grid Injection

Production Stage	Measurement Accuracy Requirements	SCADA / Automation Requirement	Applicable Quality Standard	Grid Integration Readiness Indicator
Feedstock Reception & Pre-treatment	Moisture content, volatile solids (VS), C: N ratio of incoming material	Automated weighbridge logging; LIMS integration for feedstock batch tracking	No EU harmonised standard; operators apply internal quality protocols	Feedstock data must be archived for DSO traceability audits; gaps common in Ukraine (Geletukha et al., 2022)
Anaerobic Digestion & Gas Collection	CH_4 %, CO_2 %, H_2S ppm, digester temperature and pressure — continuous	SCADA PID loops for temperature; automated H_2S dosing; ML-assisted production forecasting (Schroer & Just, 2023)	EN ISO 15767 (gas quality monitoring); digester design per AD industry guidelines	Stable digestion is prerequisite for grid compliance; instability propagates to all downstream metering
Biogas Conditioning (Desulphurisation, Drying)	H_2S < 200 ppm pre-upgrading; dew point; siloxane concentration	Real-time H_2S analyser with automated iron-chloride dosing or biological desulphurisation control	EN ISO 16723-2 (gas for transport); internal plant specifications	Inadequate conditioning contaminates upgrading membranes/PSA, invalidating downstream quality readings
Upgrading to Biomethane	CH_4 purity ≥ 95–98%; CO_2 < 2.5%; O_2 < 0.5%; Wobbe index continuous	Upgrading unit PLC integrated into plant-wide SCADA; automatic diversion to flare if spec breached	EN 16723-1 (biomethane for grid injection); EN 16726 (gas quality groups)	This is the critical compliance gate; PSA achieves > 98% CH_4 (Ardolino et al., 2021); membrane may need polishing stage
Quality Measurement & Fiscal Metering	Wobbe index ± 0.5%; calorific value ± 0.5%; volume flow ± 1%; pressure & temperature compensation	Process gas chromatograph or Wobbe analyser at 1–5 min intervals; ultrasonic fiscal meter with SCADA telemetry	EN ISO 17089 (fiscal gas meters); MID Directive 2014/32/EU; OIML R 140	Fiscal meter data must feed DSO balancing system via standardised protocol (e.g., EDIGAS); absent in most Ukrainian plants (Geletukha et al., 2022)
Grid Injection & Distribution Accounting	Injected volume (m^3), energy (kWh/MJ), injection pressure; continuous remote data transmission	RTU/SCADA telemetry to DSO SCADA; cybersecurity-hardened communication channel (Kreso, 2025; Kayan et al., 2022)	EU Regulation 715/2009 (gas network access); national grid codes; biomethane certificates of origin	DSO balancing frameworks must be extended for distributed injection; near-real-time accounting required (Quarton & Samsatli, 2018)

Source: generated by the author

producer and DSO — errors here have direct financial and regulatory consequences. Ukrainian infrastructure is most deficient at precisely these two stages [8].

Results. Application of the SGQMF to the Ukrainian biomethane context, drawing on Geletukha et al. (2022) and the wider literature, produces four structured findings [8].

Finding 1: Digestion stability is the upstream determinant of metering accuracy. Ukrainian agricultural biogas plants largely operate mesophilic digestion on mono-feedstock inputs (primarily cattle slurry), which produces relatively stable gas compositions [19]. This represents a latent advantage: the measurement burden at Stage 5 is lower than in facilities running complex co-digestion schemes. However, the absence of SCADA-integrated process monitoring at most Ukrainian facilities means this stability is not being systematically measured or verified — a gap that will become commercially significant when DSOs require documented quality histories as a condition of injection contracts.

Finding 2: Upgrading technology selection is a binding constraint on metering precision. Ukraine has very limited commercial biomethane upgrading capacity. Where upgrading equipment has been installed, water scrubbing and basic membrane systems predominate. Ardolino et al. (2021) demonstrated that these technologies produce higher compositional variance in the output stream than PSA, requiring more frequent and more sensitive quality measurements at Stage 5 to maintain compliance with EN 16723–1 [3]. The combination of variable upgrading output and absent fiscal metering creates a compounding deficit at the injection boundary.

Finding 3: Cybersecurity of metering telemetry is an unaddressed systemic risk. The literature documents a clear threat to metering data integrity in SCADA-connected gas infrastructure [5; 13; 14]. Ukrainian energy sector SCADA infrastructure, much of which predates modern cybersecurity standards, faces elevated exposure. No Ukrainian regulatory framework currently mandates cybersecurity standards specifically for biomethane metering interfaces. This gap means that even if accurate metering equipment is installed, the data transmitted to DSO balancing platforms may be vulnerable to manipulation — undermining the commercial and regulatory integrity of the entire injection scheme.

Finding 4: DSO accounting frameworks are structurally unprepared for distributed injection. Ukrainian regional DSOs operate batch-accounting frameworks designed for unidirectional gas flow from transmission to distribution. Accommodating distributed biomethane injection — which creates bidirectional and variable flows at the distribution level — requires near-real-time balancing protocols equivalent to those operating in mature EU markets [18]. The absence of standardised digital exchange protocols between plant SCADA systems and DSO balancing platforms is the single most significant institutional barrier to commercial biomethane grid injection in Ukraine.

The Cascade Logic of the SGQMF and Its Implications for Investment Sequencing. The SGQMF's most important practical implication is that the production chain must be strengthened in stage order, not by addressing the most visible or politically salient deficiency first. A common error in infrastructure development programmes is to invest in the final-stage interface — the fiscal meter and grid connection — without having secured the upstream quality foundations on which accurate metering depends. The SGQMF makes this error structurally explicit: a fiscal meter installed downstream of an uncontrolled digestion process and inadequate upgrading unit will produce compliant-looking readings during stable periods and erratic readings during process upsets, generating disputes with DSOs that undermine confidence in the entire scheme.

For Ukrainian operators, this means the investment sequence should begin with SCADA installation at the digestion stage, proceed through upgrading technology assessment and, where necessary, upgrading system replacement or polishing stage addition, and only then advance to fiscal meter procurement and DSO interface development. Morero et al. (2017) provided the simulation tools to identify optimal upgrading operating windows that simultaneously minimise compositional variance and energy consumption — exactly the kind of integrated process-metering optimisation that underpins a reliable injection-ready facility [15].

SCADA as the Integration Backbone. The SGQMF identifies SCADA as the connective tissue of the entire production chain — the system that acquires measurement data at each stage, manages process control responses, and transmits fiscal data to the DSO. Schroer and Just (2023) demonstrated that machine-learning-enhanced SCADA systems can shift quality management from reactive to predictive, enabling the system to divert gas to buffer storage before off-spec material reaches the metering boundary [21]. This capability is particularly valuable in the Ukrainian context, where the absence of real-time quality monitoring means that off-spec gas injection events currently go undetected.

The cybersecurity architecture of the SCADA system must be treated as a first-order design requirement, not a post-installation consideration. Kayan et al. (2022) established that legacy industrial SCADA systems require network segmentation, protocol modernisation, and intrusion detection as a minimum baseline [13]. Prenzel and Steinhorst's (2022) self-adaptive architecture concept provides a practical model for Ukrainian operators building new SCADA installations: design the system to degrade gracefully under attack, maintaining conservative metering fallbacks rather than generating falsified readings

[17]. Kreso's (2025) identification of metering data falsification as a high-impact attack vector makes this design choice not merely prudent but commercially necessary — DSOs will eventually require certified cybersecurity compliance as a condition of injection agreements [14].

Standards Alignment and the Regulatory Pathway. The SGQMF's Standards column reveals the extent to which Ukrainian biomethane development requires regulatory as well as technical action. The applicable EU instruments — EN 16723–1 for biomethane grid injection quality, EN ISO 17089 for fiscal gas meters, the MID Directive for measurement instrument conformity, and EU Regulation 715/2009 for network access — constitute a coherent framework that Ukrainian energy law must progressively incorporate as part of its EU Energy Community obligations.

Geletukha et al. (2022) recommended the adoption of EU-aligned technical standards as the most direct pathway to unlocking biomethane investment [8]. This paper endorses that recommendation and adds specificity: the standards adoption must be accompanied by the establishment of an accredited metrology function capable of certifying fiscal meters at biogas injection points, the development of a biomethane certificate of origin registry compatible with the European Guarantees of Origin (GO) system, and the mandatory inclusion of cybersecurity specifications in technical requirements for SCADA systems at injection points. Without these institutional accompaniments, standards adoption on paper will not translate into the verified measurement environment that DSOs and investors require.

Learning from EU Integration Experience. Scarlat et al. (2018) documented how European biomethane markets developed incrementally — initial installations operated under ad hoc bilateral agreements between producers and DSOs before standardised grid codes were established [20]. Quarton and Samsatli (2018) synthesised the lessons of early power-to-gas injection projects, noting that DSO balancing complexity increased with each additional injection point and that near-real-time data exchange became operationally necessary beyond a relatively small number of distributed sources [18].

Ukraine should treat the EU's developmental sequence as informative rather than mandatory. Given the current urgency of energy security concerns and the availability of EU technical assistance mechanisms, Ukraine has an opportunity to adopt the regulatory and technical standards framework as a package — avoiding the iterative, decade-long harmonisation process that EU member states underwent — and to commission first facilities that are designed from the outset to meet mature injection standards. The SGQMF provides the diagnostic structure to specify what 'mature injection standard' means at each stage of the production chain.

Conclusions. This paper has proposed and applied the Stage-Gate Quality and Metering Framework (SGQMF) to examine the full cycle of biogas production and grid injection, with specific focus on automation, quality measurement, and distribution integration challenges in the Ukrainian context. The SGQMF advances beyond descriptive literature review by providing a structured diagnostic tool that maps measurement accuracy requirements, SCADA obligations, quality standards, and integration readiness indicators across six sequential production stages.

The application of the framework to Ukraine confirms that the country possesses favourable upstream conditions — adequate feedstock base and relatively stable mono-substrate digestion — but faces critical deficiencies at the downstream stages of upgrading, fiscal metering, and DSO accounting integration. The cybersecurity of SCADA-linked metering systems represents an additional systemic risk that current Ukrainian regulatory frameworks do not address.

Three sequenced priorities emerge from the analysis. First, investment in SCADA automation at the digestion and conditioning stages must precede fiscal metering installation — the upstream quality environment must be controlled before downstream measurement can be meaningful. Second, adoption of EU metrology standards (EN ISO 17089, EN 16723–1) must be accompanied by accredited certification infrastructure, not merely legislative transposition. Third, DSOs must develop near-real-time digital exchange protocols for biomethane injection accounting, supported by a national certificate of origin registry compatible with European GO systems.

The SGQMF is designed to be reusable: operators, regulators, and project developers can apply it to individual facility assessments or sector-wide planning exercises by updating the Standards and Integration Readiness cells as the regulatory environment evolves. Future empirical research should test the framework against operational data from existing Ukrainian biogas facilities to validate its diagnostic accuracy and refine the measurement parameter thresholds.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
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MODERN POWER SUPPLY AUTOMATION SYSTEMS: TECHNOLOGIES, ADVANTAGES, AND DEVELOPMENT PROSPECTS

Summary. *Power supply automation technology rarely enters an industrial facility through a single, deliberate decision. More often it arrives piecemeal: a relay replaced after a failure, a communication standard adopted because a new switchgear supplier specified it, a storage unit purchased to solve an unrelated power-quality complaint. The result is that many facilities carry a mixture of automation generations without ever assessing that mixture as a whole. This paper takes stock of that situation. Drawing on twenty-five peer-reviewed sources published between 2018 and 2025, it surveys the technology available for automating power supply, from electromechanical protection and automatic reserve switching, known by its Russian-derived acronym ABP, through digitally coordinated substations built on IEC 61850, to self-healing distribution networks that integrate storage and demand-side resources into their own restoration logic. Rather than presenting these as a checklist of features to acquire, the paper argues that a facility's automation portfolio should be assessed as a coherent whole and proposes a five-level Power Supply Automation Maturity Model as a diagnostic tool for doing so. The model links each level to a distinct capital and operating profile, not only a technical one, so an upgrade decision can be weighed as an investment rather than a specification exercise. The paper closes by arguing that the more urgent question facing most industrial sites is not which new automation technology to buy, but which gaps in their existing, uneven portfolio actually justify closing first.*

Key words: *power supply automation; automatic reserve switching; ABP; substation automation; IEC 61850; self-healing distribution networks; energy storage; technology adoption.*

Introduction. Ask an electrical engineer at almost any industrial site what generation of protection and automation equipment the facility runs, and the honest answer is usually several generations at once. A rolling mill added twenty years ago may still rely on electromechanical relays and manually operated tie breakers, while a newer process line down the same yard runs microprocessor-based protection communicating over a digital bus that did not exist when the older equipment was specified. This unevenness is not evidence of neglect; it reflects how automation technology is actually adopted in practice, in response to equipment failures, vendor availability, and one-off projects, rather than through a single coherent plan.

That pattern matters because the individual technologies involved, automatic reserve switching among them, have matured considerably. Digital communication standards, chiefly IEC 61850, have turned the substation from a collection of independently wired devices into a coordinated system capable of making fast, network-wide decisions [2; 11]. Protection logic has moved from fixed timers toward adaptive, signal-based discrimination, in several cases assisted by machine learning [7; 9; 14; 19; 23; 24]. Distribution networks are increasingly designed to isolate a fault and restore supply automatically, treating distributed storage and even parked electric vehicles as flexible resources rather than passive equipment [12; 15; 16; 17; 18; 20; 22]. Each of these advances is well documented on its own terms. What is less well documented is how a facility should decide which of these advances is actually worth pursuing next, given that it is starting from an uneven baseline rather than a blank sheet.

This paper takes up that question directly. It reviews the automation literature not as a set of isolated technical contributions but as evidence of a technological progression, moving from a chronological account of that progression toward a practical model for assessing where a given facility sits within it. Section 2 traces this progression across the reviewed literature; Section 3 sets out the methodology used to convert that account into a usable model; Section 4 reports what the synthesis revealed; Section 5 presents the Power Supply Automation Maturity Model and works through how it applies to industrial and critical-infrastructure sites; Section 6 concludes.

Literature Review

1. The electromechanical and early digital baseline. Before considering where automation is heading, it is worth being precise about the baseline most facilities are still measured against. Escalera, Hayes, and Prodanovic surveyed the techniques used to assess reliability in distribution networks and found that the indices in common use were largely built for a passive, radially operated grid, an assumption that automated and distributed systems increasingly break [6]. That assumption is visible in practice at heavy industrial sites: Kornilov and colleagues, describing the power-supply arrangements at metallurgical iron-and-steel works, note that different process sections within a single plant can have sharply different tolerance for interruption, a distinction that a uniform, plant-wide protection philosophy tends to obscure [10]. Jooshaki and colleagues, working from the planning side, showed that distribution expansion under incentive-based reliability regulation can be formulated as a mixed-integer linear programme, treating reliability as a quantity optimized against cost rather than a fixed engineering target [8]. Adetokun and Muriithi added a further complication, reviewing flexible alternating current transmission system devices for voltage stability and showing that a switching event can itself destabilize voltage on a weak reserve source unless reactive power support is arranged in advance [1]. This literature suggests the electromechanical baseline was never quite as simple or uniform as commonly assumed, which matters for how any later automation upgrade should be evaluated.

2. The digitalization wave. The clearest technological discontinuity in the literature reviewed is the shift toward standardized digital communication within the substation. Aftab and colleagues traced how IEC 61850 replaced dedicated point-to-point wiring between protection devices with a shared communication bus, arguing that this shift, more than any single relay improvement, is what makes coordinated, fast decision-making across multiple protection zones practical [2]. Kumar, Abu-Siada, and colleagues reached a closely related conclusion, treating IEC 61850 adoption as the organizing event around which modern substation automation is now specified [11]. Altaf and colleagues complicated this picture by cataloguing protection difficulties specific to microgrids, where fault current can reverse direction depending on which source is active, a condition digital communication alone does not resolve without protection logic designed for variable topology [3]. Dagar, Gupta, and Niranjan reached a similar conclusion, arguing that schemes built for a passive, radial network frequently fail once a facility operates with parallel or alternating sources [5]. The digitalization wave also introduced a cost earlier, hardwired schemes did not carry: Ashraf and colleagues demonstrated that IEC 61850-based substations are vulnerable to denial-of-service attacks precisely because the communication layer enabling coordination is also an accessible attack surface, a finding that should temper any assumption that digital automation is an unqualified improvement over what it replaces [4].

Running alongside this digitalization is a parallel shift in protection philosophy, away from fixed-time logic and toward adaptive, signal-based decision-making. Han and colleagues developed a reclosing scheme that distinguishes a genuine fault from a transient using harmonic signatures in the secondary arc voltage, while Khan, Bi, and Jia surveyed the broader family of adaptive reclosing schemes built on similar logic for extra-high-voltage lines [7; 9]. Mehdi and colleagues extended this survey across AC, DC, and hybrid transmission technologies and concluded that adaptive, signal-based approaches outperform fixed-timer schemes consistently enough to be considered current state of practice [14]. More recent work applies machine learning directly to this decision problem: Saad, Kim, and Munir combined a particle filter with a convolutional neural network for single-phase reclosing, Xie and colleagues designed an adaptive scheme around a moving-average filter and quadrature signal generator for lines with shunt reactors, and Muzzammel and Raza applied a support vector machine to protection on multi-terminal HVDC systems, extending the same logic well beyond conventional AC networks [19; 23; 24]. Reclosing and reserve switching are formally distinct functions, but both depend on the same judgement, distinguishing a real, sustained disturbance from a transient one, which is why this work transfers so directly into the design of fast, adaptive ABP logic.

3. Toward autonomy: self-healing networks and integrated storage. The most recent phase visible in the literature moves automation from coordinated response toward autonomous restoration. Lu and colleagues proposed a self-healing scheme, built on mixed-integer linear programming, designed to restore supply quickly with minimal manual intervention following a fault [12]. Luo, Ge, and Xu supplied an important qualification, showing that the reliability actually delivered by such schemes is bounded by the quality of data transmission between distribution automation terminals rather than by the sophistication of the restoration algorithm alone [13]. Meteab and colleagues and Pang and colleagues each proposed their own self-healing frameworks, the former organized around efficient network-wide restoration and the latter around partitioning the network into manageable zones with flexible resource aggregation [15; 20]. Reiz, Pereira, and Leite proposed a further self-healing strategy aimed at modern distribution networks, while Mohammadi Hosseininejad and colleagues showed that self-healing performance can be enhanced by co-deploying automatic switches alongside electric vehicle parking lots, treating parked vehicles as a temporary, mobile reserve resource [18; 22].

Storage occupies an increasingly central place in this autonomous phase. Mohamad and Teh conducted a systematic review of how energy storage affects power system reliability, and a related review by Mohamad, Teh, Lai, and Chen traced the broader development of storage technology for network reliability purposes, together suggesting that storage is now designed into automation architecture from the outset rather than added afterward as a contingency [16; 17]. Yan and colleagues reviewed the methods used to assess the reliability of storage systems themselves, arguing that storage needs an assessment framework distinct from the one used for conventional generation [25]. Pavon and colleagues, examining optimal control strategies for smart grid substations, raised a concern that applies across this entire autonomous phase: transition stability, a substation's ability to move smoothly between operating states, is becoming as important a design criterion as its steady-state performance, and storage-integrated automation makes those transitions more frequent rather than less [21].

Taken together, this literature describes three overlapping technological eras rather than a single continuous improvement curve: an electromechanical baseline that is more heterogeneous than commonly assumed, a digitalization wave that brings coordination alongside new cyber risk, and an emerging autonomous phase built on adaptive logic and integrated storage. What none of this literature addresses directly is how a facility already straddling several of these eras at once should decide what to change next, which is the question this paper turns to now.

Methodology. This paper is built on a structured qualitative synthesis of twenty-five peer-reviewed journal and conference sources published between 2018 and 2025, covering substation automation, protection logic, reliability assessment, self-healing distribution, and energy storage. Rather than coding these sources against a fixed set of themes decided in advance, the sources were read chronologically by publication focus and organized into the three technological eras described in Section 2, electromechanical baseline, digitalization, and emerging autonomy, on the basis of which era's characteristic technology or concern each source primarily addressed. Each source was then coded a second time for three practical attributes: the switching or restoration time it reported or assumed, the communication or protocol dependency it required, and any capital or operating cost consideration it discussed explicitly, even in passing.

This second coding pass is what distinguishes the present synthesis from a straightforward literature summary and what feeds directly into the Power Supply Automation Maturity Model in Section 5. The technology boundaries between levels follow the eras identified in Section 2 [2; 11; 12; 15; 16; 17], while the operational account given by Kornilov and colleagues for metallurgical facilities was used to keep the lower levels of the model anchored in a real industrial setting rather than a purely theoretical progression [10]. The cybersecurity findings of Ashraf and colleagues were carried through as an explicit cost and risk consideration attached to the higher, digitally coordinated levels, rather than treated as a separate technical footnote [4]. The resulting model is a conceptual planning tool built entirely from published sources rather than site-specific measurement or cost data; no proprietary or unpublished information was used, and every claim in this paper traces back to one of the twenty-five sources in the reference list.

Results. Five observations emerged from the synthesis and are carried into the discussion that follows.

First, the reviewed literature does not describe a single automation frontier that all facilities are converging toward; it describes three overlapping eras, and most real facilities occupy more than one simultaneously, a pattern the literature acknowledges implicitly through its own uneven treatment of baseline heterogeneity, digitalization, and autonomy [6; 8; 10]. Second, the digitalization wave delivers its coordination benefits and its cybersecurity exposure as a package, not as separable options, meaning that a facility cannot reasonably adopt the communication benefits of IEC 61850 while deferring the governance obligations that come with it [2; 4; 11]. Third, adaptive and machine-learning-assisted protection logic has matured to the point where it now outperforms fixed-timer schemes across a wide range of protection functions, not only reclosing, suggesting that this logic is better understood as a general capability than as a feature specific to any one protection application [7; 9; 14; 19; 23; 24]. Fourth, the reliability gains claimed for self-healing and autonomous restoration schemes are conditional on communication infrastructure quality in a way the underlying algorithms cannot compensate for, which means the case for moving toward autonomy rests as much on a facility's telecommunications position as on its appetite for new switching logic [13]. Fifth, storage is shifting from a contingency asset toward a design input for automation architecture, and this shift changes the underlying economics of automation upgrades, since a storage investment can substitute for, rather than simply complement, certain classes of switching decision [16; 17; 25].

Taken together, these findings point toward a conclusion that is easy to state but not straightforward to act on: the technology exists to build a highly capable, largely autonomous power supply automation architecture, but almost no facility is starting from the same baseline, and the literature offers little guidance on how to sequence an upgrade path given that starting point. That sequencing problem, treated as a diagnostic and investment question rather than a purely technical one, is the focus of the discussion below.

1. Assessing a portfolio rather than choosing a technology. The central difficulty this paper has tried to

Table 1

Proposed Power Supply Automation Maturity Model (PSAMM)

Level	Description	Enabling technologies	Typical reliability outcome	Key references
0	Manual and electro-mechanical control	Fixed-time relays, manual switching, local operator judgement	Multi-second to minutes-scale interruption; recovery depends on operator response	[10]
1	Microprocessor-based digital relays with standard ABP	Configurable digital relay logic; point-to-point wiring	Switching in roughly 0.3 s to 1.5 s; improved diagnostics	[10]
2	IEC 61850-based digital substation automation	Shared digital communication bus; coordinated multi-bay protection	Faster, coordinated switching; new cybersecurity exposure	[2; 4; 11]
3	Adaptive, signal-based protection and switching logic	Signal-based fault discrimination; machine-learning-assisted decision logic	Sub-second, adaptive discrimination between genuine faults and transients	[7; 9; 14; 19; 23; 24]
4	Self-healing, storage-integrated architecture	Network-wide automated restoration; distributed storage and flexible resources (including EVs)	Automatic fault isolation and supply restoration across the network	[12; 15; 16; 17; 18; 20; 22]

Source: developed by the author

surface is that most industrial facilities are not choosing among competing automation technologies from a blank slate; they are managing a portfolio of equipment purchased at different times, for different reasons that now needs to be assessed as a whole. Framed this way, the relevant question shifts from which technology performs best in isolation, a question Section 2 answers reasonably well, to where the gaps in an existing, uneven portfolio actually justify investment. Kornilov and colleagues make this concrete: within

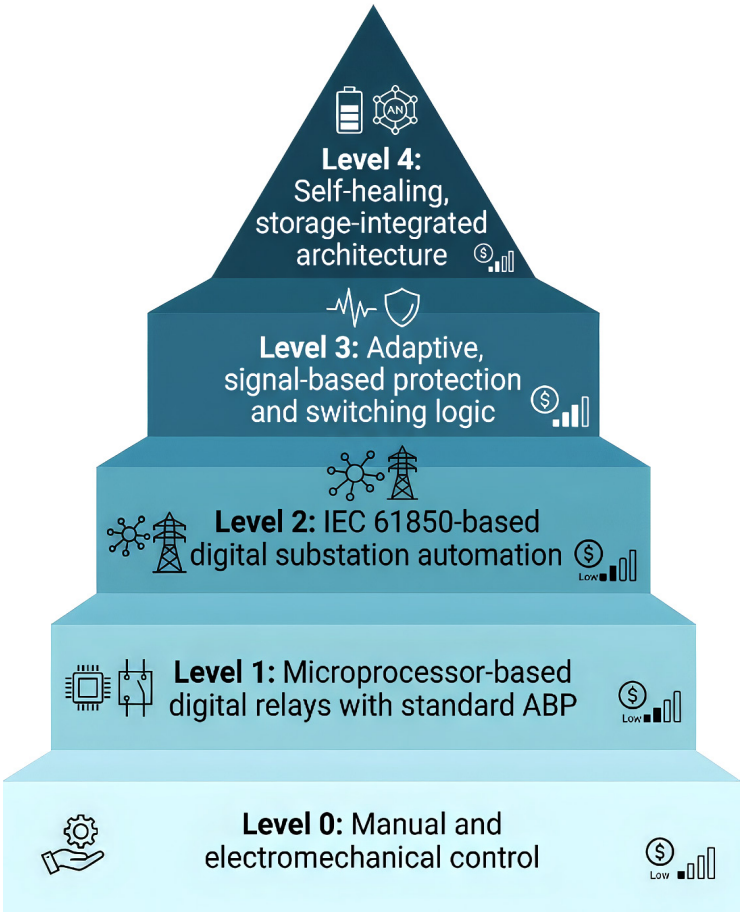


Fig. 1. Power Supply Automation Maturity Model Infographic

Source: developed by the author

Table 2

Characteristic cost profile and distinguishing capability by maturity level

Level	Characteristic cost / investment profile	Distinguishing capability gained
1	Low recurring communication cost; limited coordination across process areas	Configurable relay logic and improved diagnostics
2	New recurring cybersecurity governance cost taken on in exchange for coordination	Coordinated, multi-bay protection over a shared digital bus [4]
3	Investment in signal-processing or analytics capability beyond Level 2	Adaptive discrimination of genuine faults from transients
4	Largest upfront capital commitment, chiefly storage and communication infrastructure	Storage begins substituting for, rather than merely supplementing, certain switching decisions [16; 17]

Source: developed by the author

a single metallurgical facility, some process sections may already warrant fast, adaptive protection while others are adequately served by conventional switching, and a plant-wide policy that ignores this variation will misallocate investment in both directions [10].

2. The Power Supply Automation Maturity Model. This paper proposes a five-level Power Supply Automation Maturity Model, summarized in Table 1, as a diagnostic tool for this portfolio assessment. Level 0 corresponds to manual and electromechanical control, still standard practice at facilities such as the metallurgical works described by Kornilov and colleagues, where switching decisions rely on fixed-time relays and local operator judgement [10]. Level 1 introduces microprocessor-based digital relays and standard automatic reserve switching, adding configurable logic and diagnostics without yet requiring a shared communication bus. Level 2 corresponds to the digitalization wave described in Section 2.2, built on IEC 61850 and requiring the cybersecurity governance that Ashraf and colleagues show is inseparable from its coordination benefits [2; 4; 11]. Level 3 layers adaptive, signal-based, and in some cases machine-learning-assisted protection logic onto that digital foundation [7; 9; 14; 19; 23; 24]. Level 4 corresponds to the emerging autonomous phase, a self-healing, storage-integrated architecture in which faults are isolated and supply restored across a wider network with minimal operator involvement [12; 15; 16; 17; 18; 20; 22] (See Figure 1).

The distinguishing feature of this model, relative to treating each technology as a standalone upgrade, is Table 2, which attaches a characteristic facility profile and cost signal to each level rather than only a technical description. A Level 1 facility typically carries low ongoing communication cost but limited coordination across process areas; a Level 2 facility takes on new

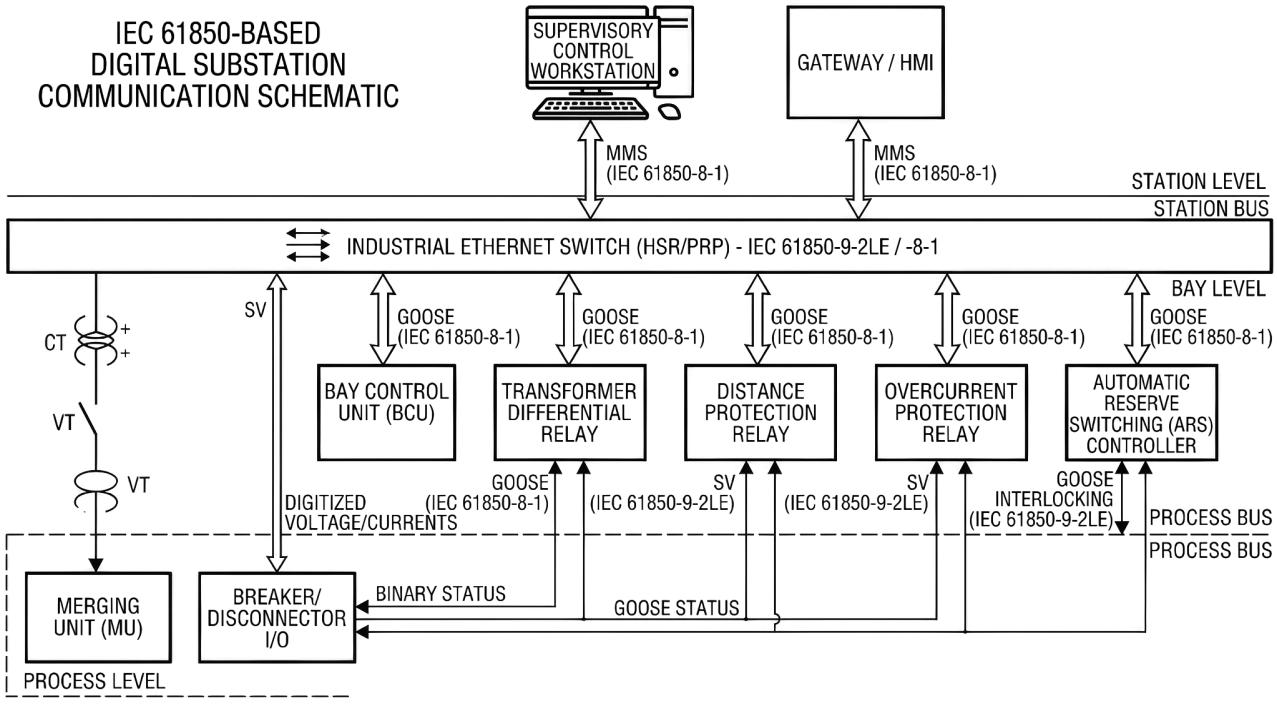


Fig. 2. IEC 61850 Digital Substation Schematic with GOOSE Messaging

Source: developed by the author

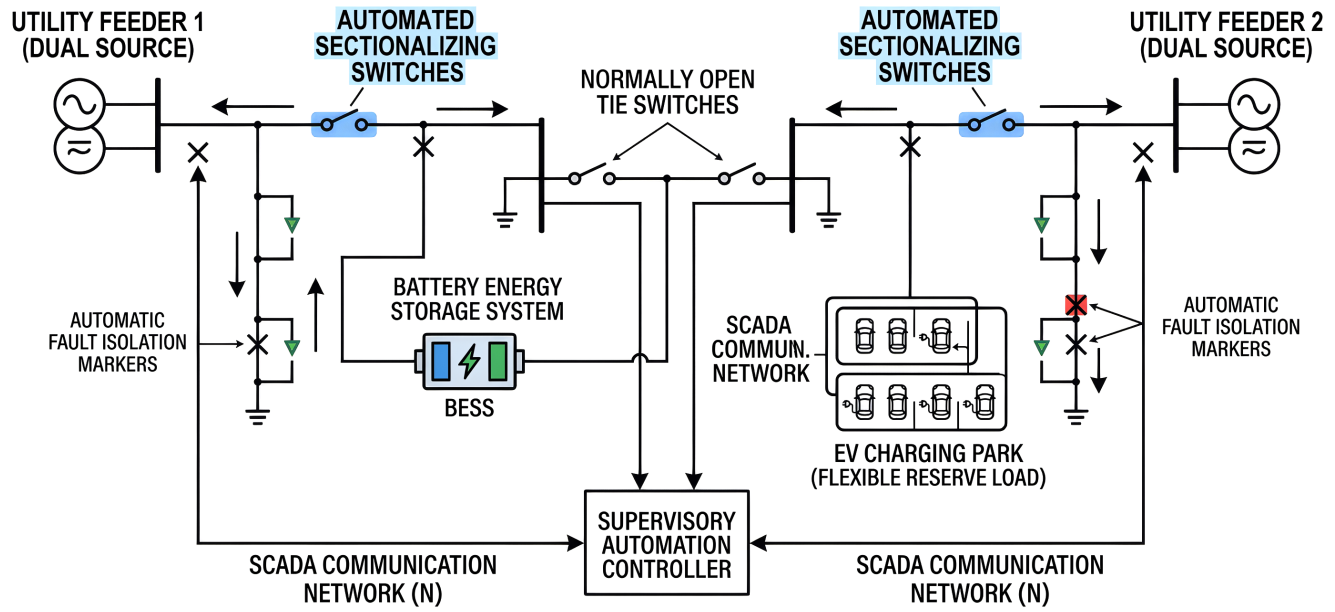


Fig. 3. Self-Healing Smart Distribution Grid
Source: developed by the author

recurring cybersecurity governance cost in exchange for that coordination; a Level 3 facility requires investment in signal-processing or analytics capability that a Level 2 facility does not; and a Level 4 facility requires the largest upfront capital commitment, chiefly in storage and communication infrastructure, but is the only level at which storage can begin substituting for, rather than merely supplementing, certain switching decisions [16; 17; 25] (See Figure 2).

3. What this means for industrial and critical-infrastructure sites. For a facility resembling the metallurgical case described by Kornilov and colleagues, the model suggests a targeted rather than uniform response: raising only the most interruption-sensitive process sections to Level 2 or Level 3, while leaving auxiliary loads at Level 1, is likely to deliver more reliability per unit of investment than a single plant-wide upgrade [3; 5; 10]. Critical infrastructure operators that already maintain a distribution automation footprint are better positioned to consider Level 4, but only if the communication-quality concerns raised by Luo, Ge, and Xu are addressed as a precondition rather than an afterthought [13]. The model also reframes the role of storage: a facility does not need to reach Level 4 to benefit from it, since the literature reviewed in Section 2.3 shows storage delivering measurable reliability value well before a full self-healing architecture is in place [16; 17; 25] (See Figure 3).

4. Limitations and directions for further work. This model was built entirely from published technical and cost signals rather than from site-specific interruption-cost or capital-expenditure data, and testing the proposed level boundaries against real transition data at facilities moving between levels is the most pressing next step. The optimization approach that Jooshaki and colleagues applied to distribution expansion planning under reliability regulation offers a workable template for turning the level-selection decision proposed here into a formal constrained-optimization problem rather than a qualitative judgement call [8]. The transition-stability concerns raised by Pavon and colleagues also merit closer attention in any staged upgrade plan, since a facility moving between levels is, almost by definition, spending more time than usual in transitional operating states that this model does not yet characterize in detail [21].

Conclusions. Most industrial facilities are not deciding whether to adopt power supply automation; they already have, unevenly, over years of piecemeal investment. The more useful question, and the one this paper has tried to answer, is how such a facility should assess the portfolio it already has and decide where the next investment actually belongs. The literature reviewed here documents a clear technological progression, from electromechanical baseline through digital coordination to adaptive, largely autonomous restoration, but offers comparatively little guidance on sequencing that progression for a facility that is not starting from zero. The Power Supply Automation Maturity Model proposed in this paper addresses that gap by attaching a concrete technical and cost profile to each stage, allowing a facility to locate itself honestly and weigh the next step as an investment decision rather than a specification exercise. Automatic reserve switching remains the anchor of this progression throughout, not because it is superseded by later stages but because every later stage depends on it working correctly. Confirming the practical value of the proposed levels against real transition and cost data at operating facilities is the logical next step for this line of work.

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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АДАПТАЦІЯ ЯК ЕЛЕМЕНТ КЛІМАТИЧНОЇ БЕЗПЕКИ В УКРАЇНІ

ADAPTATION AS ELEMENT OF CLIMATE SECURITY IN UKRAINE

Анотація. *У роботі проаналізовано основні засади кліматичної політики України з точки зору кліматичної безпеки. Показано, що основною проблемою є відсутність самого поняття кліматична безпека і розкоординованість стратегічного кліматичного планування. Визначено основні проблеми і надано рекомендації щодо інтегрованого кліматичного планування із включенням поняття кліматична безпека і адаптації як її компоненту до стратегічних документів. Оцінений масштаб втрат і вигод у сфері адаптації (у фінансовому вимірі), синергетичні ефекти від різних компонентів кліматичної безпеки (адаптації і мітігації).*

Ключові слова: *адаптація, мітігація, кліматична безпека, кліматична стійкість.*

Summary. *The paper analyzes the main principles of Ukraine's climate policy with respect to climate security. It is shown that the main problem is the absence of the very concept of climate security itself and the lack of coordination of climate strategic planning. The main problems are identified and recommendations are provided for integrated climate planning with the inclusion of the concept of climate security and adaptation as its component in strategic documents. The scale of losses and benefits in the field of adaptation (in financial terms), synergy effects from various components of climate security (adaptation and mitigation) are estimated.*

Key words: *adaptation, mitigation, climate security, climate resilience.*

Вступ. Основні компоненти кліматичної безпеки, такі як адаптація, мітігація (скорочення викидів), реагування на розгортання військових ризиків, проблеми доступу до ресурсів, взаємодія екосистеми і людини, — в Україні наразі частково закріплені в Стратегії низьковуглецевого розвитку України 2050 [1], Нацплані з енергетики та клімату 2030 [2] та інших стратегічних документах. Всі ці компоненти є нерозривно пов'язаними між собою для забезпечення кліматичної, енергетичної, продовольчої безпеки і, що найбільш важливо наразі, безпеки національної і військової.

Історично державна політика України у сфері протидії кліматичним змінам формувалася за принципом галузевої ізоляції, де кліматична безпека і адаптація, як її основний компонент, жодного разу не розглядалася як комплексна міждисциплінарна парадигма. Замість інтегрованого підходу, що поєднує екологічні, економічні та безпекові вектори, країна демонструвала фрагментарну активність. Окремі елементи адаптації (наприклад, локальні програми протидії підтопленням чи посухам на рівні підприємств чи окремих районів, стратегії адаптації окремих областей) впроваджувалися хаотично,

без належної координації між профільними міністерствами, без чіткої стратегії на національному рівні. Кліматична політика тривалий час не включала в себе взагалі поняття кліматичної безпеки, сприймалася як доповнення до міжнародних угод, а не як фундаментальний елемент національної безпеки, що призвело до відсутності єдиного координаційного центру.

Повномасштабна війна критично загострила ці системні прорахунки, наклавши нові безпекові ризики на вже існуючі кліматичні вразливості. Воєнні дії руйнують синергію компонентів, особливо мітігації та адаптації: детонація боєприпасів і масштабні лісові пожежі спричиняють додаткові викиди парникових газів, водночас знищуючи природні поглиначі вуглецю та сприяючи деградуванню ґрунтів, лісів, цілих екосистем. Руйнування критичної інфраструктури, Каховської ГЕС, іригаційних систем півдня України миттєво спотворили довгострокові кліматичні прогнози через розгортання гуманітарних та екологічних ризиків. В умовах, коли питання виживання та військової оборони є домінантними, координація політики у сфері кліматичної безпеки відійшли на периферію державних пріоритетів, що лише посилює майбутню вразливість держави до кліматичних шоків у процесі повоєнного відновлення.

Тим не менш, Україна, залишається одним із ключових гравців глобальної кліматичної архітектури. Наразі Україна є Стороною Паризької угоди (з 2015 р.), що окрім іншого, регламентує адаптацію і кліматичну стійкість як один із основних способів реагування держави на зміну клімату і безпекові ризики. Уряд знаходиться на етапі впровадження Статті 6 Паризької угоди, так у червні 2026 року затверджена Постанова Кабінету Міністрів України (КМУ) Про реалізацію експериментального проекту щодо виконання окремих положень статті 6 Паризької угоди [3]. У 2024–2025 рр. були підписані Меморандуми із Швейцарією (2022) і Японією (JICA) (2024) в рамках статті 6.2 Паризької угоди, перші проекти і скорочення викидів CO_2 очікуються у 2026–2027 рр.

При цьому, відповідно до п'ятої швидкої оцінки завданої шкоди та потреб (RDNA5) (лютий 2026, спільна оцінка Світового банку, Уряду України, Європейської Комісії, ООН, Європе́йського банку реконструкції і розвитку (EBRD) та ін.) [4], прямі збитки від війни за період лютий 2022 — грудень 2025 сягнули вже 195,1 млрд. дол. США, соціально-економічні втрати — 667 млрд. дол., загальні потреби на відновлення та реконструкцію на 10 років — 587,7 млрд. дол. Очевидно, такий масштаб втрат змінює саму парадигму кліматичного фінансування. Воно тепер неможливо без врахування безпекових ризиків, чи від безпосередньо кліматичних впливів, чи від військових або інших зовнішніх загроз. Таким чином кліматична безпека наразі стає фактором прийняття рішення щодо сталої реконструкції, забезпечення кліматичної стійкості і адаптації, зниження чутливості і ризиків для екосистем, бізнесу і населення, а надання кліматичного фінансування тепер має ґрунтуватися на нових принципах аналізу впливів і загроз [5; 6; 7].

Адаптаційна здатність та кліматична стійкість

Адаптаційна здатність — основа кліматичної безпеки будь-якої країни. Прискорені кліматичні зміни та військові дії створюють каскадні ефекти і нові рівні ризиків, впливів і загроз: посухи, повені, ерозія ґрунтів, опустелювання, руйнування життєво необхідної інфраструктури, цілих екосистем (південь і схід), деградація лісів, обмеження доступу до ресурсів з прямими екологічними наслідками для населення.

Часто ці наслідки мають транскордонний безпековий характер, наприклад, пошкодження підземного сховища газу в Україні або нафтопроводу загрожує стабільності енергопоставок до Європейського Союзу (ЄС). RDNA5 зазначає, що прямі тільки екологічні втрати за період лютий 2022- лютий 2026 вже сягнули 36 млрд. дол. (інші джерела дають ще вищі цифри), потреби на відновлення тільки у сфері лісокористування — 3,1 млрд. дол.

Україна, нажаль, не приділяла компоненту адаптації як елементу кліматичної безпеки достатньої уваги і тільки в останні роки було здійснено низку проектів адаптації і аналізу кліматичних ризиків. Це було регламентовано, серед іншого, прийнятим розробленого за підтримки міжнародних партнерів у 2024 р. Закон України «Про основні засади державної кліматичної політики» [8], що прямо вказує на необхідність розробки регіональних стратегій адаптації до зміни клімату.

У той час як на національному рівні адаптація поки що регулюється рамковими документами — такими як урядова Стратегія формування та реалізації державної політики у сфері зміни клімату на період до 2035 року — окремого затвердженого Національного плану чи Стратегії з адаптації держава ще не має. [9]

Проте регіони за підтримки міжнародних партнерів уже почали діяти самостійно.

1. Перші три пілотні регіони України (Львівська, Івано-Франківська та Миколаївська області):

У вересні 2024 року в межах фінансованого Європейським Союзом (ЄС) проєкту APENA 3 (у співпраці з Міндовкілля) було офіційно розроблено та презентовано перші детальні кліматичні стратегії для трьох областей. Вони містять довгострокові прогнози до кінця століття та чітко прораховану вартість заходів (наприклад, для Львівщини це 168 заходів на €273,7 млн.) [10; 11; 12]

2. **Закарпатська область:**

Регіон розробив власну Стратегію адаптації до зміни клімату та заходів щодо пом'якшення її негативних наслідків для Закарпатської області

в межах транскордонного проєкту (CLIMADAM) у партнерстві зі Словаччиною. Документ є прикладом того, як прикордонний регіон фокусується на управлінні ризиками повеней та збереженні лісових екосистем [13].

3. Миколаївська, Дніпропетровська, Запорізька, Херсонська області Проект UCO-GIZ-Insu-Resilience-Franfkurt School of Economics [14] розробив аналітичний звіт з аналізу ризиків і кількісної оцінки втрат і вигод від заходів адаптації для 4 областей півдня України для агросектору, будівель та інфраструктури на основі даних картографії регіонів і спеціально розроблених моделей (модифікація CLIMADA) під ці дані.

4. Фронтові та прифронтові регіони (Дніпропетровська та Сумська області).

У серпні 2025 року в межах іншого масштабного проєкту ЄС EU4ClimateResilience розпочалася активна розробка регіональних кліматичних стратегій для Дніпропетровщини та Сумщини. Особливість цих документів — поєднання кліматичного планування із повоєнним відновленням та оцінкою руйнувань, завданих військовими діями [15].

За попередніми оцінками, загальні інвестиції в проекти з адаптації і підвищення кліматичної стійкості до 2050 р. в Україні можуть сягнути 50–70 млрд. Євро, в той час як збитки від реалізації загроз — не менше 100 млрд. Євро (за відсутності реалізації проектів адаптації, що знижують кліматичні ризики). Серед основних заходів автори вказаних досліджень зазначають кліматично стійке сільське господарство (адаптивні сорти, крапельне зрошення, рециркуляція, використання біомаси), відновлення водних ресурсів (децентралізовані системи, адаптивне водорозподілення, захист від повеней, «розумні» системи), «зелені» захисні коридори та рефорестація з використанням серед іншого енергокультур, інтеграція кліматичних ризиків у оборонну стратегію (адаптація військової інфраструктури, демінування, екологічне стале відновлення знищених екосистем), озеленення інфраструктури міст.

Загальний кількісний внесок адаптації у кліматичну безпеку можна оцінити за трьома основними категоріями — сільське господарство, водне господарство, урбаністика (табл. 1).

Як видно, основний внесок у адаптацію вносить сільське господарство із масштабом втрат/інвестицій для уникнення втрат 50…120/30…80 млрд. Євро до 2050 р. Здійснення заходів з адаптації також мають мультиплікаційні ефекти для економіки, хоча для деяких секторів вони значно менші за втрати/інвестиції (більшість заходів не є окупними комерційними проектами).

Концепція синергії компонентів — адаптації і мітігації

Одним з викликів у сфері кліматичної безпеки є кількісна оцінка ефектів від заходів та визначення таких, які при впровадженні дають подвійні ефекти для різних компонентів кліматичної безпеки — мітігації і для адаптації (синергія заходів), а також мають економічні мультиплікаційні ефекти і узгоджуються зі стратегічним «зеленим» курсом України для кліматичної нейтральності.

Наприклад, відновлення та збереження водно-болотних угідь та торфовищ одночасно сприяє мітігації (зменшує викиди вуглецю та покращує його поглинання) і адаптації (регулює водний баланс, запобігаючи посухам та повеням), проекти виробництва енергії з ВДЕ мають ефект підвищення стійкості енергомереж (адаптація), децентралізації і одночасно сталого скорочення викидів CO_2 тощо (див. табл. 2).

Представлені сфери діяльності і ефекти, хоча і не є вичерпними, але дають уявлення про синергетичні ефекти, якщо кліматична безпека буде розглядатися не за окремими компонентами, а в комплексі. Подібні матриці взаємного впливу надалі можуть бути побудовані по кожному компоненту кліматичної безпеки і стати науковою основою для розробки Концепції кліматичної безпеки України.

Висновки та рекомендації

1. Скоординувати державну політику у сфері кліматичної безпеки через створення єдиного координаційного органу («centre of excellence»), Офісу

Таблиця 1

Оцінка масштабу інвестицій і втрат на адаптацію по ключовим компонентам та вплив на кліматичну безпеку

№	Компонент кліматичної безпеки	Інвестиції до 2050 р., млрд. Євро	Втрати від бездіяльності до 2050 р., млрд. Євро	Мультиплікаційні ефекти для економіки до 2050 р., млрд. Євро**	Вплив на кліматичну безпеку
1	Адаптація, кліматична стійкість	30…80	50…120	15…30	Високий
1.1	Сільське господарство (посухи, інвазія)	15…40	30…70	10…20	Високий
1.2	Водне господарство (підтоплення, повені)	10…25	15…35	3…5	Високий
1.3	Урбаністика, будівлі, озеленення	5…15	5…15	2…5	Середній

Таблиця 2

Синергія мітігації та адаптації у ключових секторах

Сфера економіки	Ефекти мітігації (зменшення викидів CO_2-екв.)	Ефекти адаптації (пристосування до наслідків)
Енергетика	Перехід на ВДЕ (сонце, вітер, біомаса, біометан), підвищення енергоефективності.	Захист енергомереж від екстремальних погодних явищ (штормів, ожеледі, військових ударів), децентралізація генерації.
Сільське господарство	Скорочення викидів від тваринництва, впровадження точного землеробства для зменшення витрат пального.	Вирощування посухостійких сортів, крапельне зрошення, системи захисту від ґрунтової ерозії, зменшення промислового забруднення.
Водне господарство	Скорочення викидів від впровадження малих ГЕС, підвищення гнучкості енергосистеми, акумуляція і балансування виробництва-споживання енергії	Стале забезпечення водою посушливих регіонів, сприяння зарибленню, відновленню річкових русел, бар'єри на шляху повеней.
Міське господарство (Урбаністика)	Розвиток екологічного громадського транспорту, впровадження енергоефективності в будівлях, «зелена» архітектура	Створення «зелених» дахів, облаштування дощової каналізації, збільшення тіньових зон.
Лісове господарство	Збільшення площ лісових насаджень для поглинання вуглецю, енергокультури, виробництво біомаси, біопалива.	Висадження порід дерев, стійких до температурних стресів, запобігання лісовим пожежам, накопичення вуглецю в ґрунті.

кліматичної безпеки, з чітко визначеними повноваженнями (наприклад, при Раді національної безпеки і оборони України чи Кабінеті Міністрів України).

2. Розглянути фінансовий інструментарій (за прикладом архітектури Ukraine Facility або еквівалентного механізму), з критеріями відбору, де кошти на проекти мають маркуватися під комбіновані заходи для реконструкції, мітігації, адаптації, реагування на військові ризики. Передбачити фінансування на зниження ризиків у сфері кліматичної безпеки, наприклад, через окремий Фонд кліматичної безпеки Включити у програми переговорів з партнерами і донорами поняття «кліматична безпека» як базисного при відновленні інфраструктури.

3. Прибрати неузгодженості між міністерствами (Міненерго/ Міндовкілля, Мінфіном/ Мінрегіоном). Чітко визначити межі повноважень та відповідальності у сфері кліматичної безпеки

4. Розробити Концепцію кліматичної безпеки і Концепцію адаптації як компоненту кліматичної безпеки як окремий інтегрований документ, що пов'яже енергетичне, кліматичне та військове планування.

5. Доповнити стратегічні документи України, такі як Національний план з енергетики та клімату на період до 2030 (НПЕК-2030), Енергетична стратегія-2050, Національна безпекова стратегія, План відновлення України, та інші пов'язані новим окремим розділом «Кліматична безпека» і «Адаптація, кліматична стійкість». Інтегрувати поняття «Кліматична безпека» у ЗУ «Про основні засади державної кліматичної політики» із конкретним визначенням завдань по реалізації для центрального органу виконавчої влади.

ДОДАТКОВА ІНФОРМАЦІЯ

ВНЕСОК АВТОРІВ: Усі автори зробили внесок порівну.
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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НЕПЕРЕРВНА ВИБІРКОВА ПЕРЕВІРКА ДОСТУПНОСТІ ДАНИХ У СХОВИЩАХ ЗАГАЛЬНОГО ПРИЗНАЧЕННЯ

CONTINUOUS DATA AVAILABILITY SAMPLING IN GENERAL-PURPOSE STORAGE

Анотація. *Вибіркова перевірка доступності даних (DAS) дозволяє легким клієнтам переконуватися, що дані фактично зберігаються в мережі. Наявні формалізації DAS моделюють одноразову перевірку блоку; для сховищ загального призначення, де дані живуть роками, формальної моделі немає. Запропоновано модель неперервного DAS: деградація кодованого об'єкта та вибіркові запити – конкуруючі пуасонівські процеси. Виведено вираз для ймовірності невиявленої втрати, порогову умову q* та межу запитів клієнта j*(ε).*

Ключові слова: *вибіркова перевірка доступності даних, децентралізовані сховища, надлишкове кодування, довговічність даних, пуасонівські процеси, бюджет вибірки.*

Summary. *Data availability sampling (DAS) allows light clients to verify that data is actually stored in the network. Existing formalizations model a one-time check of a block; for general-purpose storage, where data lives for years, no formal model exists. We propose a continuous DAS model: degradation of an encoded object and client sampling queries are competing Poisson processes. We derive the probability of undetected data loss, a threshold condition q*, and a per-client query bound j*(ε).*

Key words: *data availability sampling, decentralized storage, erasure coding, data durability, Poisson processes, sampling budget.*

Вступ. Децентралізовані сховища загального призначення — Filecoin, Storj, Walrus, Codex — захищають дані надлишковим кодуванням: об'єкт розбивається на блоки за схемою (n, k), і для відновлення достатньо будь-яких $k < n$ блоків [1]. Проте кодування саме по собі не гарантує, що блоки *фактично зберігаються*: вузол може втратити дані внаслідок збою або зловмисно приховувати їх, відповідаючи на службові повідомлення, але не видаючи вміст. Для власника даних цю проблему розв'язують доведення зберігання — proofs of retrievability (PoR) [2] та provable data possession (PDP) [3]; існують і публічно верифіковані варіанти [4], проте всі вони вимагають підготовки автентифікаторів власником під час завантаження й аудиту кожного файлу окремо — тобто не дають *стороннього* легкого клієнта без

попереднього налаштування, здатного перевірити доступність довільних чужих даних.

Альтернатива — вибіркова перевірка доступності даних (DAS), запропонована для блокчейн-масштабування [5]: клієнт запитує випадкові блоки кодованих даних, і успіх невеликої кількості запитів дає високу впевненість у доступності цілого. DAS має формальні означення та доведення безпеки [6], розширення з локальним відновленням [7] та детальні симуляційні дослідження для Ethereum [8]. Однак уся ця лінія моделює *одноразову* подію: блок розповсюджено, клієнти перевірили його доступність, протокол завершився. У сховищі загального призначення постановка інша: об'єкт зберігається місяці й роки, вузли неперервно вибувають через плинність (churn), а приховування блоку небезпечне не саме по собі, а тим, що воно *залишається невиявленим*, поки надлишковість деградує. Системи, що вже застосовують вибіркові перевірки до довгоживучих даних — Codex із сублінійною вибіркою [9] та Walrus зі storage challenges [10], — обирають частоту перевірок евристично, без аналітичного зв'язку з довговічністю даних. Найближчий розгорнутий механізм неперервної перевірки — Filecoin Proof-of-Spacetime [11] — керується доводжувачем: провайдер сам періодично публікує доведення зберігання; у DAS натомість ініціатива належить клієнтам, і саме зв'язок частоти клієнтських перевірок із довговічністю даних у жодній із цих систем не аналізується.

Отже, відкритим є базове запитання: *якою має бути інтенсивність вибірки, щоб виявлення втрат встигало за їхнім накопиченням?*

Внески цієї роботи: Формальна модель неперервного DAS: втрата і приховування блоків та вибіркові запити клієнтів — конкуруючі пуасонівські процеси; виявлення відсутнього блоку запускає відновлення. Модель поєднує DAS-постановку [6] з марківським аналізом надійності кодованих сховищ [12].

Наближений замкнений вираз для ймовірності невиявленої втрати P_loss(q) як функції сукупного бюджету вибірки q та порогова умова

$$q^* \approx n(n-k)/(\delta \cdot t_r),$$

за якої DAS-моніторинг наближається до ідеального монітора з допуском δ.

Межа

$$j^*(\varepsilon) = n \cdot \ln(1/\varepsilon)/(n-k+1)$$

на кількість запитів окремого клієнта для ε-впевненості в доступності об'єкта, з наслідком: сукупне мережеве навантаження визначається лише q і не зростає з кількістю клієнтів за агрегації вибірок.

Формальна модель
Система та модель загроз

Розглядаємо один об'єкт, закодований за схемою (n, k): n блоків розміщено на n різних вузлах, для декодування достатньо будь-яких k. Стан об'єкта $s \in \{k-1, k, \ldots, n\}$ — кількість фактично доступних блоків; $s = k-1$ — поглинаючий стан втрати. Блок стає недоступним двома шляхами з сумарною інтенсивністю λ на блок: (i) *чесна відмова* — вузол залишає мережу або втрачає дані; (ii) *приховування* — вузол відповідає на службові повідомлення, але не видає блок на запит. Ключова асиметрія: обидві події *невидимі* для системи, доки хтось не спробує отримати блок. На відміну від блокчейн-DAS, де супротивник — виробник блоку в момент розповсюдження [5], тут супротивником є підмножина вузлів зберігання протягом усього життя об'єкта.

Процес вибірки та виявлення

Клієнти колективно генерують вибіркові запити до об'єкта як пуасонівський процес із сукупною інтенсивністю q запитів за одиницю часу; кожен запит адресує рівномірно випадковий блок із n. Відповіддю слугує мала автентифікована комірка блоку (наприклад, лист Merkle-дерева з доведенням належності [9]), тож вартість запиту значно менша за розмір блоку. Запит до недоступного блоку завершується невдачею, що *виявляє* дефект. Час до виявлення конкретного відсутнього блоку розподілений експоненційно з середнім n/q. Після виявлення система запускає відновлення блоку з решти $\geq k$ доступних; час відновлення має середнє t_r. Отже, ефективна інтенсивність усунення одного дефекту обчислюється за формулою (1):

$$\mu_{DAS} = \frac{1}{n/q + t_r}. \quad (1)$$

Строго кажучи, послідовність «виявлення, потім відновлення» має фазовий (phase-type) розподіл; заміна його одним експоненційним розподілом із середнім $n/q + t_r$ — стандартне наближення марківських моделей надійності [12]. Зауважимо також консервативність: коли відсутніх блоків $m > 1$, вибірка влучає в *будь-який* із них з інтенсивністю $q \cdot m/n > q/n$, тож використання μ_DAS для всіх станів дає нижню оцінку інтенсивності виявлення і, відповідно, верхню оцінку ймовірності втрати.

Зв'язка з відновленням: ланцюг народження-загибелі

Аналогічно до марківських моделей надійності [12], система описується ланцюгом зі станами $\{k-1, \ldots, n\}$: перехід $s \to s-1$ (нова недоступність) з інтенсивністю $\alpha_s = s \cdot \lambda$; перехід $s \to s+1$ (виявлення + відновлення, $s < n$) з інтенсивністю μ_DAS. Модель навмисно протокол-агностична: конкретний механізм доведення (Merkle-доведення, KZG-зобов'язання [6], ZK-доведення [9]) впливає лише на розмір запиту та константи t_r, але не на структуру процесу.

Межі бюджету вибірки
Ймовірність невиявленої втрати

Визначимо P_loss як ймовірність того, що *епізод деградації* — період від першої недоступності в повному стані n до повернення в n або поглинання — завершиться безповоротною втратою (станом $k-1$). Перший перехід $n \to n-1$ відбувається без

конкуренції з відновленням: у повному стані нема чого виявляти. Далі втрата вимагає ще $n - k$ послідовних недоступностей до першого завершення циклу «виявлення + відновлення» (разом $n - k + 1$ відмов від n до $k - 1$). У станах $s \in \{k, \ldots, n - 1\}$ ймовірність переходу вниз становить

$$s{\cdot}\lambda/(s{\cdot}\lambda + \mu_DAS) \approx s{\cdot}\lambda/\mu_DAS$$

(наближення чинне при $\mu_DAS >> n{\cdot}\lambda$), і перемноження по станах $s = n - 1, \ldots, k$ дає формулу (2):

$$P_{loss}^{DAS}(q) \approx \frac{(n-1)!}{(k-1)!} \cdot \left(\lambda \cdot \left(\frac{n}{q} + t_r\right)\right)^{n-k}. \qquad (2)$$

Вираз (2) явно розділяє два доданки вікна вразливості: затримку *виявлення* n/q, керовану бюджетом вибірки, та затримку *відновлення* t_r, задану інфраструктурою. При $q \to \infty$ вираз збігається до ймовірності втрати системи з ідеальним монітором (миттєвим виявленням), для якої вікно дорівнює лише t_r.

Порогова умова q^*

Ідеальний монітор виявляє недоступність миттєво (границя $q \to \infty$), тож

P_loss^ideal = $((n - 1)!/(k - 1)!)\cdot(\lambda{\cdot}t_r)^{n - k}$.

Визначимо надлишок ризику

R(q) = P_loss^DAS(q) / P_loss^ideal =
= $(1 + n/(q{\cdot}t_r))^{n - k}$;

комбінаторний коефіцієнт скорочується. Вимагаючи $R(q) \le 1 + \delta$ для допуску $\delta << 1$ і розкладаючи за малим $n/(q{\cdot}t_r)$, отримуємо формулу (3):

$$\boxed{q^* \approx \frac{n \cdot (n-k)}{\delta \cdot t_r}} \qquad (3)$$

– мінімальний сукупний бюджет вибірки, за якого DAS-моніторинг втрачає не більше ніж частку δ довговічності порівняно з миттєвим виявленням. Практичні наслідки: q^* зростає лінійно з n при фіксованому запасі $n - k$ (за пропорційної надлишковості $n - k \propto n$ зростання квадратичне), лінійно з $n - k$ (більший запас означає, що ризик визначається глибшим хвостом добутку, чутливішим до затримки виявлення), і обернено пропорційний t_r — у системах зі швидким відновленням вузьким місцем стає саме виявлення, і вибірка мусить бути інтенсивнішою. Оскільки розклад утримує лише перший порядок за δ, формула трохи занижує потрібний бюджет (похибка $O(\delta^2)$: наприклад, $R(q^*) \approx 1.105$ замість цільового 1.1 при $\delta = 0.1$, $n - k = 20$).

Впевненість окремого клієнта

Розглянемо тепер легкого клієнта, який разово перевіряє доступність об'єкта. Щоб зробити об'єкт невідновним, супротивник має приховати щонайменше $n - k + 1$ блоків, тобто частку $\beta_0 = (n - k + 1)/n$. Клієнт, що надсилає j незалежних рівномірних запитів, не влучає в жоден прихований блок з ймовірністю $(1 - \beta_0)^j \le \exp(-j{\cdot}\beta_0)$. Вимога, щоб ця ймовірність не перевищувала ε, дає формулу (4):

$$j^*(\varepsilon) = \frac{n \cdot \ln(1/\varepsilon)}{n - k + 1}. \qquad (4)$$

За формулою (4) для типової конфігурації $n = 30$, $k = 10$ та $\varepsilon = 10^{-9}$ достатньо $j^* \approx 30$ запитів; оскільки запит повертає малу автентифіковану комірку, а не блок цілком (§ 2.2), сумарний обсяг завантаження становить незначну частку розміру об'єкта — у цьому й полягає практичний сенс DAS для сховищ. Межа консервативна через експоненційну оцінку: точна геометрична умова $(1 - \beta_0)^j \le \varepsilon$ дає $j \approx 18$ за тих самих параметрів. Зауважимо розподіл ролей: межа *$j(\varepsilon)$ захищає* окремого* клієнта від приховування «тут і зараз», тоді як умова q^* з § 3.2 гарантує *системну* довговічність у часі; перша не залежить від λ, друга — акумулює запити всіх клієнтів, тож за агрегації вибірок (наприклад, через gossip-поширення результатів [8], яке, втім, додає власне припущення про чесність ретрансляції) сукупне навантаження мережі визначається лише q^*, а не кількістю клієнтів.

Висновки. Ми запропонували першу, наскільки нам відомо, формальну модель вибіркової перевірки доступності даних як *неперервного* процесу для довгоживучих об'єктів у децентралізованих сховищах загального призначення — на противагу одноразовій блокчейн-постановці наявних формалізацій [6; 7]. Ключові результати — наближений замкнений вираз P_loss(q), порогова умова $q^* \approx n(n - k)/(\delta{\cdot}t_r)$ та клієнтська межа $j^*(\varepsilon)$ — пов'язують бюджет вибірки з довговічністю даних і дають аналітичну основу для калібрування частоти вибіркових перевірок у системах на кшталт Codex [9] і Walrus [10], де сьогодні її обирають евристично.

Обмеження. Модель передбачає незалежні відмови, пуасонівські процеси вибірки та відмов, рівномірну вибірку блоків і чесну доставку результатів запитів; корельовані відмови, атаки на мережевий рівень вибірки та стратегічного супротивника, що адаптує приховування до спостережуваної інтенсивності запитів, залишаються поза межами розгляду.

Майбутня робота: валідація моделі симуляцією та на трасах відмов реальних мереж; нерівномірна вибірка, зважена за популярністю і віком об'єктів; ігрова постановка проти адаптивного супротивника; інтеграція з локальним відновленням у дусі [7].

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ПОЖЕЖНА БЕЗПЕКА ПРИ БУДІВНИЦТВІ ЗАХИСНИХ СПОРУД ЦИВІЛЬНОГО ЗАХИСТУ: НА ПРИКЛАДІ ЗАКЛАДІВ ОСВІТИ

FIRE SAFETY IN THE CONSTRUCTION OF CIVIL DEFENSE PROTECTIVE STRUCTURES: THE CASE OF EDUCATIONAL INSTITUTIONS

Анотація. *У статті розглянуто питання забезпечення пожежної безпеки при будівництві та подальшій експлуатації захисних споруд цивільного захисту (СЦЗ) на прикладі закладів освіти. На прикладі запроектованого сховища для*

укриття 500 осіб на території комунального закладу загальної середньої освіти «Святовасилівський ліцей» проаналізовано джерела пожежної небезпеки будівельного майданчика, розроблено уніфіковану схему організації пожежної безпеки, виконано категорування тимчасових та основних приміщень за вибухопожежною та пожежною небезпекою, обґрунтовано номенклатуру та розміщення первинних засобів пожежогасіння, а також розглянуто питання пожежної безпеки СЦЗ під час подальшої експлуатації. Обґрунтовано, що належний рівень пожежної безпеки об'єкта цивільного захисту досягається лише за умови комплексного поєднання архітектурно-планувальних рішень, інженерно-технічних засобів захисту та організаційних заходів на всіх етапах його життєвого циклу.

Ключові слова: *пожежна безпека, захисна споруда цивільного захисту, будівельний майданчик, категорування приміщень, засоби пожежогасіння, заклад освіти, пожежна небезпека.*

Summary. *The article examines fire safety during the construction and subsequent operation of civil defense protective structures (SCZ), using educational institutions as an example. Based on a designed shelter for 500 people at the premises of the «Sviatovasylivskyi Lyceum» general secondary education institution, the sources of fire hazard at the construction site are analyzed, a unified scheme for organizing fire safety is developed, temporary and permanent premises are categorized by explosion and fire hazard, the range and placement of primary fire-extinguishing equipment is substantiated, and fire safety issues during the subsequent operation of the SCZ are considered. It is substantiated that an adequate level of fire safety at a civil defense facility is achieved only through a comprehensive combination of architectural-planning solutions, engineering-technical protection measures, and organizational actions at all stages of its life cycle.*

Key words: *fire safety, civil defense protective structure, construction site, premises categorization, fire-extinguishing equipment, educational institution, fire hazard.*

Вступ. Пожежна безпека на етапах проектування, будівництва та експлуатації захисних споруд цивільного захисту належить до пріоритетних складових організації безпечного проведення будівельно-монтажних робіт і подальшої експлуатації об'єкта за призначенням [3; 6]. Це питання стає особливо гострим для підземних сховищ, призначених для укриття населення (учнів, здобувачів освіти, військовослужбовців, курсантів, слухачів курсів, працівників, персоналу). Пожежа на будь-якій стадії життєвого циклу такого об'єкта здатна спричинити суттєві матеріальні втрати, травмування здобувачів освіти та працівників, руйнування будівельних конструкцій і зрив планових строків уведення в експлуатацію, а на функціонуючому сховищі може створити пряму загрозу життю людей.

Об'єктом розгляду є нове будівництво захисної споруди цивільного захисту (СЦЗ) на прикладі будівництва СЦЗ на території комунального закладу загальної середньої освіти «Святовасилівський ліцей» [32; 33]. Споруда, що проектується, розрахована на укриття 500 осіб і належить до об'єктів цивільного захисту (ЦЗ) із підвищеними вимогами до пожежної безпеки, як під час будівництва, так і під час експлуатації СЦЗ. Будівельний майданчик такого або схожого об'єкта вирізняється значною кількістю тимчасових споруд, електрообладнання, будівельної техніки, наявністю паливно-мастильних матеріалів, зварювальних установок та інших ймовірних джерел займання. В той же час паралельне виконання земляних, арматурних, бетонних, електромонтажних і вогневих робіт підвищує ймовірність виникнення пожежонебезпечних ситуацій як всередині СЦЗ, біля споруди, так і на будівельному майданчику в цілому.

Згідно вимог статті 2 Кодексу цивільного захисту України [1], захисні СЦЗ — це інженерні споруди, що забезпечують захист населення від небезпечних чинників, зумовлених надзвичайними ситуаціями, воєнними діями чи терористичними актами. Відповідно до статті 32 Кодексу, СЦЗ становить основний вид фонду захисних споруд і є переважно підземною спорудою, у якій забезпечуються умови для тривалого не менш ніж 48 годин, перебування великої кількості людей (згідно до проекту, на території КЗ ЗСО «Святовасилівський ліцей» передбачено укриття 500 осіб) [32; 33]. Саме ця специфіка: навчальний заклад, замкнений підземний простір, висока місткість і тривалий час перебування людей і формує особливі вимоги до пожежної безпеки приміщень підземного сховища ЦЗ, що відрізняють його від звичайних адміністративних, спортивних, навчальних чи побутових приміщень будівель закладів освіти [5; 15].

Актуальність дослідження. Актуальність теми зумовлена масштабним будівництвом та реконструкцією захисних споруд ЦЗ в закладах освіти України в умовах воєнного стану, коли укриття стало обов'язковим елементом освітньої інфраструктури [16; 20]. Об'єкт ЦЗ одночасно поєднує дві вимоги підвищеної відповідальності, а саме: має захищати значну кількість людей від небезпечних факторів НС і водночас сам не повинен ставати джерелом небезпеки, зокрема пожежної.

Аналіз статистичних даних показує, що переважна частина пожеж на будівельних об'єктах спричинена порушеннями вимог пожежної безпеки, недотриманням технології виконання робіт та впливом людського фактору. За даними статистики ДСНС України, понад 30% пожеж на будівельних майданчиках зумовлені несправністю електрообладнання або недотриманням правил його експлуатації [13; 14; 15]. Це засвідчує потребу в системному підході

до організації пожежної безпеки об'єктів ЦЗ та обґрунтуванні комплексу відповідних організаційних і технічних заходів, чому й присвячено це дослідження.

Окремої уваги потребують вимоги розділу 7 «Забезпечення евакуації людей» ДБН В.1.1–7:2016 [4], згідно з якими для забезпечення безпечної евакуації людей повинні передбачатися заходи, спрямовані на створення умов для своєчасної та безперешкодної евакуації у разі виникнення пожежі й на захист людей на шляхах евакуації від дії небезпечних чинників пожежі. Оскільки на захисні СЦЗ вимоги цього ДБН поширюються лише частково, забезпечення пожежної безпеки таких об'єктів досягається поєднанням його положень зі спеціальними вимогами ДБН В.2.2–5:2023 [5] та Кодексу цивільного захисту України [1]. Комплексне врахування цих вимог на всіх етапах життєвого циклу підземного СЦЗ і обумовлює актуальність обраної теми дослідження [12; 14].

Матеріали та методи дослідження. Питання пожежної безпеки захисних СЦЗ та об'єктів освіти активно досліджуються у вітчизняній і зарубіжній науковій літературі протягом останніх шести років. Проведений критичний аналіз дозволяє виокремити кілька провідних напрямів.

Вітчизняні дослідження. Українські вчені в умовах війни зосереджуються на проєктуванні укриттів та підвищенні їх захисних властивостей. У праці [22] обґрунтовано підходи до влаштування підземних захисних споруд для груп житлових будинків та інженерно-технічні заходи цивільного захисту. У роботі [24] за допомогою геоінформаційного моделювання розв'язано задачу раціонального розміщення укриттів у житловій забудові з урахуванням радіуса пішохідної доступності. Спільним для вітчизняних праць є акцент на конструктивній стійкості та розміщенні укриттів, тоді як питання пожежної безпеки приміщень захисних споруд висвітлені фрагментарно.

Пожежна безпека захисних споруд. Зарубіжні дослідники приділяють увагу комплексній оцінці стану укриттів. У праці [25] на прикладі об'єкта в Польщі виконано оцінку модернізаційного потенціалу захисних СЦЗ з детальним аналізом конструкції, захисту від радіації, пожежної безпеки та ергономіки, а також виявлено законодавчі прогалини — підхід, близький до предмета цього дослідження. В оглядовій роботі [26] систематизовано параметри заглиблених «blast-resistant» укриттів, а в дослідженні [27] проаналізовано поширення диму та вентиляцію в захищених приміщеннях, що є критичним для безпеки учнів, здобувачів освіти та персоналу закладів освіти, що перебувають у замкненому просторі.

Пожежна безпека будівель. Значну кількість публікацій присвячено загальним підходам до оцінювання пожежної небезпеки. Огляди [28; 29] систематизують методи оцінки пожежного ризику будівель, стратегії запобігання пожежам і актуальні проблеми структурної пожежної безпеки, тоді як в аналізі [30] відображає динаміку досліджень технологій запобігання й локалізації пожеж упродовж 2010–2023 років. У сукупності ці роботи становлять методичне підґрунтя для аналізу пожежної небезпеки об'єктів різного призначення, зокрема підземних споруд.

Пожежна безпека закладів освіти. Окремий напрям становить безпека навчальних будівель, де перебуває велика кількість дітей. У дослідженні [31] запропоновано інструмент оцінки відповідності протипожежних заходів у навчальних закладах нормативним вимогам, а у роботі [23] узагальнено заходи з пожежної безпеки та навчання в школах. Ці дослідження підкреслюють, що для закладів освіти визначальними є системи раннього виявлення пожежі, оповіщення та евакуація персоналу та учнів.

Таким чином, попри значний обсяг досліджень щодо конструктивної стійкості укриттів, пожежної безпеки будівель та закладів освіти, комплексне питання забезпечення пожежної безпеки захисної споруди цивільного захисту, що споруджується безпосередньо в закладі освіти, з урахуванням особливостей будівельного майданчика, категорування приміщень та експлуатації підземного сховища залишається недостатньо висвітленим, що й визначає наукову новизну цього дослідження.

Основна дослідницька частина. Організація пожежної безпеки під час будівництва та експлуатації захисної СЦЗ здійснюється відповідно до чинних законодавчих, нормативних та нормативно-технічних документів України [1–9]. Відповідно до Кодексу цивільного захисту України забезпечення пожежної безпеки покладається на керівника підприємства, установи або організації, який зобов'язаний організувати виконання вимог нормативних актів та створити умови для безпечного виконання робіт. Державні будівельні норми [6] встановлюють обов'язкові вимоги до організації пожежної безпеки на будівельних майданчиках щодо утримання території, складування матеріалів, виконання вогневих робіт та забезпечення об'єкта засобами пожежогасіння, а державні будівельні норми [5] визначають вимоги безпосередньо до захисних споруд ЦЗ, включаючи забезпечення їх пожежної безпеки та безпечної евакуації людей, як представлено на розробленою авторами загальної уніфікованої схемі організації пожежної безпеки на будівельному майданчику (рис. 1).

Аналіз пожежної небезпеки будівельного майданчика. Незважаючи на те, що основна споруда є підземною та виконується переважно з негорючих матеріалів (бетону, залізобетону, металевих конструкцій), на стадії будівництва на майданчику одночасно розміщуються тимчасові будівлі, електрообладнання, паливно-мастильні матеріали,

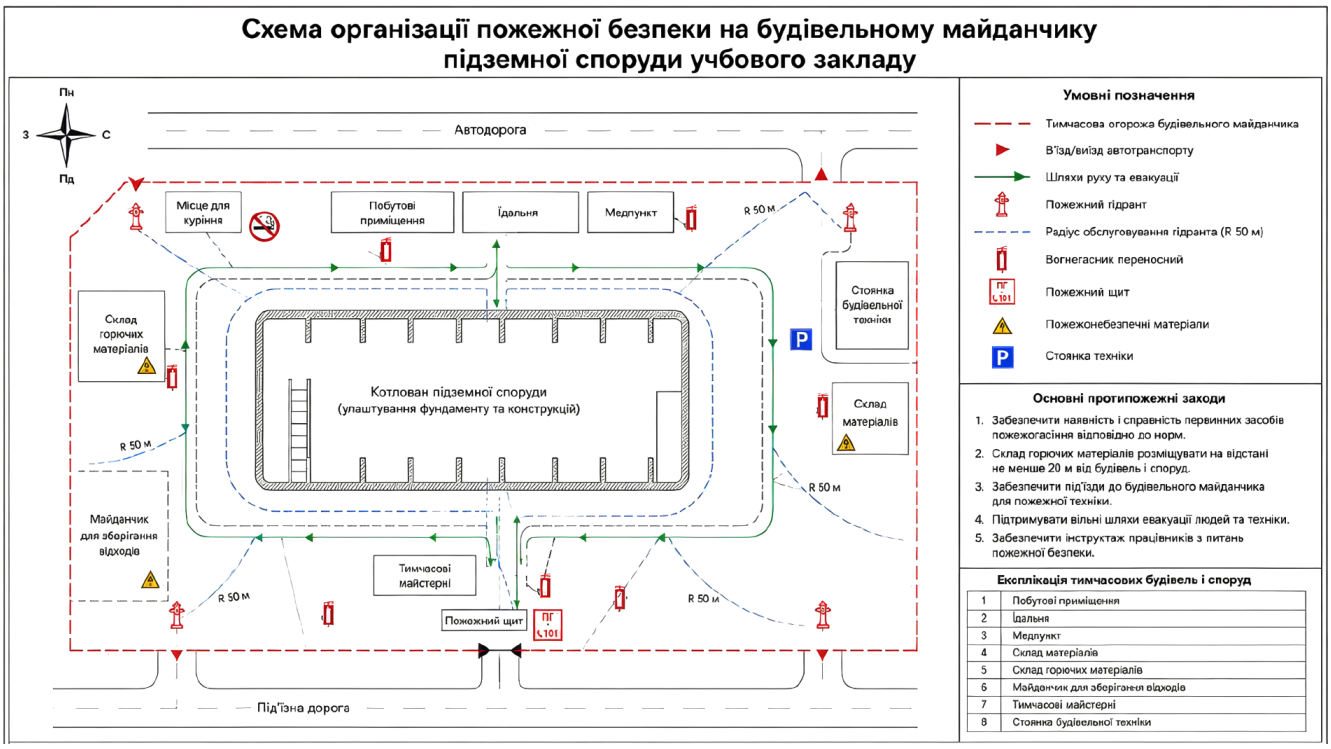


Рис. 1. Схема організації пожежної безпеки на будівельному майданчику
Джерело: розробка авторів

кабельна продукція, дерев'яна опалубка, теплоізоляційні матеріали та інші горючі речовини. До основних джерел пожежної небезпеки належать електричні мережі та електрообладнання, вогневі роботи під час монтажу арматурних каркасів і закладних деталей, а також паливно-мастильні матеріали, у разі розгерметизації ємностей яких можливе швидке поширення пожежі.

Найбільш пожежонебезпечними об'єктами будівельного майданчика є електрощитова, зварювальний пост та склад паливно-мастильних матеріалів (високий рівень ризику), а також побутові приміщення й кабельні мережі (середній рівень ризику). На будівельному майданчику пожежа може поширюватися тепловим випромінюванням, конвекцією, перекиданням полум'я, через кабельні комунікації та вентиляційні канали. Для обмеження поширення пожежі необхідно дотримуватися протипожежних розривів, виконувати зонування території, своєчасно прибирати горючі відходи та застосовувати негорючі матеріали [11; 17].

Категорування приміщень за пожежною небезпекою. Відповідно до вимог ДБН В.1.1–7:2016 [4] та галузевих норм пожежної безпеки приміщення об'єкта повинні бути віднесені до відповідних категорій за вибухопожежною та пожежною небезпекою. Оскільки споруда є захисним укриттям для 500 осіб, більшість її основних приміщень після введення в експлуатацію належатимуть до категорії Д (негорючі речовини та матеріали). Проте на стадії будівництва окремі тимчасові приміщення мають підвищену пожежну небезпеку: склад ПММ — категорії А, електрощитова та побутові вагончики належать до категорії В, зварювальна дільниця — до категорії Г, а склад металоконструкцій та майбутнє сховище — до категорії Д.

Забезпечення об'єкта первинними засобами пожежогасіння. Первинні засоби пожежогасіння (рис. 2) призначені для ліквідації загорянь на початковій стадії їх розвитку. До них належать порошкові, вуглекислотні та водопінні вогнегасники, пожежні щити, ящики з піском і пожежний інвентар. Вибір засобів пожежогасіння (рис. 3) залежить від класу пожежі: для твердих горючих речовин (клас А) застосовують воду, піну та порошок, для горючих рідин (клас В) — піну й порошок, для горючих газів (клас С) — порошок, а для електроустановок (клас Е) — вуглекислотні та порошкові вогнегасники [8; 9].

Для даного об'єкта рекомендується використовувати порошкові вогнегасники ВП-5 та ВП-9, а також вуглекислотні ВВК-3,5 та ВВК-5. Первинні засоби пожежогасіння повинні розміщуватися на в'їзді до будівельного майданчика, біля складів матеріалів, у побутових приміщеннях, біля електрощитових, у місцях виконання вогневих робіт та біля пунктів заправлення техніки [10]. Пожежний щит комплектується багром, ломом, пожежною сокирою, лопатами, відрами, ящиком із піском та покривалом для ізоляції осередку горіння (рис. 2).

Пожежна безпека під час експлуатації СЦЗ. Після завершення будівництва та введення в експлуатацію захисна споруда повинна забезпечувати



Рис. 2. Комплектація та розміщення пожежного щита
Джерело: розробка авторів

належний рівень пожежної безпеки протягом усього терміну служби. Особливість СЦЗ полягає в тому, що в умовах надзвичайної ситуації в ньому можуть тривалий час одночасно перебувати до 500 осіб, тому будь-яка пожежа або задимлення створюють значну загрозу життю людей. Можливими джерелами пожежної небезпеки під час експлуатації є електрощитові, кабельні траси, вентиляційне обладнання, дизель-генераторні установки, акумуляторні батареї та системи освітлення [19].



Рис. 3. Класифікація вогнегасників за призначенням
Джерело: розробка авторів

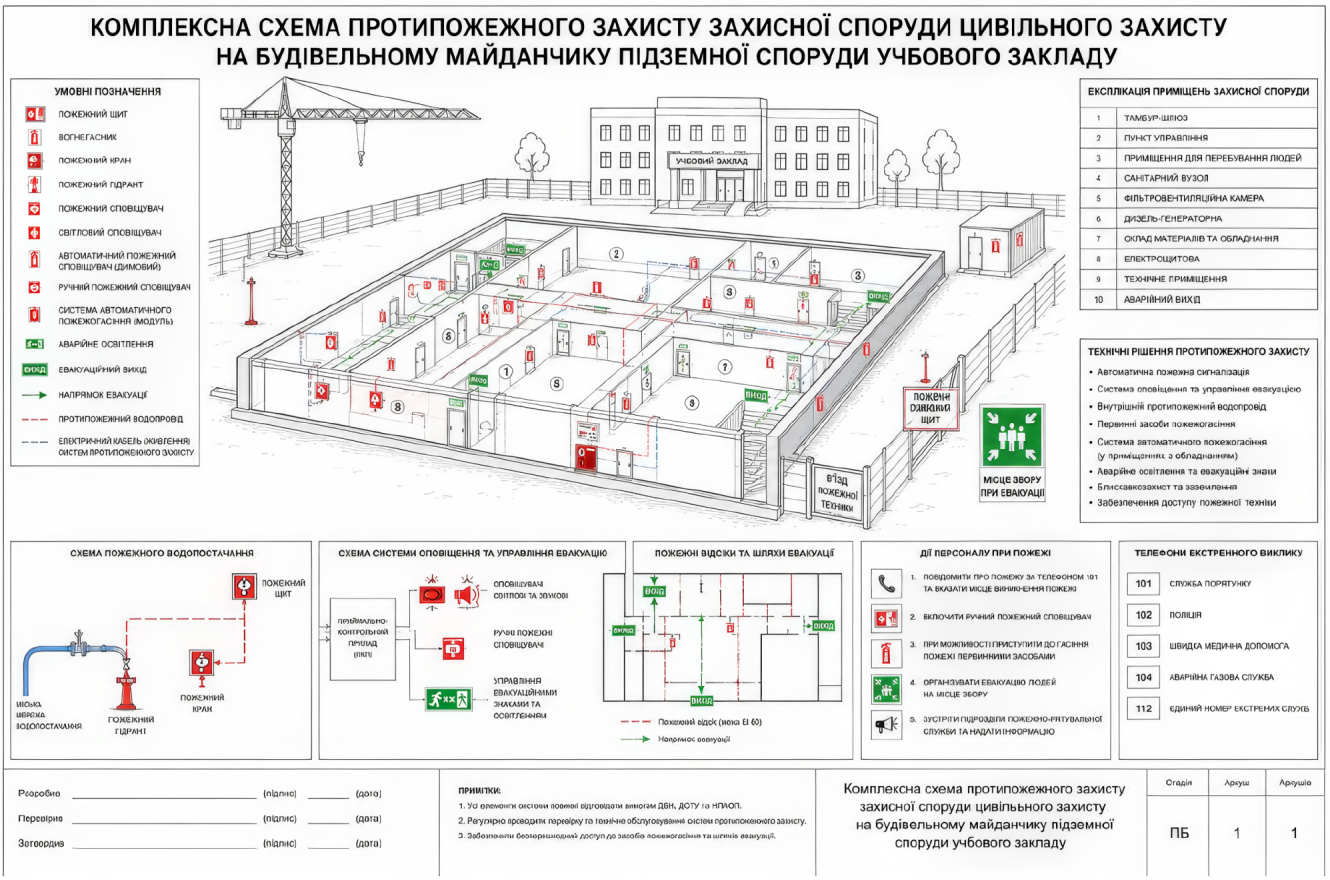


Рис. 4. Комплексна схема протипожежного захисту захисної споруди цивільного захисту

Джерело: розробка авторів

Для забезпечення пожежної безпеки СЦЗ обладнується автоматичною пожежною сигналізацією, системою оповіщення про пожежу, аварійним освітленням, системою димовидалення, первинними засобами пожежогасіння та системою контролю стану інженерних мереж [7; 18]. Особлива роль належить системам раннього виявлення пожежі, які дозволяють оперативно реагувати на виникнення небезпечної ситуації. Під час експлуатації обов'язково проводяться планові огляди приміщень, перевірка справності систем сигналізації, технічне обслуговування вентиляції, контроль електрогосподарства, а також навчання персоналу та тренування з евакуації.

Висновки. Проведений аналіз питань пожежної безпеки об'єктів цивільного захисту на прикладі запроектованого сховища для укриття 500 осіб, а також критичний огляд сучасних вітчизняних і зарубіжних досліджень дозволяють зробити такі обґрунтовані висновки.

1. Визначено, що забезпечення належного рівня пожежної безпеки захисної СЦЗ повинно здійснюватися на всіх етапах її життєвого циклу від підготовки будівельного майданчика до введення об'єкта в експлуатацію та подальшого використання за призначенням. Найбільш ефективним підходом є впровадження системи організаційних і технічних заходів, спрямованих на попередження виникнення пожеж та мінімізацію їх наслідків.

2. Встановлено, що основними джерелами пожежної небезпеки на будівельному майданчику є електрообладнання й тимчасові електромережі, зварювальні роботи та місця зберігання паливно-мастильних матеріалів [13; 19]. Категорування приміщень СЦЗ, що проведене на прикладі навчального закладу за пожежною небезпекою та обґрунтування раціонального розміщення первинних засобів пожежогасіння підтвердили необхідність постійного контролю протипожежного стану об'єкта на всіх стадіях БМР під час будівництва та в подальшому під час експлуатації СЦЗ.

3. Обґрунтовано, що під час експлуатації СЦЗ, визначальну роль відіграють системи раннього виявлення пожежі, оповіщення, аварійного освітлення та димовидалення [7; 18]. Цей висновок узгоджується з результатами зарубіжних досліджень пожежної безпеки захисних споруд [25] та закладів освіти [31; 33], які підтверджують провідну роль систем раннього виявлення та оповіщення для об'єктів з масовим перебуванням людей. Належний рівень пожежної безпеки досягається лише за умови комплексного поєднання архітектурно-планувальних рішень, інженерно-технічних засобів захисту та організаційних заходів [5; 15].

4. Наукова новизна дослідження полягає в комплексному розгляді пожежної безпеки СЦЗ, що споруджується безпосередньо на території існуючого закладу освіти громади, з одночасним урахуванням специфіки будівельного майданчика, категорування приміщень підземного сховища та особливостей його експлуатації, на відміну від оглянутих робіт, у яких ці аспекти розглядалися окремо: конструктивна стійкість укриттів [22; 26], розміщення СЦЗ [24] та пожежна безпека будівель загалом [28–30]. Виявлено, що чинна нормативна база потребує узгодження вимог пожежної безпеки з вимогами до захисних СЦЗ, що є предметом подальших досліджень.

Подане дослідження спиралось на попередніх роботах [32; 33], а подальші дослідження доцільно спрямувати на розроблення методики оцінки пожежного ризику захисних СЦЗ з урахуванням специфіки закладів освіти, а також на обґрунтування раціональної номенклатури та розміщення засобів протипожежного захисту для сховищ різної місткості [15]. Актуальним є уточнення підходів до категорування приміщень підземних сховищ за вибухопожежною та пожежною небезпекою на стадії будівництва з урахуванням стадійності виконання будівельно-монтажних робіт [4; 6].

Окремим напрямом є вивчення особливостей забезпечення пожежної безпеки під час одночасного перебування в укритті значної кількості людей, зокрема дітей та осіб з обмеженою мобільністю, а також обґрунтування вимог до систем раннього виявлення пожежі, оповіщення та димовидалення для підземних захисних споруд [7; 18; 21]. Це дозволить підвищити ефективність протипожежного захисту сховищ, які експлуатуються в закладах освіти.

Перспективним залишається розроблення типових проєктних рішень протипожежного захисту, що можуть бути інтегровані у проекти нового будівництва укриттів у закладах освіти, зокрема швидко споруджуваних захисних СЦЗ модульного типу [16; 20]. Реалізація зазначених напрямів сприятиме формуванню оновлених нормативних вимог щодо пожежної безпеки об'єктів цивільного захисту в умовах воєнного стану.

ДОДАТКОВА ІНФОРМАЦІЯ

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ЗАСТОСУВАННЯ МЕТОДІВ ШТУЧНОГО ІНТЕЛЕКТУ В ПОЄДНАННІ З ТРИВИМІРНИМ МОДЕЛЮВАННЯМ У СЕРЕДОВИЩІ PETREL ДЛЯ ОПТИМІЗАЦІЇ ТЕХНОЛОГІЇ РОЗРОБКИ ГАЗОВИХ РОДОВИЩ З АКТИВНИМ ВОДОНАПІРНИМ РЕЖИМОМ

APPLICATION OF ARTIFICIAL INTELLIGENCE METHODS COMBINED WITH THREE-DIMENSIONAL MODELLING IN THE PETREL ENVIRONMENT FOR OPTIMISING THE DEVELOPMENT TECHNOLOGY OF GAS FIELDS WITH AN ACTIVE WATER DRIVE

Анотація. *Розглянуто можливості інтеграції методів машинного навчання у класичний цикл геолого-гідродинамічного моделювання газових покладів з активним водонапірним режимом, реалізований у програмному середовищі Petrel у поєднанні з симуляторами ECLIPSE та INTERSECT. Запропоновано гібридний робочий процес, у якому чисельна гідродинамічна модель зберігає роль фізичного «еталона», а сурогатні (проксі) моделі на основі нейронних мереж і ансамблевих алгоритмів беруть на себе обчислювально витратні задачі – автоматизовану адаптацію моделі до історії розробки, багатоваріантну оптимізацію сітки свердловин і режимів їх експлуатації, а також раннє прогнозування прориву пластової води. Окреслено обмеження підходу та вимоги до вхідних даних.*

Ключові слова: *газове родовище, водонапірний режим, тривимірне моделювання, Petrel, штучний інтелект, машинне навчання, проксі-модель, адаптація моделі, прорив води, коефіцієнт газовилучення.*

Summary. *The paper considers the integration of machine learning methods into the conventional geological and reservoir simulation workflow for gas reservoirs produced under an active water drive, implemented within the Petrel software platform coupled with the ECLIPSE and INTERSECT simulators. A hybrid workflow is proposed in which the numerical reservoir model retains the role of a physics-based reference, while surrogate (proxy) models built on neural networks and ensemble algorithms take over the computationally expensive tasks, namely assisted history matching, multi-variant optimisation of well placement and well operating regimes, and early prediction of water breakthrough. Six areas of machine learning application are identified: prediction of petrophysical properties in the interwell space, surrogate modelling, automated history matching with probabilistic P10/P50/P90 forecasting, water breakthrough forecasting from both synthetic and field time-series data, optimisation of the development system, and physics-informed neural networks. An eight-stage workflow is presented in which every optimum found on the surrogate model is verified by a full reservoir simulation run. The limitations of the approach and the requirements for input data quality are outlined.*

Key words: *gas reservoir, water drive, three-dimensional modelling, Petrel, artificial intelligence, machine learning, proxy model, history matching, water breakthrough, gas recovery factor.*

Актуальність. Значна частина газових покладів Дніпровсько-Донецької западини та Передкарпатського прогину перебуває на завершальній стадії розробки й експлуатується за водонапірного режиму. Саме цей режим є основною причиною втрат вуглеводнів: защемлення газу водою, що просувається по найбільш проникних пропластках, суттєво знижує кінцевий коефіцієнт газовилучення порівняно з га-

зовим режимом виснаження, а обводнення окремих свердловин нерідко настає раніше, ніж це передбачали проєктні документи. Ключове інженерне завдання тому полягає не у максимізації миттєвого дебіту, а в управлінні швидкістю та геометрією просування фронту води.

У попередньому дослідженні автора обґрунтовано роль тривимірного моделювання у середовищі Petrel як інструменту [1, 2], що дозволяє інтегрувати геофізичні, геологічні та промислові дані, відтворити просторову структуру покладу, локалізувати газоводяний контакт і за допомогою симуляторів ECLIPSE або INTERSECT відтворити багатофазну фільтрацію. Проте практичне застосування цього інструментарію стикається з обмеженням обчислювального характеру, яке з розвитком деталізації моделей лише загострюється.

Постановка проблеми. Один повний прогін високороздільної моделі великого газового покладу триває від кількох годин до кількох діб. Водночас коректна адаптація моделі до історії розробки (history matching) та пошук оптимальної системи розміщення свердловин вимагають сотень і тисяч таких прогонів [3]. Через це на практиці інженер змушений обмежуватися десятком-двома детермінованих сценаріїв, обраних експертно, що не гарантує ані потрапляння в область оптимуму, ані коректної оцінки невизначеності прогнозу. Додатковим джерелом похибки є параметри аквіфера — його об'єм, провідність і ступінь гідродинамічного зв'язку з покладом визначаються найменш достовірно, тоді як саме вони найсильніше впливають на прогноз водоприпливу.

Розв'язання цієї суперечності між потрібною деталізацією та наявним обчислювальним ресурсом і становить основну мету застосування методів штучного інтелекту (ШІ) в описуваному класі задач.

Напрями застосування методів машинного навчання.

1. Уточнення розподілу фільтраційно-ємнісних властивостей. Класичні геостатистичні методи (кригінг, послідовне гаусове моделювання SGS) заповнюють міжсвердловинний простір на основі варіограмного аналізу. Алгоритми машинного навчання — випадковий ліс, градієнтний бустинг (XGBoost, LightGBM), нейронні мережі — дозволяють доповнити цей підхід, встановивши нелінійні залежності між сейсмічними атрибутами, кривими ГДС та керновими визначеннями пористості й проникності. Особливе значення це має для виявлення високопроникних пропластків та зон тріщинуватості, якими вода прориває до вибою свердловин у першу чергу [5].

2. Сурогатні (проксі) моделі. Це найбільш результативний напрям. Сурогатна модель — це алгоритм, навчений на обмеженій вибірці повних гідродинамічних розрахунків (як правило, 100–300 прогонів, спланованих методами планування експерименту — латинський гіперкуб, Box–Behnken), який відтворює відгук пласта за секунди замість годин [4]. У літературі показано, що проксі-моделі на основі штучних нейронних мереж перевершують традиційні поліноміальні та кригінгові метамоделі за точністю відтворення цільової функції при історичній адаптації [5]. Для покладів з водонапірним режимом окремо перевірено підхід «фізично підтриманого» проксі-моделювання, орієнтований саме на прогнозування переміщення фронту води [7].

3. Автоматизована адаптація моделі до історії розробки. Замість ручного підбору проникності та параметрів аквіфера сурогатна модель вбудовується в контур оптимізації, де мінімізується нев'язка між фактичними й розрахунковими значеннями пластового тиску, дебітів газу та обводненості. Для цього застосовують генетичні алгоритми, метод рою частинок (PSO), диференціальну еволюцію, ансамблеві методи (ES-MDA, EnKF) та байєсову оптимізацію [3, 6]. Принципово, що результатом є не єдина «підігнана» модель, а ансамбль рівноймовірних реалізацій, який дає змогу подати прогноз у ймовірнісній формі P10/P50/P90 — що для водонапірного режиму значно чесніше за детермінований прогноз.

4. Раннє прогнозування прориву пластової води. Тут використовують два взаємодоповнювальні класи моделей. Перший — регресійні моделі, навчені на синтетичній вибірці симуляційних розрахунків, які пов'язують час прориву води з параметрами пласта, відстанню перфорації від ГВК і темпом відбору [8]. Другий — моделі часових рядів (LSTM, GRU, гібридні CNN-LSTM), навчені безпосередньо на промислових даних свердловин: динаміці вибійного та гирлового тисків, дебіті, вмісті води й хлоридів у продукції [9]. Такі моделі здатні виявити передвісники обводнення за кілька місяців до його фактичного прояву, що дає час на оперативне коригування режиму роботи свердловини.

5. Оптимізація системи розробки. Маючи швидкий проксі-симулятор, стає можливим перебрати тисячі варіантів: координати й траєкторії нових свердловин (у тому числі горизонтальних та багатостовбурних), інтервали й висоту перфорації над ГВК, розподіл відборів між свердловинами, послідовність введення їх у роботу [6]. Цільова функція при цьому формулюється комплексно — максимум кінцевого газовилучення або чистого дисконтованого доходу за обмежень на критичну депресію та допустиму обводненість. Перспективним є застосування навчання з підкріпленням (reinforcement learning) для динамічного керування режимами свердловин, коли агент навчається підтримувати відбір нижче критичного значення, за якого починається конусоутворення.

6. Фізично-інформовані нейронні мережі (PINN). Напрям, що усуває головну ваду суто статистичних моделей — здатність давати фізично некоректний результат за межами навчальної вибірки. У PINN рівняння нерозривності та закон Дарсі

вводяться безпосередньо у функцію втрат, завдяки чому мережа залишається узгодженою з фізикою фільтрації навіть на екстраполяції.

Технічна реалізація в середовищі Petrel. Суттєвою перевагою Petrel є те, що описані методи не потребують виходу за межі платформи. Модуль Python Tool Pro та середовище розробки Ocean SDK дозволяють викликати бібліотеки scikit-learn, XGBoost, TensorFlow або PyTorch безпосередньо з проєкту, оперуючи властивостями сітки, даними свердловин і результатами симуляції як звичайними об'єктами. Функціонал Uncertainty and Optimization забезпечує планування експерименту та запуск серій розрахунків, а хмарне середовище DELFI — паралельне виконання ансамблю прогонів. Таким чином, геологічна модель, гідродинамічний симулятор і алгоритм машинного навчання працюють з єдиним джерелом даних, без експорту та пов'язаних із ним втрат інформації.

Запропонований гібридний робочий процес. На основі викладеного пропонується така послідовність дій: (1) побудова базової тривимірної геологічної моделі в Petrel з машинно-навченим прогнозом ФЄП у міжсвердловинному просторі; (2) формування ансамблю геологічних реалізацій, що відображають невизначеність структури й параметрів аквіфера; (3) планування експерименту та виконання обмеженої серії повних розрахунків в INTERSECT; (4) навчання сурогатної моделі на отриманій вибірці й контроль її точності на незалежній підвибірці; (5) автоматизована адаптація до історії розробки з отриманням ансамблю прийнятних моделей; (6) оптимізація розміщення свердловин і режимів їх роботи на сурогатній моделі; (7) обов'язкова верифікація найкращих сценаріїв повним гідродинамічним розрахунком; (8) періодичне перенавчання моделі в міру надходження нових промислових даних, тобто перехід до концепції цифрового двійника родовища.

Принциповим є сьомий етап: сурогатна модель звужує простір пошуку, але остаточне рішення завжди підтверджується фізично обґрунтованим розрахунком. Саме таке розмежування ролей відрізняє інженерне застосування ШІ від некритичного покладання на «чорну скриньку».

Обмеження та ризики. Ефективність описаних методів прямо залежить від якості й повноти вхідних даних: за відсутності систематичних вимірювань пластового тиску, регулярних досліджень свердловин та достовірного обліку супутньо видобутої води навчання моделі втрачає сенс. Обмеженою є й екстраполяційна здатність — сурогатна модель достовірна лише в межах діапазону параметрів, на якому вона навчена, тому кожне суттєве розширення умов вимагає нових розрахунків. Слід також ураховувати ризик перенавчання за малих вибірок і складність інтерпретації результатів, що частково знімається методами пояснюваного машинного навчання (SHAP, аналіз важливості ознак).

Висновки. Інтеграція методів штучного інтелекту у процес тривимірного геолого-гідродинамічного моделювання в середовищі Petrel не замінює чисельну симуляцію, а знімає її головне практичне обмеження — обчислювальну вартість багатоваріантних розрахунків. Для газових родовищ з активним водонапірним режимом це відкриває можливість переходу від поодиноких детермінованих сценаріїв до систематичної ймовірнісної оптимізації, у якій цільовою функцією є не миттєвий дебіт, а керування просуванням фронту води. Очікуваними практичними результатами є скорочення тривалості адаптації моделі, обґрунтоване відтермінування прориву води у видобувних свердловинах і, як наслідок, підвищення кінцевого коефіцієнта газовилучення. Подальші дослідження доцільно спрямувати на апробацію запропонованого робочого процесу на конкретному покладі з тривалою історією розробки та кількісну оцінку отриманого приросту точності прогнозу.

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ВПЛИВ РОЗМІРУ НАПИЛЕНОЇ ЧАСТКИ НА ТЕПЛОВИЙ СТАН СИСТЕМИ «ЧАСТКА-ОСНОВА»

INFLUENCE OF THE SIZE OF A SPRAYED PARTICLE ON THE THERMAL STATE OF THE PARTICLE-BASE SYSTEM

Анотація. *В роботі наведено результати досліджень теплових процесів під час реалізації енергозберігаючої технології газотермічного напилення.*

Ключові слова: *двошарова система «частка-основа», товщина розпиленої частки, температурний режим.*

Summary. *This paper presents the results of a study of thermal processes during the implementation of energy-saving thermal spraying technology.*

Key words: *two-layer "particle-base" system, sprayed particle thickness, temperature regime.*

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Однією з найбільш актуальних проблем для розвитку енергетики є проблема підвищення ефективності та довговічності енергетичного обладнання. Важливу роль у підвищенні економічності та ресурсу роботи відповідальних вузлів обладнання відіграють технології їх захисту від зношування та корозії, зокрема, такі як газотермічне напилення [1–5]. Відтак актуальними є дослідження, спрямовані на удосконалення цих прогресивних енергозберігаючих технологій.

Ця робота присвячена аналізу питань, пов'язаних із тепловим станом систем «частка-основа» при газотермічному нанесенні покриттів. Дослідження проведено з метою визначення залежності теплового стану системи від товщини напиленої частки.

Математична модель досліджуваного нелінійного процесу теплопереносу в системі «частка-основа» може бути представлена у вигляді

$$\frac{\partial}{\partial x}\left(\Lambda_i \frac{\partial \theta_i}{\partial x}\right) = C_{V_i} \frac{\partial \theta_i}{\partial Fo} \quad i = 1,2 \qquad (1)$$

$$(0 < x < \delta,\ 0 < Fo \le Fok)$$

$$\left[\frac{\partial \theta_i}{\partial x} + (-1)^i \cdot B_i \cdot \theta_i\right]\Big|_{x=x_r} = (-1)^i \cdot B_i \cdot \theta_c \qquad (2)$$

$$x = \begin{cases} 0 & при\ i = 1 \\ \delta & при\ i = 2 \end{cases}$$

$$\Lambda_1 \frac{\partial \theta_1}{\partial x}\Big|_{x=\delta_1} = \Lambda_2 \frac{\partial \theta_{21}}{\partial x}\Big|_{x=\delta_1},\ \theta_1\big|_{x=\delta_1} = \theta_2\big|_{x=\delta_1}, \qquad (3)$$

$$\theta_i\big|_{Fo=0} = \theta_{i0}, \qquad (4)$$

де $\theta = t/t_{10}$; $Fo = \alpha_0 \cdot \tau / \delta_{p_1}^2$; $B_i = \alpha \cdot \delta_{p_1} / \lambda_0$;

$x = x_p / \delta_{p_1}$; $\delta = \delta / \delta_{p_1}$;

$\Lambda = \frac{\lambda}{\lambda_0}$; $C_v = c_v / c_{v0}$;

θ_c — безрозмірна температура довкілля;

δ_p — товщина системи;

δ_{p_1} — товщина частки, що розтеклася;

i — величини з індексом i відносяться відповідно до частки при $i = 1$ та до основи при $i = 2$.

Розв'язання поставленої задачі (1)–(4) проводилося з використанням комбінованого ітераційного методу [1]. Нижче наведено результати виконаних обчислювальних експериментів, що відповідають наступним значенням вихідних даних:

$\theta_{20} = \theta_c = 0{,}016$; $B_i = 0{,}66 \cdot 10^{-6}$; $\delta_2 = \delta - \delta_1 = 1000$; матеріал покриття — сплав Fe83B17. Характерні результати виконаних чисельних досліджень наведено на рис. 1.

Подані результати відповідають трьом ситуаціям, коли величина δ_1 має різні значення (δ_1 = 40; 10 і 1) при інших незмінних параметрах. Проведений аналіз показав, що загальні закономірності зміни теплового стану досліджуваного об'єкта при різних товщинах напилюваної частки δ_1 виявилися аналогічними.

Подані результати відповідають трьом ситуаціям, коли величина δ_1 має різні значення (δ_1 = 40; 10 і 1) при інших незмінних параметрах. Проведений аналіз показав, що загальні закономірності зміни теплового стану досліджуваного об'єкта при різних

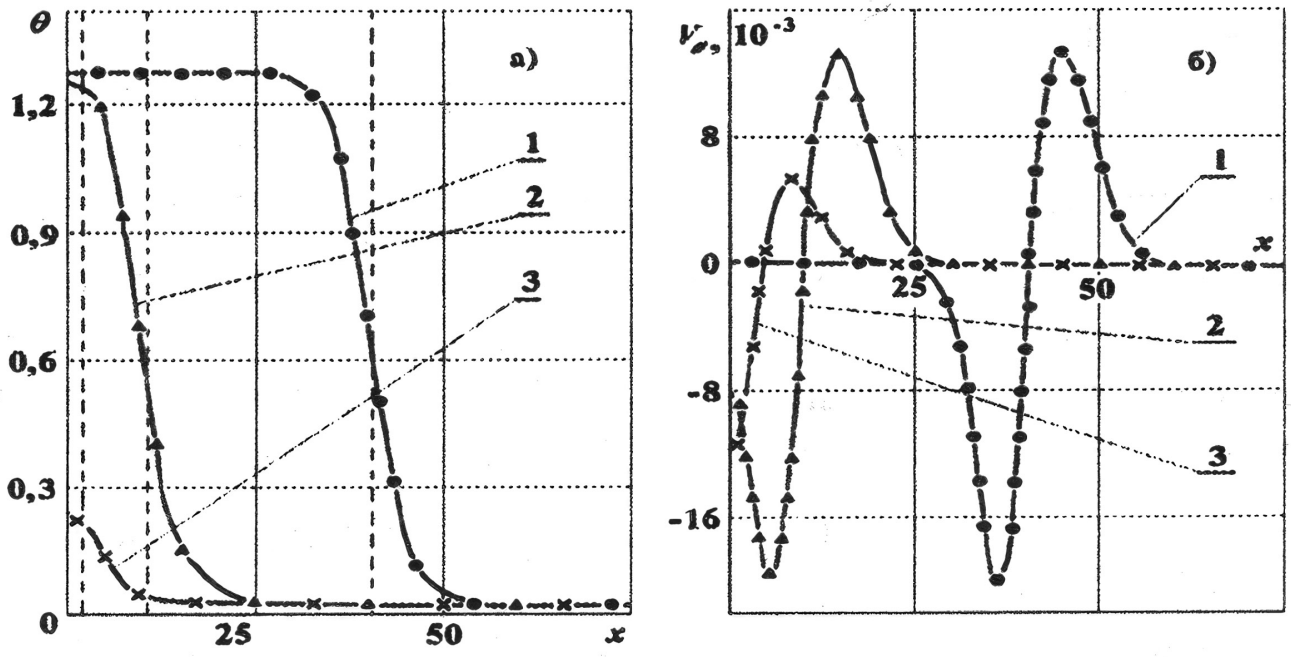


Рис. 1. Розподіл температури (а) та швидкості зміни температури (б) за товщиною двошарової системи «частка зі сплаву $Fe_{83}B_{17}$ — сталева основа» при $Fo = 8{,}69 \cdot 10^{-12}$, $\theta_{10} = 1{,}28$ для різних значень δ_1: 1 — δ_1 = 40,0; 2 – 10,0; 3 — 1,0

товщинах напилюваної частки δ_1 виявилися аналогічними.

Однак встановлено, що в кількісному відношенні характеристики процесу теплопереносу можуть істотно залежати від величини δ_1. Так, тривалість процесу в цілому *Fo* становить $1{,}086 \cdot 10^4$; $7{,}126 \cdot 10^2$ та 7,99 відповідно для $\delta_1 = 40$; 10 і 1. Тобто число Фур'є *Fo* для порівняних варіантів товщини відрізняється приблизно в 1360 разів.

Наступна особливість, що заслуговує на увагу, — суттєва відмінність тривалості стадій процесу. Наприклад, більшим значенням δ_1 відповідають помітно менші відносні тривалості третьої стадії та більші — другої стадії.

Крім того, отримані дані свідчать про те, що товщина частки, що розтеклася, може істотно позначатися на значенні температури об'єкта в цілому. А саме, у початковий період у межах дуже малого часового інтервалу процес теплопереносу протікає практично однаково для різних товщин δ_1 і локалізується у порівняно малій підобласті, що прилягає до поверхні контакту. Однак з часом різниця температур при різних товщинах δ_1 стає дуже суттєвим. При цьому чим тонше розтеклася частка, тим нижче температура як в частці, так і в основі. Наприклад, для *Fo* = 8,69, безрозмірні температури зовнішньої поверхні покриття θ_n дорівнюють 1,28 і 0,23 при $\delta_1 = 40$ і 1 відповідно (див. рис. 1а).

Аналіз процесу теплопереносу, свідчить також, що більшим товщинам частки, що розтеклася, відповідають менші розміри незбуреної зони в основі. Так, при $Fo = Fo_1$ глибина проникнення теплової дії в основу Δx_n становить 58,6; 15,1 і 1,48 для $\delta_1 = 40$; 10 і 1 відповідно.

Висновки. Результати виконаних досліджень показали, що геометричні характеристики напилюваної частки можуть істотно впливати на особливості теплообміну в процесі газотермічного нанесення покриття. Зокрема, від товщини частки, що розтеклася, залежить як тривалість окремих стадій процесу, так і температура розглянутого об'єкта в цілому.

ДОДАТКОВА ІНФОРМАЦІЯ

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ПІДВИЩЕННЯ ТЕПЛОВОЇ ТА ЕКОЛОГІЧНОЇ ЕФЕКТИВНОСТІ ГАЗОСПОЖИВАЛЬНИХ КОТЕЛЬНИХ УСТАНОВОК

INCREASING THERMAL AND ENVIRONMENTAL EFFICIENCY OF GAS-BURNING BOILER PLANTS

Анотація. *Запропоновано нову теплоутилізаційну установку для підігрівання і зволоження дуттьового повітря з розширеним колом нагріваних теплоносіїв різного потенціалу для парових котлів. Наводяться результати досліджень установки для системи «котел – теплоутилізаційна установка» з котлом номінальною теплопродуктивністю 0,63 МВт в різних режимах експлуатації. Показано, що застосування пропонованої установки дозволяє підвищити коефіцієнт використання теплоти палива котла на 2,8...6,5%.*

Ключові слова: *газоспоживальні котли, димові гази, нагрівання і зволоження дуттьового повітря, ефективність.*

Summary. *The new heat-recovery plant for heating and humidifying the combustion air with an extended range of heated coolants of different potential for steam boilers is proposed. The results of research on the unit for the "boiler – heat-recovery plant" system with a boiler at a nominal heat output of 0.63 MW in different operating modes are presented. It is shown that the use of the proposed plant allows increasing the coefficient of the use heat of fuel of boiler by 2.8...6.5%.*

Key words: *gas-fired boiler, exhaust gases, heating and humidification of the combustion air, efficiency.*

Вступ. На сьогодні в Україні через неухильне підвищення вартості палива постає необхідність його ощадного споживання. Разом з тим також посилюються вимоги та нормативи щодо контролю та зниження забруднення навколишнього середовища від спалювання цього палива. Тому розробленню енергозбережувальних та природоохоронних технологій для паливоспоживальних об'єктів приділяється підвищена увага. Зокрема, в комунальній теплоенергетиці застосовуються технології глибокої утилізації теплоти відхідних димових газів котельних установок, що здатні суттєво покращити теплову та екологічну ефективність цих установок. А саме, збільшення теплової ефективності досягається завдяки підвищенню ККД котла, а покращення екологічних показників реалізується в основному через зниження витрати палива [1, 2]. Разом з тим, чим глибше охолоджуються димові гази, тим вище тепловий та екологічний ефект теплоутилізації. Зазвичай у застосовуваних технологіях найчастіше використовуються теплоутилізаційні системи, призначені для нагрівання зворотної тепломережної води та дуттьового повітря перед їхнім надходженням у котел. Через сталу тенденцію, спрямовану на посилення вимог щодо зниження викидів оксидів азоту у продуктах згоряння котельних установок останнім часом розробляють модернізовані теплоутилізаційні технології, в яких досягається підвищений екологічний ефект завдяки суттєвому зменшенню зазначених викидів з відхідними газами даних установок. Цей ефект обумовлений використанням частини теплоти газів котла на зволоження дуттьового повітря [3–5]. Надходження зволоженого повітря в процесі спалювання природного газу в котлі призводить до зниження температури горіння палива, що впливає на зменшення утворення оксидів азоту в топковому просторі. Особливістю роботи котелень з такими теплоутилізаційними системами є підвищений вміст вологи у димових газах. Дослідження спрямовані на покращення теплових та екологічних характеристик таких систем є актуальним завданням.

Мета роботи полягає у розробленні ефективних теплоутилізаційних систем для підігрівання і зволоження дуттьового повітря та визначенні їхніх теплових показників.

Методика проведення досліджень. Методика досліджень базувалася на використанні нормативного методу теплового розрахунку котельних установок та методики Інституту технічної теплофізики НАН України [1; 6; 7].

Основні завдання дослідження полягали: у розроблені нової схеми теплоутилізації (рис. 1) з використанням контактного апарату для нагрівання і зволоження дуттьового повітря та виконанні теплового розрахунку котельної установки з пропонованою системою теплоутилізації в різних режимах експлуатації котла.

Дослідження виконувались для системи «котел — теплоутилізаційна установка» з котлом номінальною теплопродуктивністю 0,63 МВт. При цьому приймалося, що в діапазоні теплового навантаження котла від 40 до 100% коефіцієнт надлишку повітря в топці котла змінюється від 1,65 до 1,2 відповідно.

Теплоутилізаційна установка містить газохід 1, який з'єднує її на вході з котлоагрегатом та з димовою трубою на виході. В пропонованій установці застосовуються поверхневі водяні теплообмінники різного призначення і контактний апарат для підігрівання і зволоження дуттьового повітря. Теплообмінною поверхнею водяних теплообмінників слугують пучки оребрених біметалевих труб (сталева основа і алюмінієве поперечне оребрення), а контактного апарату — насадка з гофрованих полівінілхлоридних (ПВХ) пластин [1].

Основними перевагами запропонованої комплексної теплоутилізаційної системи у порівнянні з традиційними теплоутилізаторами для підігрівання і зволоження дуттьового повітря є підвищення коефіцієнта використання теплоти палива до 6,5% завдяки розширенню кола нагріваних теплоносіїв та наявність додаткового захисту газовідвідного тракту котельної установки від конденсатоутворення [8] за умов підвищеного вологовмісту димових газів.

Результати досліджень. Розрахункові дослідження виконувались в різних режимах навантаження котла, оскільки підвищення температури дуттьового повітря та його зволоження

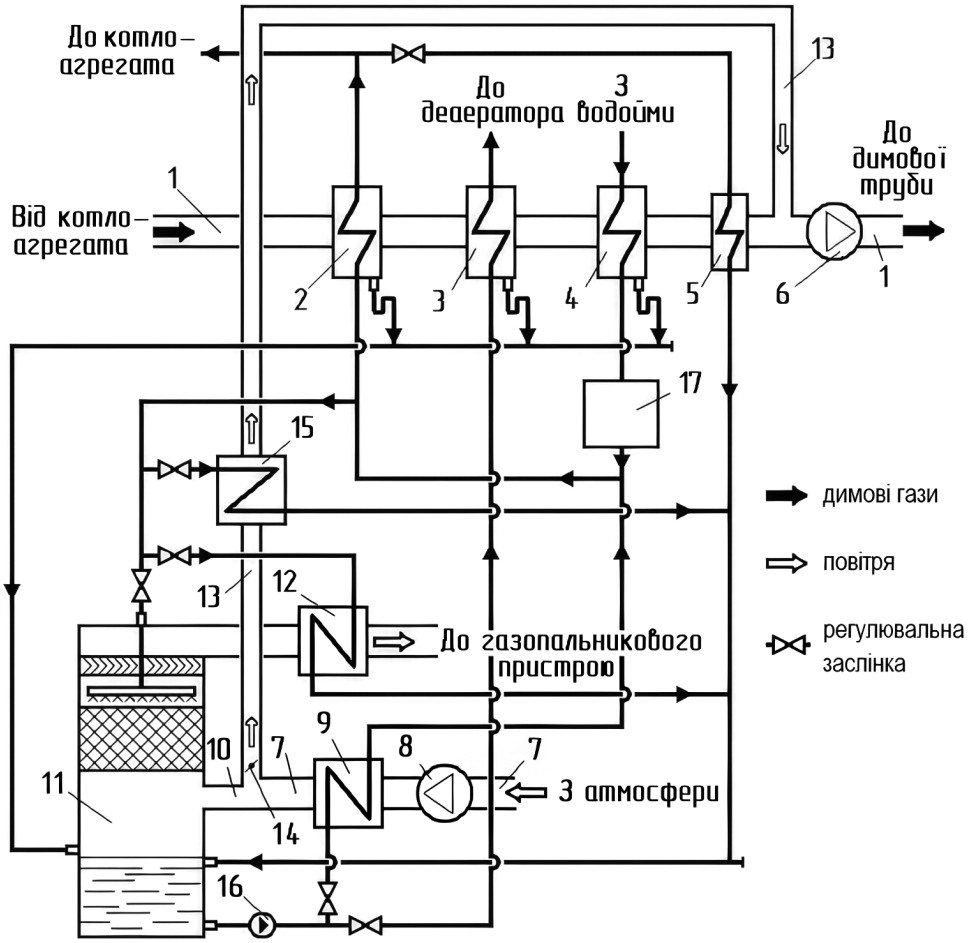


Рис. 1. Принципова схема теплоутилізаційної установки для підігрівання і зволоження дуттьового повітря з розширеним колом нагріваних теплоносіїв різного потенціалу для парових котлів:
1 — газохід; 2 — поверхневий водогрійний теплоутилізатор (ПВТ); 3, 4 — підігрівачі системи ХВО; 5 — газопідігрівач (ГП); 6 — димосос; 7, 10 — повітровід; 8 — вентилятор; 9 — повітрогрійний теплообмінник (ПТ); 11 — контактний водоповітряний тепломасообмінник (КВТ); 12 — повітродогрівач (ПД); 13, 15 — повітряний канал системи захисту димового тракту з відповідним теплообмінником; 14 — регулювальна заслінка; 16 — насос; 17 — система хімводоочищення (ХВО)

Таблиця 1

Режимні показники теплоутилізаційної установки з навантаженням котла 100% ($G_{пг}$ = 70,17 м³/год; ά =1,2)

Найменування параметра	Позначення	Розмірність	Елемент теплоутилізаційної установки				
			ПВТ	ГП	ПТ	КВТ	ПД
1	2	3	4	7	8	9	10
Теплопродуктивність	Q	кВт	17,7	5,4	8,2	61,2	5,7
Витрата води	Gв	кг/с	0,20	0,20	0,20	0,72	0,20
Температура води на вході	tввх	°С	69,1	90,2	77,0	69,1	83,8
Температура води на виході	tввих	°С	90,2	83,8	67,2	48,8	77,0
Витрата газів (повітря)	Gг (Gпв)	кг/с	0,36	0,36	0,29	0,29	0,29
Температура газів (повітря) на вході	tгвх (tпввх)	°С	159,3	62,0	10,0	37,2	50,0
Температура газів (повітря) на виході	tгвих (tпввих)	°С	114,1	76,0	37,2	50,0	68,9
Аеродинамічний опір	DH	Па	41,8	33,8	9,1	149,9	15,1
Гідравлічний опір	DP	кПа	0,2	0,1	0,1	17,0	0,1

в поверхнево-контактній частині теплоутилізаційної системи впливають на температуру горіння, тепловий баланс котла, вихідні параметри газів, витрату палива, ККД котла тощо. Тому котел та комплексна теплоутилізаційна установка розглядалися як взаємопов'язані елементи єдиної системи. Особливість даного розрахунку полягає в тому, що вихідні параметри димових газів котла є вхідними для утилізаційної установки, а вихідні параметри дуттьового повітря з установки стають вхідними для котла.

За результатами виконаних розрахункових досліджень визначено теплові, гідравлічні та режимні характеристики системи «котел — теплоутилізаційна установка» для запропонованої нової комплексної теплоутилізаційної системи з підігріванням та зволоженням дуттьового повітря.

За результатами цих досліджень встановлено, що застосування пропонованої комплексної установки дозволяє підвищити коефіцієнт використання теплоти палива котла на 2,8…6,5% в залежності від режиму його експлуатації.

Характерні результати розрахункових досліджень системи «котел — теплоутилізаційна установка» подано в табл. 1. Тут наводяться значення основних робочих характеристик такого системи під час роботи котлоагрегату в номінальному режимі.

Висновки

1. Запропоновано нове технічне рішення комплексної теплоутилізаційної установки з розширеним колом нагріваних теплоносіїв різного температурного потенціалу для підігрівання та зволоження дуттьового повітря з додатковим захистом газовідвідного тракту котельної установки від конденсатоутворення за умов підвищеного вологовмісту відхідних димових газів.

2. Виконано розрахункові дослідження основних робочих характеристик теплообмінних елементів (теплоутилізаторів) пропонованої теплоутилізаційної системи при її експлуатації з газоспоживальним котлом номінальною тепловою потужністю 0,63 МВт.

3. Показано, що застосування пропонованої комплексної установки дозволяє підвищити коефіцієнт використання теплоти палива котла на 2,8…6,5%.

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ВНЕСОК АВТОРІВ: Усі автори зробили внесок порівну.
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