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LEADERSHIP DYNAMICS IN PHYSICALLY INTENSIVE MOBILE WORK TEAMS: A BEHAVIORAL TAXONOMY FOR CREW LEADERS IN MOVING SERVICES

Summary. Leadership research has produced detailed models for office managers, military officers, surgical team leads, and cockpit captains. Crew leaders in the moving and relocation industry share none of those working conditions yet carry comparable responsibility for team output, safety, and client satisfaction. They lift furniture alongside their crews, manage shifting job demands across unfamiliar buildings, and serve as the sole point of contact between the company and the client, all within a single shift. No published taxonomy captures the specific leadership behaviors that this combination of physical labor, operational management, and client interaction demands. This study develops the Field Leadership Behavior Inventory (FLBI), a 12-item observational instrument organized into three categories: task-oriented, relational, and adaptive behaviors. Trained observers coded 120 shifts at a mid-size carrier in the northeastern United States across two six-month periods. Shifts led by crew leaders who scored in the top quartile on relational and adaptive behaviors recorded on-time completion rates 14 percentage points higher, damage incident rates 47% lower, and client satisfaction scores 0.8 points higher on a 5-point scale than shifts led by bottom-quartile scorers. Task-oriented behaviors showed weaker differentiation; how a crew leader relates to the team and responds to changing conditions appears to matter more than procedural control alone.

Key words: crew leadership, team dynamics, physically demanding work, leadership behaviors, moving services, field team management.

Introduction. A crew leader in the moving industry wakes up at 5 a.m., checks a dispatch sheet listing two or three jobs, and meets a team that may include workers they have never supervised before. By 8 a.m. they are carrying a dresser down a fourth-floor stairwell. By 10 a.m. they are explaining to a client why the antique bookshelf needs custom wrapping that was not quoted in the original estimate. By noon they are deciding whether the team can handle a second job across town or whether fatigue has made the afternoon schedule unrealistic. Few of these tasks appear in the leadership literature reviewed below.

Leadership theory has built its evidence base in settings where the leader is not physically engaged in the team task. Transformational leadership was validated through questionnaire studies of managers, military officers, and educators who lead from desks, briefing rooms, or podiums [2]. Functional leadership theory identified 15 leadership functions organized around transition and action phases of team

performance, drawing data from manufacturing plants and R&D laboratories where the team leader oversees work but does not perform it [10]. Research on leadership in extreme contexts accounts for threat, time pressure, and complexity, but the settings studied are military and emergency operations where the leader coordinates without sharing the physical workload [6]. What connects all these frameworks is an unspoken premise: leading is a cognitive activity performed by someone whose body is free. A moving crew leader hauls the same weight as every other team member, and that effort depletes the cognitive resources that leadership depends on.

Team process models reinforce this blind spot. Marks et al. proposed a taxonomy of team processes organized into transition, action, and interpersonal categories, a framework that has shaped more than two decades of team research [9]. Transition processes (mission analysis, goal specification, strategy formulation) happen before task execution; action processes



(monitoring, coordination, backup) happen during it. In moving, both happen simultaneously and the person leading the transition process is also performing the action. When a crew leader stops to reformulate the loading sequence after discovering an extra bedroom, the reformulation happens mid-task, not at a planning table. A review of team effectiveness research covering hundreds of studies noted that the physical context of teamwork remains an understudied moderator of team processes. Nearly two decades later, the gap persists [7].

Shared leadership offers a partial answer. Pearce and Sims found that distributing leadership across team members was a stronger predictor of effectiveness in change management teams than vertical leadership from a single appointed leader [11]. In moving, informal task sharing happens naturally: an experienced mover may take charge of wrapping fragile items while the crew leader manages the truck loading sequence. In practice, however, an external accountability structure constrains this distribution: the client expects one person to own the conversation, and the company holds one person responsible for the shift outcome. Psychological safety, the belief that speaking up will not be punished, predicts learning behavior and error reporting in work teams [5]. For a moving crew assembled that morning and unlikely to work together again tomorrow, building that climate in the first fifteen minutes of a shift is a leadership task rarely examined in the literature on stable teams.

One variable that leadership models have largely ignored is the leader's own physical state. Barling and Cloutier reviewed how leader mental health shapes leadership quality and found that depleted leaders fall back on passive and transactional behaviors even when the situation calls for something more active [1]. Physical fatigue works the same way. Four hours into a stairwell carry, a crew leader simply has less cognitive capacity for motivating people or rethinking the plan than that same person had at 8 a.m. Burke et al. tested which leadership behaviors are functional in team settings and found that task-focused and person-focused behaviors both predicted performance, but that the relative weight shifted depending on task demands [3]. Moving amplifies this effect because task demands stay high throughout the shift, change without warning, and fall on the leader's shoulders just as heavily as on anyone else's.

Against this background, the present article proposes the Field Leadership Behavior Inventory (FLBI), a 12-item structured observation tool that classifies crew leader behaviors into three categories: task-oriented (sequencing, equipment oversight, pace setting, quality checks), relational (encouragement, physical co-participation, conflict de-escalation, break management), and adaptive (scope communication, role reassignment, expectation management, tempo adjustment under fatigue). FLBI was applied to 120 observed shifts at a mid-size carrier in the northeastern United

States to test which behavior categories and individual behaviors are associated with better shift-level outcomes in on-time completion, damage incidence, and client satisfaction. Where earlier interventions at this company addressed crew allocation and field decision protocols, the present analysis shifts the unit of observation from the job or the deviation event to the crew leader as an individual actor whose behavioral choices shape the shift from start to finish.

Literature Review. Bass and Avolio's Full Range Leadership Model organizes leader behavior along a spectrum from passive avoidance through transactional exchange to transformational influence [2]. Transformational leadership in this model has four components. Idealized influence involves modeling behaviors that followers respect. Inspirational motivation means articulating a vision that energizes the group. Intellectual stimulation encourages people to try new approaches, and individualized consideration requires attending to what each follower needs to develop. Podsakoff et al. showed that transformational behaviors explained variance in followers' trust and citizenship behaviors that transactional rewards alone could not account for [12]. Later studies found a similar pattern in military, educational, healthcare, and corporate samples. A practical problem arises, however, with the model's measurement instrument. Followers fill out the Multifactor Leadership Questionnaire after weeks or months of working under the same leader. A moving crew leader works with a given team for one shift, sometimes for a single three-hour job. There is no accumulated impression to rate; what matters is observable behavior within that window.

Functional leadership theory shifts attention from who the leader is to what the leader does for the team. Zaccaro et al. defined team leadership as identifying and satisfying whatever a team needs to function [15]. Morgeson et al. built on that idea by sorting leadership functions into two temporal phases. Before the task begins (transition phase), leaders compose the team, define the mission, set expectations, plan, train, make sense of the situation, and give feedback [10]. During the task (action phase), they monitor progress, manage boundaries, challenge the team, perform the task themselves, solve problems, supply resources, encourage self-management, and support a positive social climate. Burke et al. tested several of these functions and found that both task-focused acts (structuring, monitoring) and person-focused acts (supporting, developing) contributed to performance, though the balance between them shifted with the type of task [3]. For moving crews, this functional lens works better than trait or style models because it points to concrete, observable acts rather than abstract tendencies. Where it falls short is a blind spot shared with every framework in Table 1: none of the listed functions considers what happens when the leader is physically performing the team task and running low on the cognitive energy that leadership demands.

Two additional research streams inform the design of FLBI. First, team development and adaptation research raises the question of how quickly a group can become functional. Tuckman described four stages that small groups move through: forming, storming, norming, and performing. Groups in his studies interacted over weeks or longer [13]. Moving crews do not have that luxury; someone who announces role assignments in the first five minutes of a shift is compressing what Tuckman observed as an organic process into a deliberate act. LePine looked at what happens when task demands change unexpectedly and found two things: teams with strong goal commitment adapted faster, and individual cognitive ability mattered for adaptation speed regardless of group composition [8]. For moving, this means that putting the right person on the right task after an on-site surprise is not just a logistical convenience but a leadership act with measurable performance consequences. DeChurch and Mesmer-Magnus extended this line of work by meta-analyzing the relationship between shared mental models and team performance [4]. Shared cognition predicted both team process quality and outcomes, especially when mental models were task-focused rather than team-focused. In moving, the person who announces the loading sequence before the first box is carried creates a task-focused mental model that substitutes for the team familiarity built over weeks in other work settings.

Second, research on leader interventions in self-managing teams addresses the tension between directing and empowering. Wageman examined 43 self-managing teams at Xerox and found that leaders who provided clear direction at the start and coaching

during execution produced better outcomes than leaders who either micromanaged throughout or withdrew entirely [14]. Effective intervention was about timing, not volume: brief, well-placed coaching moments outperformed continuous oversight. Moving crew leaders face an amplified version of this dynamic because the physical pace of the work does not allow for extended conversation. Coaching must fit into the brief pause between one carry and the next. This constraint makes behavioral specificity essential: a crew leader who says "slow down on the stairs, the banister is loose" is performing a person-focused leadership function compressed into a format that no existing leadership instrument captures [3].

Across these six frameworks and two additional research streams, a pattern emerges: each body of work illuminates one or two dimensions of the moving crew leader's role while leaving others unaddressed. Transformational leadership captures the motivational dimension but not the physical one. Functional leadership captures the behavioral dimension but assumes the leader stands apart from the task. Team process models capture coordination but not fatigue. FLBI was designed to integrate these partial views into a single observation instrument calibrated for the specific conditions of physically intensive, client-facing, single-shift mobile teamwork.

Materials and Methods. Data were collected at a USDOT-registered household goods carrier operating in a major metropolitan area in the northeastern United States. Unlike prior analyses of dispatch-level and deviation-level records at the same company, the present study operates at a different unit: the individual crew leader observed across an entire shift. A trained

Table 1

Leadership frameworks and their applicability to physically intensive mobile work teams

Framework	Key Construct	Studied Contexts	Applicability to Moving	Limitation for Moving
Full Range Leadership [2]	Transformational vs transactional behaviors	Office, military, education	Inspirational motivation and individualized consideration relevant to crew morale	Requires ongoing leader-follower relationship; crews rotate daily
Functional Leadership [10; 15]	Leadership functions across transition and action phases	Manufacturing, R&D, project teams	Transition/action distinction maps onto pre-job briefing and during-job execution	Does not model leader performing physical task alongside team
Team Processes [9]	Transition, action, interpersonal process categories	Laboratory and project teams	Process categories applicable to crew coordination and conflict management	No fatigue or physical workload dimension; assumes phase separation
Shared Leadership [11]	Distributed influence across team members	Knowledge work, change management	Informal task sharing occurs naturally among experienced movers	Single point of client accountability limits distribution
Psychological Safety [5]	Voice behavior, error reporting, learning	Healthcare, technology teams	Error reporting relevant to damage prevention and safety	Climate builds over repeated interaction; crews may meet once
Extreme Context Leadership [6]	Threat, complexity, time urgency	Military, emergency response	Physical risk, time pressure, unpredictable conditions present	Leader coordinates but does not share physical workload

Source: compiled by the author from published literature

observer, an office staff member with four years of operational experience but no active crew role during the study period, accompanied crews on 120 shifts between March 2024 and February 2025. On a typical move, the crew leader assigns functional roles (lead mover controlling the sequence, a stabilizer managing balance on heavy items, and a spotter clearing the path), and FLBI codes how the leader manages these assignments across the shift. Observer presence may have influenced crew leader behavior; this reactivity concern is addressed in the limitations discussion in Section 4. Sixty shifts fell in Period A (March through August 2024, before the introduction of structured protocols at the company) and sixty in Period B (September 2024 through February 2025, after protocol adoption). Shifts were selected to cover all days of the week, both peak and off-peak seasons, and a range of job types (local apartment moves, office relocations, long-distance loads). Fourteen crew leaders were included in the study, with each leader appearing in five to twelve shifts depending on scheduling availability. Given the small number of crew leaders, quartile boundaries used in the analysis are approximate, and results should be interpreted as indicative patterns rather than definitive effects. Crew composition varied across shifts; the observer recorded which team members were present but coded only the crew leader's behavior.

FLBI classifies crew leader behaviors into three categories of four items each. Task-oriented behaviors capture how the leader organizes and controls the physical work: workload sequencing (announcing which rooms or items to load first and in what order), equipment staging oversight (verifying that dollies, blankets, straps, and specialty tools are positioned before carrying begins), pace setting (adjusting speed verbally or through personal example to match job demands), and quality checkpoints (pausing to inspect wrapping, stacking, or truck loading before proceeding to the next stage). Relational behaviors address team energy and cohesion. Verbal encouragement covers any instance where the leader acknowledges effort by name or gives brief positive feedback during a carry. Physical co-participation means the leader works alongside the crew on heavy or awkward items instead of directing from the truck. Conflict de-escalation involves stepping in when disagreements over task allocation or pace arise between team members. Break timing captures whether the leader initiates rest periods based on workload and weather conditions or waits for crew members to ask. Adaptive behaviors cover responses to changing conditions. Scope communication means informing the team promptly when job parameters shift. Role reassignment involves moving crew members between tasks as needs emerge or fatigue becomes visible. Client expectation management refers to reframing timelines or costs when on-site conditions force a departure from the original quote. Tempo adjustment captures moments when the leader reduces pace or changes the task sequence

because cumulative fatigue shows up in slower movement, longer pauses, or a rising error count.

For each shift, the observer carried a printed coding sheet divided into 30-minute blocks. Within each block, the observer recorded whether each of the 12 behaviors was exhibited at least once (binary: observed / not observed). Binary coding was chosen over frequency counts to reduce observer judgment load during physically active shifts where precise tallying would be impractical. At shift end, the observer summed the block-level codes to produce a shift-level score for each behavior (ranging from 0 to the number of blocks in that shift, typically 4 to 8 depending on shift length) and a category score (sum of the four behaviors within each category). To assess inter-rater consistency, a second trained observer accompanied the primary observer on 15 of the 120 shifts (12.5%). Agreement on individual behavior codes reached 87% across the 15 dual-coded shifts; Cohen's kappa was not computed due to the small dual-coding sample, so this figure should be interpreted as a descriptive indicator of consistency rather than a formal reliability coefficient. Disagreements concentrated in the relational category, where the boundary between verbal encouragement and routine conversation required the most judgment.

Three shift-level outcome measures were recorded independently of FLBI coding. On-time completion was coded as a binary variable: whether the crew finished the job within the time window quoted to the client, with a 15-minute grace period. Damage incidence counted the number of items reported as scratched, dented, or broken on the post-job inspection form completed by the crew leader and countersigned by the client. Client satisfaction was measured through a single-item five-point rating scale ("How satisfied are you with the crew's performance today?" anchored at 1 = very dissatisfied and 5 = very satisfied), administered by phone within 48 hours of the move by an office staff member who had no knowledge of the FLBI scores for that shift. Outcome data were matched to FLBI scores by shift date and crew leader identity. Analysis compared outcome means across FLBI quartiles (top 25% vs bottom 25% of crew leaders on each behavior category), with differences assessed using Mann-Whitney U tests given the non-normal distribution and small number of crew leaders per quartile. Individual behaviors within each category were examined separately to identify which specific acts carried the strongest association with shift outcomes.

Results and Discussion. Across all 120 observed shifts, task-oriented behaviors appeared in the highest proportion of 30-minute coding blocks, followed by relational and then adaptive behaviors. Table 2 reports observation rates for each of the 12 FLBI items.

Pace setting and workload sequencing appeared on almost every shift; crew leaders consistently set a rhythm and announced what to load first. Equipment staging showed up in about two-thirds of coding blocks,

Table 2

FLBI behavior observation rates (% of 30-minute blocks, mean across 120 shifts)

Category	Behavior	Observation Rate
Task-oriented	Workload sequencing	81%
	Equipment staging oversight	64%
	Pace setting	84%
	Quality checkpoints	54%
	Category mean	70.8%
Relational	Verbal encouragement	61%
	Physical co-participation	74%
	Conflict de-escalation	29%
	Break timing	48%
	Category mean	53.0%
Adaptive	Scope communication	44%
	Role reassignment	39%
	Expectation management	36%
	Tempo adjustment	31%
	Category mean	37.5%

Source: compiled by the author from observer coding sheets (120 shifts, 14 crew leaders)

mostly at the start of each job and after the truck was repositioned. Quality checkpoints were less common, appearing in just over half of blocks. Leaders, it seems, chose speed over inspection when the physical effort was sustained. Among relational behaviors, physical co-participation stood out at 74%, consistent with the expectation that most crew leaders spent the majority of each shift carrying alongside their teams, not supervising from a distance. Conflict de-escalation was the rarest behavior at 29%, which reflects the low base rate of visible interpersonal friction on any given shift, not leader avoidance. Adaptive behaviors clustered below 45% because they depend on triggering events (scope changes, emerging fatigue, client questions) that do not occur in every coding block.

Leaders were ranked by their mean category score across all observed shifts, then grouped into quartiles. Shifts led by the four highest-scoring crew leaders on the combined relational-adaptive dimension ($n = 31$ shifts) were compared with shifts led by the four lowest-scoring crew leaders ($n = 28$ shifts). Parallel

comparison was conducted for the task-oriented dimension. Table 3 reports the results.

Relational and adaptive behaviors separated high-performing from low-performing crew leaders far more sharply than task-oriented behaviors did. On-time completion differed by 14 percentage points across relational-adaptive quartiles but by only 4 points across task-oriented quartiles. Damage incidence nearly halved in the top relational-adaptive group (0.39 vs 0.74 per shift), while task-oriented quartile differences were marginal and statistically non-significant. Client satisfaction followed the same pattern: a gap of 0.8 points on a 5-point scale between relational-adaptive extremes, versus 0.2 points for task-oriented extremes.

Why did task-oriented behaviors, the most frequently recorded category, predict outcomes so weakly? One explanation is ceiling effects: because workload sequencing and pace setting appeared on nearly every shift regardless of leader quality, they failed to differentiate strong leaders from weak ones. A behavior that everybody performs cannot predict who performs well.

Table 3

Shift outcomes by FLBI category quartile (top 25% vs bottom 25% of crew leaders)

Category and Outcome	Top Quartile ($n = 31$ shifts)	Bottom Quartile ($n = 28$ shifts)	Difference	p (Mann-Whitney)
Relational + Adaptive				
On-time completion (%)	90.3	76.0	+14.3 pp	< 0.01
Damage incidents (per shift)	0.39	0.74	-47.3%	0.02
Client satisfaction (1-5)	4.6	3.8	+0.8	< 0.01
Task-oriented				
On-time completion (%)	84.6	80.2	+4.4 pp	0.31
Damage incidents (per shift)	0.53	0.62	-14.5%	0.44
Client satisfaction (1-5)	4.2	4.0	+0.2	0.38

Source: compiled by the author from FLBI coding and matched shift outcome records

Morgeson et al. noted a similar pattern in their review: task-structuring functions are necessary for team functioning but rarely sufficient for team excellence, which depends more on interpersonal and adaptive functions [10]. Burke et al. arrived at the same conclusion from a different direction, finding that person-focused leadership behaviors gained predictive weight as task complexity increased [3]. Moving fits squarely into that logic. Carrying, wrapping, and loading furniture is physically hard but procedurally simple, so a baseline level of task management gets the job done. Where crew leaders diverge is in how they keep the team's energy up, handle friction when it surfaces, and pivot when something unexpected changes the plan.

When individual behaviors were examined, four stood out. Break timing had the tightest connection to on-time completion. Crew leaders who called breaks before anyone looked exhausted finished on schedule

more often than those who waited for someone to ask. Late breaks created a recognizable cascade: the team pushed past its efficient output window, needed longer to recover, then rushed through the remaining work, which produced both delays and handling errors. Tempo adjustment was most closely linked to damage: leaders who slowed the pace after noticing fumbled grips or labored breathing saw roughly half the damage counts of shifts where the original speed held. Verbal encouragement tracked most closely with client satisfaction, likely because clients watched crew interactions throughout the day and read a positive, talkative team as a sign of professionalism. Scope communication, functionally close to the client disclosure protocol used at the same company, was linked to both satisfaction and punctuality; telling the client early about a scope change appears to head off the cascading delays that come with last-minute renegotiation.

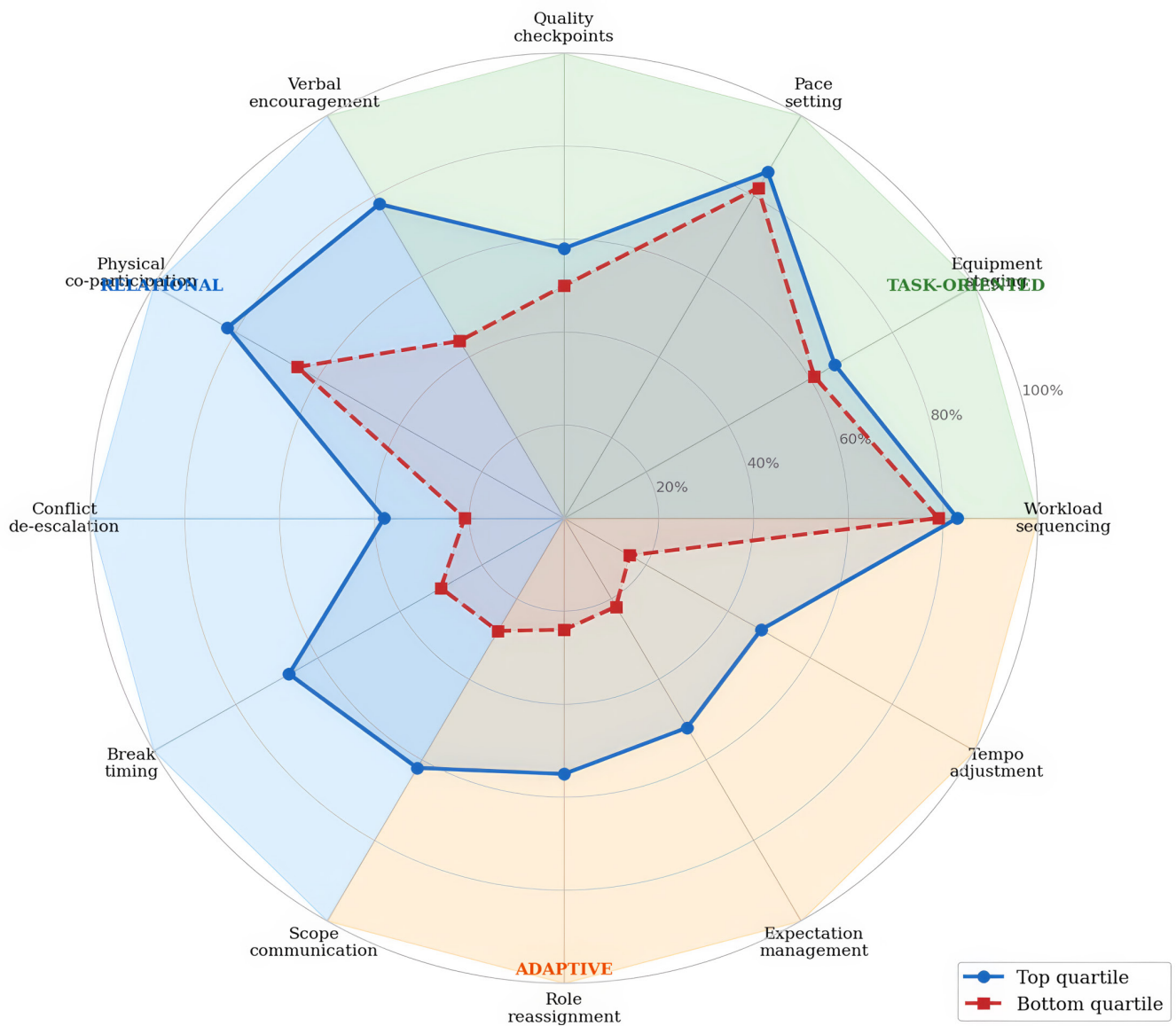


Fig. 1. FLBI behavior profiles: top-quartile vs bottom-quartile crew leaders (relational-adaptive ranking)

Source: author's development based on observer coding data

Connecting these findings to the theoretical frameworks reviewed in Section 2 points to a consistent interpretation. Bass and Avolio's inspirational motivation and individualized consideration map onto verbal encouragement and break timing: the leader signals that effort is valued and that individual capacity is being monitored [2]. Marks et al.'s interpersonal process category, which includes conflict management and affect management, maps onto conflict de-escalation and tempo adjustment [9]. Wageman's finding that well-timed coaching outperforms continuous oversight aligns with the observation that break timing and tempo adjustment, both brief interventions delivered at specific moments, were associated with outcomes more strongly than persistent procedural behaviors like pace setting [14]. What FLBI adds to these established frameworks is an instrument that captures all three dimensions (task, relational, adaptive) simultaneously in a setting where the leader is physically embedded in the task, something that questionnaire-based or laboratory-based instruments cannot replicate.

Period B shifts (after protocol adoption) scored modestly higher on adaptive behaviors than Period A shifts (41.2% vs 33.8% mean block rate, $p = 0.04$, Mann-Whitney), while task-oriented and relational scores stayed flat. Crew leaders trained on a structured field decision protocol used scope communication and expectation management more often, probably because the protocol handed them a ready-made vocabulary for those conversations. Encouragement, co-participation, and break timing did not shift between periods, which makes sense: these are interpersonal habits, and a decision protocol does not touch them.

Several limitations require acknowledgment and qualify the strength of the conclusions drawn here. The study took place at a single company in one metropolitan market; carriers with different crew sizes, compensation models, or geographic conditions may produce different behavioral distributions. Fourteen crew leaders and 120 shifts constitute a small sample by quantitative standards, and with only four leaders per quartile, a single atypical individual can shift groups substantially. Results should be read as suggestive patterns in need of replication, not as confirmed effects. Observer presence on the truck and at the job site is the most significant threat to internal validity. Crew leaders who knew they were being watched may have performed leadership behaviors they would otherwise skip, a classic reactivity effect. Because inflation would affect all leaders in roughly the same direction, the relative ranking used in quartile analysis is more trustworthy than absolute behavior rates, but even relative rankings may have shifted if some leaders were more reactive to observation than others. Binary block-level coding sacrifices granularity: a leader who encourages the team once in a 30-minute window receives the same score as one who does so ten times. A future version of FLBI could incorporate intensity

or frequency scaling for behaviors that vary in dosage. Client satisfaction was measured with a single item; a multi-item scale covering communication quality, care with belongings, and punctuality would give a fuller picture. Finally, correlation is not causation. Crew leaders who score high on relational and adaptive behaviors may also be more experienced, more agreeable, or more motivated than low scorers, and any of those unmeasured differences could independently drive the outcome gap. Seasonal variation adds another layer of uncertainty: Period A fell during summer peak months and Period B during winter, and differences in job volume, daylight hours, or crew fatigue patterns between seasons may have influenced both leader behavior and shift outcomes independently of FLBI adoption. No control group of unobserved crew leaders was available, so the possibility that improvements reflect general organizational learning or other concurrent changes cannot be excluded.

Conclusions. FLBI started with a practical question: if a crew leader is lifting furniture, running the operation, and talking to the client all at the same time, which specific behaviors separate a good shift from a bad one? Observation of 120 shifts at a single moving company produced a clear pattern. Relational and adaptive behaviors (encouragement, co-participation, break timing, scope communication, role reassignment, tempo adjustment) separated top-performing from bottom-performing crew leaders by margins that were both statistically significant and operationally meaningful. Task-oriented behaviors turned up on nearly every shift and told us little about who led well and who did not.

Three contributions emerge from this work. First, no comparable behavioral taxonomy for physically intensive mobile work teams appears in the reviewed literature; FLBI fills that gap. Existing instruments measure leadership through follower questionnaires administered after weeks of interaction or through post-hoc ratings of team functions. FLBI measures what the leader actually does, in real time, on a printed coding sheet carried by an observer walking alongside the crew. Second, the finding that relational and adaptive behaviors outweigh task-oriented behaviors in predicting shift outcomes adds field evidence to a theoretical proposition advanced from laboratory and survey data: person-focused leadership functions gain importance as task demands increase. Moving provides an extreme test of that proposition because task demands include the leader's own physical exhaustion. Third, FLBI's three-category structure (task, relational, adaptive) offers a practical diagnostic for crew managers. Someone who sequences work efficiently but neglects break timing or avoids scope conversations with clients can be coached on specific, named behaviors rather than receiving vague feedback about 'leadership style.'

Adoption requires minimal resources. FLBI coding sheets fit on a single page. Observer training at the study site took one four-hour session followed by five

supervised ride-alongs before independent coding began. New crew leaders at the company typically need one to two months of supervised fieldwork before independent assignment, a timeline that targeted FLBI-based coaching could potentially compress. Companies without a dedicated observer could use periodic ride-alongs by operations managers or pair new crew leaders with experienced ones for mutual observation, converting FLBI from a research instrument into a peer feedback tool.

Four directions would extend the evidence base. Replication across multiple carriers with larger crew

leader samples would test whether the relational-adaptive advantage holds in companies with different crew sizes, compensation structures, and geographic markets. Following individual crew leaders over six to twelve months would show whether FLBI scores shift with experience and, if they do, which behaviors improve quickly and which prove stubborn. A peer-rated version of FLBI, where crew members score each other after each shift, would move the instrument out of the research setting and into daily operations.

ДОДАТКОВА ІНФОРМАЦІЯ

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MICRO-CONVERSION ENGINEERING: THE IMPACT OF WEBSITE STRUCTURE AND THANK YOU PAGES ON LEAD-TO-CUSTOMER CONVERSION

Summary. In this paper, we investigate conversion optimisation of online marketing applications from both a structural and behavior perspective within a website system and post-lead interaction methodologies. Conversion as an endpoint of the funnel, as seen in traditional marketing frameworks, is not discussed in this paper, which will argue that conversion is initiated when a lead is captured rather than when it is reached. In essence, the author develops the Post-Lead Conversion Enhancement Layer (PCEL), in alignment with the IMELF (Integrated Marketing Efficiency and Lifecycle Framework) framework, to organize post-lead interaction across all dimensions of conversion. Building on previous customer experience, marketing analytics and omni-channel system literature, the study reconceptualizes the website as a dynamic conversion mechanism not as a static interface. From a micro-conversion perspective, this paper presents the Thank You Page as a valuable yet still untapped micro-conversion site which helps improve trust, persuade consumers, and result in follow-through engagement and further engagement after a lead. The observations show that the structural and behavioral inconsistencies in post-lead responses have a direct and profound impact on the effectiveness of the conversion with the consequence that often the customer progression provides little gain. This study contributes to theory through the intersection of conversion dynamics with customer journey models, and practical implications for maximizing organizational marketing ROI through structural improvements instead of higher expenditure.

Key words: conversion optimization, website structure, thank you page, customer journey, marketing analytics, micro-conversion, UX design, post-lead engagement, ROMI, PCEL framework.

Introduction. The digital marketing landscape has matured into complex and seamless mechanisms where the customer experience is made up of numerous connected touchpoints rather than a linear route. Traditional conversion models (e.g., funnel-based) perceive customer movement as a linear trajectory from awareness to purchase. The popular models are commonly used in practice, but are becoming less representative of fragmented, non-linear, and iterative digital interactions seen in contemporary digital engagement.

Recent studies have shown that the behavior of users follows no established path in digital mediums. Instead, they are shown to move dynamically between platforms, continue being exposed to information, and reassess their decision-making process [9; 17]. Thus, the conversion process cannot be construed as a single event but has to be viewed as the product of a processual sequence of behavioral interactions.

This lack of consistency is a challenge because while recent developments in customer journey mapping and the marketing analytics literature have paved the way for a deeper understanding of customer

experiences, these frameworks still fail to explain how specific user actions combine to lead to resulting conversions. Journey-based approaches focus on experience and interaction [2; 10], yet their structural details are often less precise. Conversely, funnel-based models are highly structured but do not encapsulate behavioral complexity. This enduring disunity suggests a key hole in marketing theory: it does not present a unified framework that connects behavioral dynamics with systematic design logic.

One aspect to this gap, which is largely unfathomable, is from the post-lead phase of the conversion strategy. Most popular models overlook the interaction that leads to conversion into paying customers and generally have a close-to-completion status for lead capture. But data reveals a large level of conversion loss that occurs post-lead generation, revealing structural deficiencies within post-lead engagement systems. One of the most important but often neglected aspects of the conversion process is our first, formal interaction after a lead gets received — the Thank You Page. Though key strategically, this is positioned as

a passive response interaction for confirmation, rather than functioning at the heart of the conversion process.

As there is a lack of consideration of micro-behavioral transitions in the lead-to-customer journey we see also this is a broader limitation in marketing theory. To cope with these limitations, the study develops the notion of Micro-Conversion Engineering, defined as the systematic design and optimisation of successive user actions leading to conversion. It is based on the Integrated Marketing Efficiency and Lifecycle Framework (IMELF) and looks at the conversion layer bringing together website architecture, post-lead decisions, and behavioral effects within an integrated analytics framework.

The aim of this research is to consider the impact of website structure and Thank You Page design on lead-to-customer conversion in a micro-conversion context. This approach departs from macro-conversion focus on conversion rates to a more nuanced view of marketing performance when it comes to digital interactions.

This research contributes in three main ways. First, it reconceptualizes conversion as a series of micro-level behavioral interactions rather than a single outcome. Second, it emphasizes the strategic value of website architecture as a behavioral system influencing both pre- and post-lead activity. Third, it reframes the Thank You Page from a transactional endpoint into a conversion acceleration node within the post-lead phase.

Literature Review

From Macro-Conversions to Micro-Conversion Processes

Conversion is often conceptualized as a discrete outcome in traditional marketing models, usually portrayed as the ultimate outcome in a funnel. While this may be useful for aggregated performance measurement, it does not explain the behavior that leads to conversion. Recent studies, however, question this assumption by focusing more on customer decisions made through incremental interactions rather than a single event.

In digital settings, user behavior is characterized by fragmentation, iteration, and non-linearity [9; 17]. Customers interact across multiple touchpoints, review information, and make ongoing decisions. Consequently, conversion should be understood as a processual phenomenon consisting of multiple components that, when observed, reflect changes in intention and engagement.

These elements can be called micro-conversions — intermediate user actions (such as content engagement, form submission, or interaction with post-click elements) leading to the final conversion. Thanks to the advent of marketing analytics, these behaviors can now be followed at finer points [1; 5].

However, despite the availability of detailed behavioral data, current models often lack the structural

perspective needed to systematically explain these actions. Such disparity underscores the importance of moving away from outcome-based measurement towards a process-oriented analysis that model's conversion as a sequence of interconnected behavioral events. From this point of view, we see the Conversion Layer of the IMELF (Integrated Marketing Efficiency and Lifecycle Framework), which focuses on the mechanisms that transform leads into customers.

Website Structure as a Behavioral Architecture

The main context of digital interactions and relationships — the website — serves not simply as a repository of information but also as a behavioral structure that guides user behavior. The design, navigation, and informational structure of websites are known to play prominent roles in user engagement, the development of trust, and decision-making processes [3; 10].

Structurally, website architecture provides a framework that guides the sequence and accessibility of information through predetermined paths [12]. However, it is well established that users rarely follow these intended paths as designed, even though some studies suggest that a limited number of users may still proceed linearly. Instead, users move dynamically between elements depending on their personal goals, needs, context, and perceived relevance [2; 6].

This discrepancy between the created paths and the embodied behavior will result in a structural tension in the conversion process. Whereas firms wish to streamline navigation for maximum system performance, users desire the flexibility and freedom [11]. Consequently, poorly constructed sites introduce friction, create additional cognitive burden, and make it harder to move toward conversion [14].

Additionally, website design does not only create pre-lead interactions but set expectations that impact behavior afterward as well, including responses post-lead. As a result, website architecture is treated as an essential part of the conversion system that underpins the IMELF framework; it is the foundational construction which both prompts user interaction and also organizes behavioral responses at each stage of the interaction process.

Post-Lead Interaction and the Role of Thank You Pages

Although much of the literature has focused on pre-conversion stages, the post-lead phase has received relatively limited attention in marketing studies. In conventional models, lead capture is generally treated as an “end,” or a successful outcome. However, empirical evidence suggests that many leads do not convert into customers, indicating the presence of significant issues in the post-lead process [14].

The Thank You page is the first controlled user interaction in this stage, usually shown soon after form submission or lead capture. So, while it plays a critical role strategically, it often remains underused, serving just as a confirmation page rather than an

active element of conversion. The Thank You Page is a transition between two stages — a bridge in which users pay heightened attention and intent.

Users at this point are especially receptive to guidance, reinforcement, and additional value propositions. As a result, the structure and content of this page can have a profound impact on subsequent actions including further engagement, trust-building, and progression toward purchase.

However, a systematic framework for analyzing post-lead interactions remains underdeveloped. While customer experience literature emphasizes the importance of continuity across touchpoints [2; 16], it does not sufficiently account for the structural role of post-lead elements such as the Thank You Page.

Within the IMELF Conversion Layer, the Thank You Page is conceptualized as a conversion acceleration node. Depending on its alignment with user expectations and overall system design, it can either facilitate progression toward conversion or contribute to behavioral drop-off.

Conversion Discontinuities in Lead-to-Customer Transition

The step from lead to customer is a critical, if also vulnerable, stage in the marketing process. Even when you are able to acquire leads successfully, many consumers leave before they have made a purchase, creating considerable conversion failures [11]. This phenomenon illustrates the existence of conversion discontinuities which are described as areas where the advancement of users is interrupted when the system's architecture does not match user behaviors.

Such discontinuities can be caused by multiple sources such as unclear next steps, lack of reinforced trust, insufficient value communication, inconsistency from one touchpoint to another and so on in their entirety. This has its own limitations: fragmentation between platforms and interactions in omnichannel environments makes things worse [4; 8].

Marketing analytics has tools to reveal patterns of drop-off and engagement [7; 13], yet they often fail to explain how such patterns emerge. By this mechanism it is difficult to understand why these phenomena occur. Without a set of tools that connect behavioral data to system design, an organization can simply treat symptoms, rather than root causes [12].

Conversion discontinuities point out the need to consider micro interactions in the context of the marketing system more generally. Specific friction and drop-off should be singled out to identify areas for targeted intervention or optimization.

Methodology

Research Design

The framework of this research is conceptual and theory-building research; which will help in systematic structure of micro-conversion process and how it plays a role in a digital marketing environment. The study builds on a rigorous synthesis of contemporary

literature on customer journey mapping, digital marketing systems, marketing analytics, and conversion behavior.

By doing this it is also possible to locate deficiencies in the conceptualization and operationalization of post-lead interactions within existing marketing models. Rather than relying on primary empirical data collection, the study adopts analytical conceptualization, which provides an opportunity for the formal development of a framework integrating behavioral, structural, and process-oriented perspectives on conversion.

IMELF and the Conversion Layer

This study uses the Integrated Marketing Efficiency and Lifecycle Framework (IMELF), which was formulated by the author as several layers for understanding marketing activity. IMELF encompasses a structural, an efficiency, and a lifecycle perspective, whereas the current research focuses on the Conversion Layer that manages how leads evolve into customers.

Conversion in this layer is not a discrete event — rather, it is a combination of micro-conversions, the smaller tasks which, all of themselves cumulatively, result in the final purchase. These micro-conversions are interactions such as form submission, content engagement, trust validation, and post-lead responses.

This layer also studies two main structural components:

- Website architecture — the medium where the pre- and post-lead traffic takes place in an environment;
- Thank You Page mechanisms, the first structured interaction post lead capture and a critical point for influencing subsequent customer behavior.

These components are combined into one, cohesive conceptual model, the Post-Lead Conversion System (PLCS), and cover the stage that leads to the closing of lead acquisition to customer conversion.

Analytical Model: Micro-Conversion Flow

An analysis is conducted that is informed by the micro-conversion flow model mapping out the user's flow from discovery to conversion through a set of behavioral patterns. Within this model:

- Pre-lead interaction logic (pre-lead user expectation and intent formation), website structure;
- The Thank You Page acts as a behavioral redirection node, affecting immediate post-lead actions;
- Follow-up interactions (e.g., follow-up engagement, trust reinforcement) ascertain the likelihood of conversion.

A major analytical consideration is a shift in attention to determine conversion discontinuities, where user engagement weakens or breaks as a result of the misalignment between system design and users' expectations (See Figure 1; Table 1).

Analytical Procedure

The study uses a behavioral-structural alignment analysis, containing:

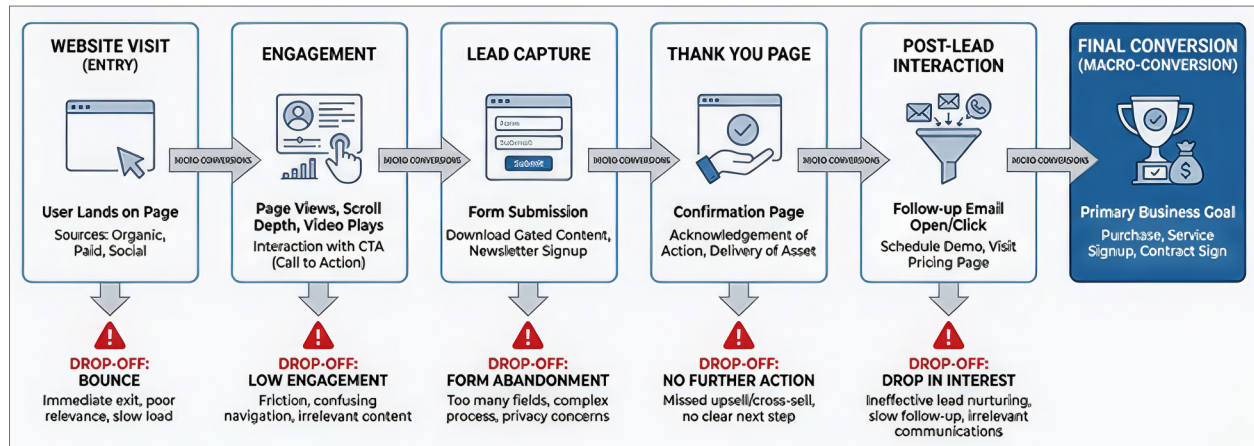


Fig. 1. Micro-Conversion Flow

Table 1

IMELF Conversion Layer Components

Component	Role in Conversion Layer
Website Structure	Shapes pre-lead behavior
Micro-Conversions	Define behavioral progression
Thank You Page	Post-lead transition node
PLCS	Integrates full conversion process
Conversion Discontinuities	Identify inefficiencies

1. Breakdown of the conversion process into micro-conversion stages;
2. A mapping of user interaction points within website and post-lead environments;
3. Recognition of behavioral drop-off patterns associated with specific structural elements;
4. Realizing where conversion inefficiencies exist, particularly in post-lead stages. Here we are able to discover micro-level inefficiencies which traditional funnel measures do not capture but whose effectiveness greatly affect your overall conversion performance.

Research Results

Decomposition of the Conversion Process into Micro-Conversions

It can be seen quite clearly in the analysis that there is no single conversion event which can explain the lead to customer transition. In truth, it is best

conceptualized as an array of micro-conversions, each individual point of activity representing a discrete behavioral step that contributes to the overall progression toward purchase.

Many micro-conversions can be reached by means of pre-lead and post-lead interactions such as content engagement, form submission, confirmation acknowledgment, and subsequent interaction with post-lead elements.

Notably, this suggests that while organizations largely streamline their pre-lead interactions, their post-lead stages remain structurally underdeveloped. There is thus an imbalance that causes a less than optimal conversion process wherein the initial engagement is captured reasonably well but the development towards the purchase is weakly supported.

Such fragmentation indicates a lack of continuity in the Post-Lead Conversion System (PLCS) within the IMELF Conversion Layer (See Table 2).

Table 2

Micro-Conversion Stages

Stage	Micro-Conversion Action	User Intent	Risk Factor
Website Entry	Page visit	Exploration	Low relevance
Engagement	Content interaction	Information evaluation	Cognitive overload
Lead Capture	Form submission	Initial commitment	Trust concerns
Thank You Page	Confirmation + next step	Expectation of guidance	Lack of direction
Post-Lead Interaction	Follow-up engagement	Validation	Loss of interest
Final Conversion	Purchase / agreement	Decision finalization	Competing alternatives

Website Structure as a Determinant of Pre-Lead Behavioral Alignment

Results reinforce the need for the architecture of the website to set the path of behavior for the users before leading them. A number of factors, including navigation layout, information hierarchy, and interaction semantics, jointly influence how readers perceive the offers on offer and support intentions formation.

Yet, a repeated pattern arises that the design of navigation paths does not match the behavior of users that makes the navigation paths. Users frequently deviate from the intended flows of content, return to old pages, and only interact with content to a limited extent depending on how pertinent they think it is. This misfit generates cognitive friction and decreases the effectiveness of micro-conversion sequences.

At the same time, a lot of pre-lead activity sets expectations, something that builds on during and beyond the post-lead phase. Users mostly cancel out when those expectations are not met post lead capture. Because this discovery clarifies that website design shouldn't be considered a self-contained component, but a continuity mechanism across the whole conversion lifecycle.

The Thank You Page as a Conversion Acceleration Node

These results reemphasize that the structure of the website needs to guide users towards the way of behavior first, and steer them before leading them. A number of factors such as the design of navigation, information hierarchy and the semantics of interactions combine to shape readers' perceptions of the presented offers, and the formation of support intentions.

Yet, a frequent trend emerges that the interface design of navigation paths does not fit the behavior of the users that shapes the navigation paths. Users often stray off the path users originally intended by these types of flows of content, return to old pages and only engage with content to some degree depending on how relevant they believe it is. This misfit leads to cognitive friction and undermines the efficacy of micro-conversion sequences.

At the same time, there is a heavy proclivity for pre-lead activity to establish expectations — something that is taken up during and beyond the post-lead phase. Customers mostly cancel out when those expectations are not met after lead capture. This discovery makes it obvious that website design is not a solo thing but a continuity mechanism across the whole conversion lifecycle.

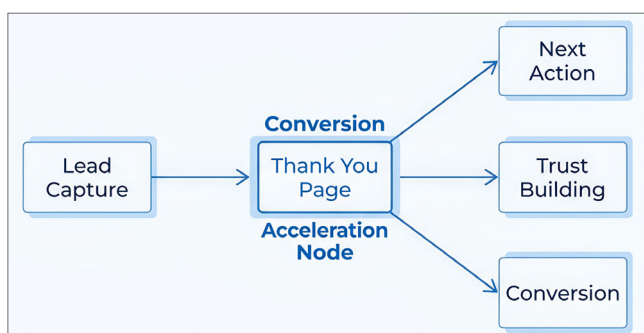


Fig. 2. Thank You Page as Conversion Node

This is categorized under conversion discontinuity in the IMELF framework, and this discontinuity occurs at the transition from lead capture to post-lead engagement.

Identification of Conversion Discontinuities in the Post-Lead Phase

This particular analysis identified various types of conversion discontinuities in the lead-to-customer transition. Such discontinuities include breaks in the micro-conversion flow, where user progression is interrupted due to structural misalignment. There are three major types of discontinuities (See Table 3):

- Directional discontinuity, where users receive no future guidance after lead capture as to what to do next;
- Informational discontinuity, failure to reinforce or expand the value proposition in the post-lead phase;
- Experiential discontinuity: the tone, design, or logic of the interaction suddenly changes meaningfully, which diminishes perceived coherence.

Without cohesive post-lead design strategies, these discontinuities are particularly acute. Thus, the conversion process becomes fragmented, with each stage operating independently rather than integrated into one continuous whole.

Structural Integration within the Post-Lead Conversion System (PLCS)

The result indicates that for proper conversion effectiveness, a system which amalgamates pre-lead and post-lead interaction is needed.

The proposed Post-Lead Conversion System (PLCS) attempts to solve this problem by considering the conversion process in the form of a continuous sequence of micro-conversions, rather than discrete stages.

In this system the Thank You Page is the centre, the core of all transactions, linking lead capture to subsequent engagement. When structured correctly,

Table 3

Types of Conversion Discontinuities

Type	Description	Example	Impact
Directional	No clear next step	Static Thank You Page	User drop-off
Informational	Weak value reinforcement	No additional offer	Reduced motivation
Experiential	Inconsistent interaction	Different tone/design	Loss of trust

it may help to maintain continuity, reinforce the value, and guide users toward further interaction.

In the absence of such integration, traditional conversion metrics fail to capture inefficiencies. By contrast, the PLCS is the mechanism for identifying and addressing micro-level inefficiencies, thereby improving overall conversion performance.

Discussion

Reframing Conversion in Light of Existing Research

The results of this research reinforce and extend previous ones providing alternative interpretations of conversion that is linear or outcome-driven. According to research that highlights the non-linearity of customer behavior [9; 17], the findings indicate that conversion can be conceptualised through a processual sequence of micro-conversions rather than a single event.

Although previous studies have mainly centered on customer journeys in this area [2; 10], the current study expands on this idea by creating a structural and behavioral integration within the IMELF Conversion Layer. More specifically, it moves beyond descriptive mapping toward mechanistic explanation, identifying how individual interactions can either contribute to or disrupt conversion outcomes.

Website Structure and Behavioral Alignment

This result related to website architecture supports prior research that emphasized the importance of digital environments in shaping user behavior [3]. In line with customer journey literature, users exhibit non-linear navigation patterns and selective engagement [6].

However, by showing that misalignment between intended pathways and actual behavior results in quantifiable inefficiencies at the micro-conversion level, this study expands on what is already known. Although previous research recognizes that user behavior varies, it does not completely understand the structural implications of this variability. By connecting behavioral deviance to conversion discontinuities, the current findings close this gap and offer a more useful analytical framework.

The Under-Theorized Role of Post-Lead Interactions

One of the primary contributions of this study is filling a gap in the literature concerning post-lead interactions. Although existing research on customer experience addresses continuity across touchpoints [15; 16], it does not explicitly explore the structural role of interfaces like Thank You Pages.

The paper's results imply a key transition node in the Thank You Page that both corroborates and extends the premise of a sequential customer experience, rather than an isolated interaction. However, in contrast to previous research, this research locates the Thank You Page as an active conversion mechanism rather than a passive confirmatory element (See Figure 3; Table 4).

This reinterpretation adds to the body of knowledge by exposing under-explored dimensions of the conversion process and illustrating its influence on user behavior.

Conversion Discontinuities and System Fragmentation

The identification of conversion discontinuities aligns with research on fragmentation in omnichannel systems [4; 8]. Similar to these studies, the findings highlight the challenges associated with integrating multiple touchpoints into a coherent system.

The current study, however, expands on this line of inquiry by presenting a micro-level viewpoint and demonstrating that fragmentation appears both within individual interaction sequences and at the channel level.

Conversion discontinuities, then, are the behavioral manifestation of structural misalignment in digital systems. This viewpoint offers a conceptual framework for analyzing observed drop-off and engagement patterns, which enhances marketing analytics research [5; 7].

Theoretical Implications for IMELF

Thus, the research extends the Conversion Layer of the Integrated Marketing Efficiency and Lifecycle

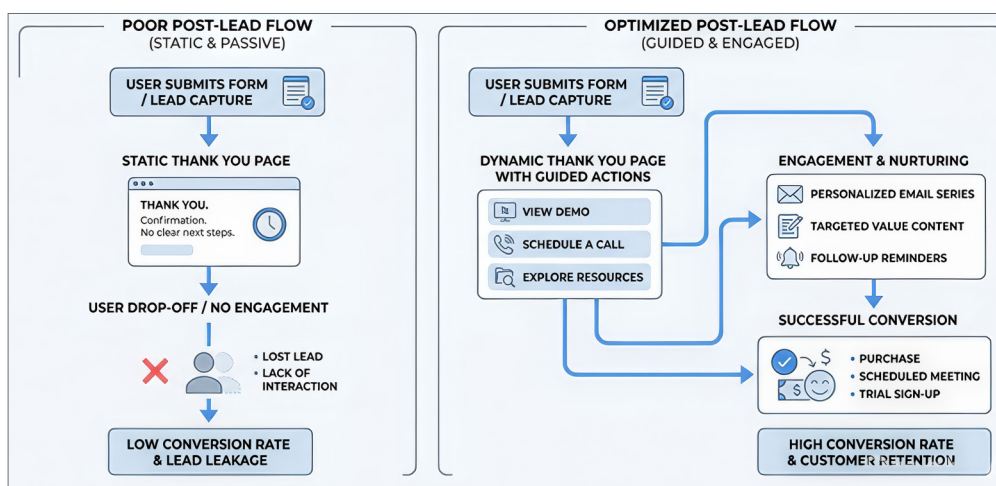


Fig. 3. Poor vs Optimized Post-Lead Flow

Table 4

Thank You Page Optimization Elements

Element	Function	Expected Effect
Clear Next Step	Guides user action	Reduces uncertainty
Value Reinforcement	Confirms decision	Increases trust
Engagement Trigger	Encourages further interaction	Extends session
Personalization	Aligns with user expectations	Improves relevance

Framework (IMELF). Whereas the existing literature tackles structural and experiential aspects of marketing systems, this study offers a behavioral-process dimension that bridges system design with user action.

In addition to providing a more operationalized model and analytical framework for IMELF, the methodology formalizes ideas like conversion discontinuities, micro-conversions, and the Post-Lead Conversion System (PLCS). This closes the gap between process-oriented marketing structures and descriptive customer journey models seen in the literature.

Conclusions. This study makes an important contribution by identifying micro-conversions as important analytical units to provide a more fine-grained view of how user actions build into conversion outcomes. Website structure is evident to operate as a behavioral architecture in this respect as a behavioral structure of both pre-lead interactions and post-lead expectations.

The study also highlights the vital importance of the post-lead period, which is underdeveloped in both theory and practice. In particular, the Thank You Page is repositioned as a node that accelerates conversions

and can influence user behavior at a crucial point in the contact sequence. In addition to conversion breakdowns, a poor design approach during this stage might result in a significant decline in potential clients.

To overcome these obstacles, the study introduces the concept of Micro-Conversion Engineering, implemented as part of the Conversion Layer of the Integrated Marketing Efficiency and Lifecycle Framework (IMELF).

It takes a long-term, detailed analysis of conversion processes at the micro level, linking behavioral data with system design and improving it, and finally, presents a systematic method for improving this approach to conversion work that integrates both aspects.

The study contributes to the body of literature by offering a process-oriented and structurally grounded perspective on conversion. This perspective has theoretical significance and helps to operationalize and increase marketing effectiveness in the digital space.

Empirical tests of the framework should be conducted in future work to establish the applicability of the model across new and larger industries as well as different platforms.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

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ІСТОРИЧНІ НАУКИ

ІСТОРИЧНІ ДЖЕРЕЛА У ФОРМУВАННІ ГРОМАДЯНСЬКОЇ КОМПЕТЕНТНОСТІ СТУДЕНТІВ

HISTORICAL SOURCES IN THE FORMATION OF STUDENTS' CIVIC COMPETENCE

Анотація. У статті проаналізовано роль історичних джерел у процесі формування громадянської компетентності студентської молоді. Визначено освітній та виховний потенціал історичних документів. Обґрунтовано, що робота з першоджерелами розвиває критичне мислення, вміння протидіяти маніпуляціям та формує свідому громадянську позицію. Запропоновано дієві методи інтеграції джерельного матеріалу в освітній процес.

Ключові слова: історичне джерело, компетентність, програма політичної партії.

Summary. The article analyzes the role of historical sources in the process of forming civic competence of students. The educational potential of historical documents is determined. It is substantiated that working with primary sources develops critical thinking, the ability to counteract manipulation, and forms a conscious civic position. Effective methods of integrating source material into the educational process are proposed.

Key words: historical source, competence, political party program.

Практична потреба у підвищенні якості гуманітарної підготовки студентів зумовлює пошук дієвих засобів розвитку їхньої громадянської свідомості. Провідна роль у цьому процесі належить системній роботі з історичними джерелами в межах особистісно орієнтованого навчання. Впровадження комплексної методичної системи, на відміну від розрізнених засобів, забезпечує глибоке засвоєння знань, вдосконалює дослідницькі навички та трансформує теоретичні здобутки у стійкі громадянські компетентності.

В. Молоткіна, О. Тарапон зазначають доцільність побудови освітнього процесу на уроках історії відповідно до принципів багатоаспектного, систематичного та цілеспрямованого використання історичних документів. Дослідниці переконують, що такий формат роботи «сприяє підвищенню мотивації до навчання, створює можливості для самостійного

процесу навчання, розширює можливості діалогу в освітньому процесі, формує дослідницькі вміння та навички» [1, с. 109].

П. Мороз, І. Мороз вказують, що робота з історичними джерелами на уроках історії має носити системний характер, при цьому поступово ускладнюючи як самі джерела, так і завдання до них. Завдання мають розроблятися на основі дослідницького та диференційованого підходів до навчання, мати різнорівневий характер з їх поступовим ускладненням [2, с. 151].

Ми погоджуємось з Т. Ковбасюк, що «історичний документ стане для учнів невичерпним джерелом потрібних знань лише за умови, якщо його використовувати в процесі навчання не у формальному інформаційно-цитатному плані, а шляхом безпосередньої творчо-пошукової роботи учнів над текстом» [3, с. 126].

Розглядаючи використання візуальних джерел на уроках історії, В. Молоткіна, Л. Хмельницька констатують: на сучасному етапі мета використання візуальних джерел змінилася. Якщо раніше вони слугували доповненням і закріпленням тексту параграфу підручника, то тепер учні повинні навчитися самостійно отримувати з них інформацію. Адже візуальні джерела можуть передавати інформацію так само, як і текстові, але вони зрозуміліші, виразніші та легші для сприйняття [4, с. 232]. Ефективна робота з історичними джерелами забезпечує реалізацію діяльнісного і компетентнісного підходів, які є одними з провідних (поряд з особистісно орієнтованим та аксіологічним) у сучасному освітньому процесі [5, с. 45–46].

Т. Ткаченко, Т. Соловйова, О. Ткаченко зауважують, що високу результативність має використання методу порівняльного аналізу різних історичних джерел. Цей метод передбачає роботу учнів і студентів із кількома джерелами, що відтворюють відмінні погляди на одну подію. Це допомагає виявити розбіжності у трактуванні минулого та дозволяє здобувачам освіти передусім аналізувати інформацію, а не просто сприймати її. Така діяльність сприяє усвідомленню складності і багатогранності історичних процесів, з'ясуванню достовірності змісту документів, формуванню власної думки [6, с. 110]. У підсумку маємо активізацію пізнавальної діяльності, підвищення внутрішньої, соціальної та ціннісно-сислової мотивації здобувачів освіти на заняттях історії.

У межах викладання історичних дисциплін залучаємо студентів до критичного аналізу програм політичних партій. Такий формат роботи не лише поглиблює знання про генезу українського багатопартійного дискурсу початку ХХ ст., а й виступає ефективним інструментом розвитку громадянської компетентності. Він дозволяє здобувачам вищої освіти осмислити тогочасний суспільно-політичний контекст та усвідомити історичну роль молоді у процесах державотворення.

У вступі наголошуємо на тому, що на початку ХХ ст. розвиток національно-політичного руху потребував принципово нових організацій, які були б в змозі задовольнити не тільки культурні, а й суспільно-політичні запити українського населення. Такими організаціями стали національні політичні партії. Виникнення українських партій у Наддніпрянщині на рубежі ХІХ–ХХ ст. було зумовлене ширшим включенням до національного руху радикально налаштованої молоді, її подальшою політизацією, утворенням і діяльністю політичних партій у західноукраїнських землях. Далі студенти діляться на групи і приступають до опрацювання програмних документів, застосовуючи алгоритм. Додатковим фокусом дослідження виступає специфіка репрезентації інтересів молоді у програмах вітчизняних політичних партій.

Після кожна група презентує власні нароби. Політичним маніфестом першої у Наддніпрянській

Україні Революційної української партії (РУП, 1900 р.) стала написана за її проханням М. Міхновським і видана у Львові «Самостійна Україна». Цю брошуру навряд чи можна назвати системним та послідовним викладом завдань організації. Перспективи розвитку майбутньої Української держави, питання внутрішньополітичного та соціально-економічного устрою у цій програмі не розглядалися. По суті, цією брошурою молодь задекларувала виникнення в українському національному русі радикального напрямку.

Відносно становища молоді М. Міхновський радше розставляє акценти у стосунках між старшим поколінням українофілів та молодією генерацією: «покоління з так званого українофільського табору своєю бездієвістю, своєю надзвичайною інертністю відіпхнули від себе цілий ряд рухів молоді, що стояла на українсько-національному ґрунті» [7, с. 17]. Автор «Самостійної України» наголошує, що між молодією Україною й українофілами немає ніяких зв'язків: «Через свою тактику й політику українофіли лишилися без потомства, і сучасна молода Україна вважає себе безпосереднім спадкоємцем Шевченка, а її традиції йдуть до Мазепи, Хмельницького та короля Данила минаючи українофілів» [7, с. 17].

На Правобережній Україні майже одночасно з РУП у 1900 р. була створена Українська соціалістична партія (УСП), яка у своїй діяльності орієнтувалася на Польську соціалістичну партію (ППС). У серпні 1900 р. був розроблений «Нарис програми української партії соціалістичної». У червні–грудні 1903 р. УСП об'єдналася з РУП. Згодом, після короткочасного самостійного існування, на початку 1904 р. більшість членів УСП вступили до лав Польської соціалістичної партії.

Восени 1902 р. націонал-демократична частина РУП заснувала Українську народну партію (УНП). Ідеолог партії — М. Міхновський написав програму, що вийшла друком у Чернівцях у 1906 р.

У жовтні 1904 р. на з'їзді Всеукраїнської загальної безпартійної демократичної організації (БЗБДО) було проголошено заснування Української демократичної партії (УДП), яка мала стати загальнонаціональним об'єднанням без класових відмінностей [8, с. 189]. У практичній діяльності партія не йшла далі звернень до царського уряду з проханням здійснити незначні реформи й забезпечити українцям рівні з росіянами права. У березні 1905 р. на партійному з'їзді було схвалено програму УДП.

Українська радикальна партія (УРП) була створена після виходу зі складу Української демократичної партії радикальної частини її членів. Цілі та напрямки своєї діяльності радикали викладали в «Платформі Української радикальної партії».

Революційні події 1905 р., а також слабкість матеріальної бази призвели наприкінці зазначеного року до об'єднання УРП та УДП в Українську радикально-демократичну партію (УРДП).

До другого з'їзду Революційної Української Партії в грудні 1905 р. Центральний комітет підготував проєкт нової програми. Вона не була прийнята через розкол цієї організації, але становить певний теоретичний інтерес. Тоді ж шляхом перейменування РУП виникла Українська соціал-демократична робітничка партія (УСДРП) та була прийнята «Програма Української Соціал-Демократичної Партії».

Прагнучи привернути на свій бік різні верстви населення, використати їхню силу для здійснення своїх партійних вимог, новостворені партії у програмових документах намагалися охопити всі аспекти суспільного життя: економічний, політичний, культурний. Робилися спроби вирішити аграрне, соціальне та національне питання. Неабияке значення у своїх програмах партії відводили проблемам молоді.

Так, у соціальній сфері програми Революційної української партії, Української радикально-демократичної партії, Української народної партії, Української соціал-демократичної робітничої партії наголошували на повній забороні праці дітей до шістнадцяти років [9, с. 40, 49, 92, 97]. У своїх партійних документах РУП, УНП, УРП, УРДП та УСДРП вимагали для підлітків від шістнадцяти до вісімнадцяти років максимального 6-годинного робочого дня. Крім того, РУП, УНП та УСДРП виступали за заборону нічної праці для дітей-підлітків [9, с. 40, 49, 97]. У програмах Народної та Соціал-демократичної робітничої партій наголошувалося на необхідності створення на фабриках і заводах дитячих притулків, де б робітниці могли безпечно залишити своїх дітей.

Усі задекларовані політичні перетворення носили характер загальногромадянських прав, опосередковано відповідаючи й прагненням молоді у цій сфері. За загальне, рівне, безпосереднє виборче право з таємним голосуванням для кожного громадянина старше двадцяти років, без різниці статі виступали РУП та УСДРП [9, с. 41, 98]. Українська радикальна та об'єднана радикально-демократична партія вимагали для кожного громадянина двадцяти одного року, без різниці статі, віри і національності, права обирати та бути обраним. Вимоги демократичних свобод слова, совісті, друку, страйків, зборів і спілок були зазначені у політичних програмах РУП, УСП, УНП, УДП, УРП, УРДП та УСДРП [9, с. 41, 44, 58, 80, 83]. Українська радикально-демократична партія проголошувала рівні для всіх громадянські права й повинності та скасування привілеїв усіх класів, станів, статі, віри й нації [9, с. 89]. Партійний документ Української соціал-демократичної робітничої партії наголошував також на необхідності надання кожній нації права на культурне і політичне самовизначення [9, с. 98].

Програмовий документ кожної української політичної партії початку ХХ ст. містив широкий спектр культурно-освітніх вимог. Виступали за право отримувати обов'язкову, безплатну, загальну освіту

дітям до шістнадцяти років Революційна, Соціалістична, Радикальна, Соціал-демократична робітничка українські партії [9, с. 41, 44, 85, 98]. Радикальна партія декларувала «надання молоді, що має хист до науки, на період навчання у вищих навчальних закладах безплатної освіти та при потребі засобів до життя з крайових або громадських коштів» [9, с. 86]. Окремим пунктом програм РУП, УСП та УРП оговорювалося державне забезпечення учнів підручниками, одягом, їжею [9, с. 41, 44, 85]. Революційна українська партія, її наступниця Соціал-демократична робітничка партія, Народна та Радикально-демократична партія обов'язковим вважали створення відповідної кількості шкіл для кожної нації [9, с. 41, 98, 67, 90].

Програмовий документ Радикальної партії підпорядковував початкову, середню та вищу освіту Народній Раді, окружним сеймам і громаді [9, с. 85–86]. УСДРП виступала за передання всієї народної освіти в Україні до відомства Українського Сейму [9, с. 98]. Об'єднана радикально-демократична партія наголошувала на потребі розробити шкільні програми таким чином, щоб молодь переходила до наступної освітньої ланки без спеціального екзамєну [9, с. 90–91]. Автономія вищих навчальних закладів проголошувалася у документах УДРП та УНП [9, с. 69, 91].

Національні політичні партії по-різному вирішували мовне питання. Революційна українська та Соціал-демократична робітничка партії виступали за рівноправність усіх мов у громадських, державних та освітніх інституціях [9, с. 40, 97]. Демократична партія вимагала введення народної мови на всіх рівнях суспільного життя [9, с. 81]. Програми радикальної й радикально-демократичної партій наголошували на необхідності впровадження в освітніх та урядових установах української мови [9, с. 86, 91].

На відміну від інших партій програмовий документ Української народної партії мав досить докладну розробку молодіжного питання. У соціально-економічній сфері, крім вищезазначених вимог, заборонялася праця підлітків на шкідливих для здоров'я виробництвах [9, с. 49]. Серед політичних вимог проголошувалася свобода національності, свобода українського слова і друку [9, с. 58]. У культурно-освітньому напрямку декларувалося: підпорядкування освітніх установ усіх рівнів в Україні українському народу; відокремлення школи від державної влади та передання її у розпорядження територіальних громад; заборона втручання уряду до внутрішнього життя українських шкіл; утримання шкіл в Україні за рахунок українського парламенту із використанням додаткових громадських коштів; а також відмова від примусової загальної освіти, поки «школа буде в руках уряду чужого народу». Освітньою справою в Україні, за задумом Української народної партії, мала завідувати незалежна від уряду Шкільна Рада, обрана таємним, рівним,

безпосереднім і загальним голосуванням. Окрім головної Шкільної Ради, на місцях мали діяти місцеві шкільні ради [9, с. 67–69].

Підбиваючи підсумки аналізу програмових документів українських політичних партій початку XX ст. студенти визначають наступне. Національні партії надавали певну увагу проблемам дітей та молоді, прагнули вирішення нагальних молодіжних питань. Насамперед, вони декларували необхідність змін щодо полегшення умов праці на виробництві, створення можливості для отримання молоддю початкової, середньої та вищої освіти, надання молоді права брати участь в управлінні державою. Крім того, в результаті проведеної роботи здобувачі вищої освіти роблять такий вагомий висновок: у віковому складі українських політичних партій початку XX ст. абсолютно домінувала молодь — переважно люди віком від 17 до 30 років. Український партійно-політичний рух цього періоду мав виразне «студентське обличчя», що суттєво відрізняло його від європейських консервативних партій.

Таким чином, робота з історичними джерелами навчає студентів самостійно здобувати знання, аналізувати інформацію та висловлювати власну думку. Це сприяє розвитку дослідницьких компетентностей, які є важливими не лише у вивченні історії та громадянської освіти, але й для успішної самореалізації в будь-якій сфері діяльності. Робота з історичними джерелами створює сприятливі умови для практичного застосування творчих завдань через партнерство здобувачів освіти та викладача.

Використання історичних джерел є фундаментальним інструментом у процесі формування громадянської компетентності студентської молоді. Аналіз нормативних актів, мемуарів, усних джерел, артефактів тощо дозволяє здобувачам освіти не просто засвоювати готові знання, а самостійно аналізувати минуле, розвивати критичне мислення та протидіяти маніпуляціям. Робота з першоджерелами сприяє глибокому розумінню причинно-наслідкових зв'язків в історії, формуванню національної ідентичності, патріотизму та свідомої громадянської позиції.

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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ІНВЕНТАРНА РЕФОРМА ТА СОЦІАЛЬНОЕКОНОМІЧНА ТРАНСФОРМАЦІЯ ДЕРАЖНЯНСЬКОГО ЕЛЮЧА (1845–1851 РР.): СПРОБА МІКРОІСТОРИЧНОЇ РЕКОНСТРУКЦІЇ

LAND REFORM AND SOCIO-ECONOMIC TRANSFORMATION IN DERAZHNYANSKOYE (1845–1851): AN ATTEMPT AT A MICROHISTORICAL RECONSTRUCTION

Анотація. У статті здійснено мікроісторичну реконструкцію впливу інвентарної реформи 1847–1848 рр. на соціально-економічну трансформацію Деражнянського ключа Летичівського повіту Подільської губернії в 1845–1851 рр. На основі інвентарних книг, камеральних описів, статистичних матеріалів та судових справ проаналізовано географічний і власницький статус маєтку, структуру земельного фонду, систему селянських повинностей, внутрішню соціальну стратифікацію селянської громади та співвідношення поміщицького й селянського землекористування. Показано, що інвентарна реформа, покликана уніфікувати розміри нагів і повинностей поміщицьких селян, фактично легалізувала вже існуючу асиметрію на користь фільваркового господарства та консервацію кріпосницьких відносин. Особливу увагу приділено порівнянню інвентарної моделі Деражні з казенним селом Кальня та шляхетським анклавом Попівці, що дозволило виявити специфіку магнатського ключа як напівіндустріального комплексу з багатовимірною експлуатацією селянської праці. Доведено, що поєднання жорсткої інвентарної регламентації, просторової чересполосиці, монополії на лісові й сінокісні угіддя та розгалуженої системи прихованих повинностей сформувало вибухонебезпечний комплекс соціальних суперечностей, який у пореформений період матеріалізувався в масових земельних конфліктах і судових протистояннях.

Ключові слова: інвентарна реформа, інвентарні правила, Деражнянський ключ, Подільська губернія, магнатський фільварок, селянські нагілі, панщина, соціальна стратифікація, мікроісторія.

Summary. The article offers a microhistorical reconstruction of the impact of the 1847–1848 inventory reform on the socio-economic transformation of the Derazhnia estate complex (key) in the Letychiv county of Podillia province between 1845 and 1851. Drawing on inventory books, cameral descriptions, statistical reports and court records, the study analyses the estate's geographical and ownership setting, the structure of the land fund, the system of peasant obligations, the internal social stratification of the rural community, and the balance between landlord and peasant land use. It shows that the inventory reform, officially designed to standardise peasant allotments and obligations, in practice legalised the existing asymmetry in favour of the manorial (folwark) economy and contributed to the conservation of serfdom in RightBank Ukraine. Special attention is paid to a comparison of Derazhnia's inventory model with the neighbouring state village of Kalnia and the petty noble enclave of Popivtsi, which reveals the specificity of the magnate estate as a semiindustrial complex based on multidimensional exploitation of peasant labour. The article argues that the combination of strict inventory regulation, spatial stripfarming patterns, monopolisation of forests and meadows, and a dense network of hidden obligations generated an explosive set of social tensions that, in the postreform period, resulted in widespread land conflicts and legal disputes.

Key words: inventory reform, Inventory Rules, Derazhnia key, Podillia province, magnate folwark estate, peasant land allotments, corvée labour, social stratification, microhistory.

Наукова проблема статті полягає у встановленні характеру та наслідків інвентарної реформи для соціально-економічної трансформації Деражнянського ключа в 1845–1851 рр., а також у виявленні того, якою мірою інвентарна регламентація змінила або, навпаки, закріпила традиційні форми поміщицького землеволодіння, селянських повинностей і внутрішньої структури маєтку.

Методологічною основою дослідження стали принципи історизму, об'єктивності та системності, а також методи мікроісторичного, порівняльного, історико-генетичного, проблемно-хронологічного та структурно-функціонального аналізу, що дало змогу реконструювати соціально-економічну трансформацію Деражнянського ключа в контексті інвентарної реформи середини XIX ст.

Аналіз останніх досліджень і публікацій. Проблематика інвентарної реформи 1847–1848 рр. на Правобережній Україні вже привертала увагу дослідників, однак переважно в загальноімперському або регіональному вимірі, без детальної мікроісторичної реконструкції окремих маєткових комплексів. У працях та довідкових матеріалах наголошується, що інвентарні правила були спрямовані на уніфікацію селянських наділів і повинностей, але фактично сприяли консервації кріпосницьких відносин. Значну увагу в літературі приділено також селянським виступам, спричиненим упровадженням інвентарів, що засвідчує високу соціальну напругу в регіоні.

Водночас наявні праці здебільшого зосереджуються на загальних наслідках реформи, її нормативній базі та реакції селянства, тоді як локальні форми функціонування інвентарної системи в межах конкретних маєтків, механізми перерозподілу земельного фонду, внутрішня стратифікація селянства та інституційна організація маєткового управління залишаються недостатньо вивченими. Окремі дослідження з мікроісторії доводять продуктивність такого підходу для локальної історичної реконструкції, однак до проблеми Деражнянського ключа цей інструмент майже не застосовувався.

Метою статті є здійснення мікроісторичної реконструкції соціально-економічної трансформації Деражнянського ключа в 1845–1851 рр. під впливом інвентарної реформи та виявлення її реальних наслідків для структури землеволодіння, системи селянських повинностей і внутрішньої організації маєтку.

Виклад основного матеріалу дослідження. Деражнянський ключ у середині XIX століття являв собою цілісну адміністративно-господарську одиницю в межах Летичівського повіту Подільської губернії, економічний потенціал якої був детермінований як вигідним географічним розташуванням, так і тривалою історією формування приватновласницьких маєтків. Географічний каркас ключа формувалася навколо гідрологічної системи річки Вовк,

на обох берегах якої розкинулося містечко Деражня. Згідно з даними камерального та топографічного опису кінця XVIII — початку XIX століття, річка утворювала в межах населеного пункту просторий став завдяки наявності греблі, а з лівого боку в неї впадала безіменна притока.

Ландшафт характеризувався поєднанням лісових масивів з лівого боку та пологих косогорів з правого, що створювало сприятливі умови як для розвитку млинарства, так і для організації панських господарств [1, арк. 103–106 зв.]. Топонімічна спадщина регіону, зокрема наявність урочища «Завалля» із залишками валу та канави, свідчить про давню традицію фортифікації та оборонного значення цього поселення ще в період Речі Посполитої [9, с. 65–75].

Історична еволюція власницького статусу Деражні демонструє класичну для Правобережжя траєкторію переходу від королівських володінь до приватної магнатської власності. Перші документальні згадки про поселення датуються 1431 роком, коли воно перебувало у володінні польської шляхти (зокрема, роду Одровонжів), а з 1538 року, після викупу королевою Боною, Деражня отримала статус королівського міста, що згодом було підкріплено наданням магдебурзького права у 1614 році [11, с. 6–11]. Проте впродовж XVII–XVIII століть, внаслідок складних геополітичних процесів та зміни власників (від І. Виговського до А. Любомирського), поселення поступово втрачало міський статус, трансформуючись у приватновласницьке містечко. До моменту проведення інвентарної реформи 1847–1848 років Деражнянський ключ перебував у володінні впливового магнатського роду Рациборовських, які інтегрували містечко та прилеглі села (зокрема Кальню та Корицинці) в єдину економічну систему маєтку [13, с. 103–104].

Інвентарна реформа, ініційована імперською владою з метою обмеження свавілля поміщиків та фіксації розмірів селянських наділів і повинностей, стала першим кроком до систематизації землеволодіння в Деражнянському ключі. На момент складання інвентарних описів (1845–1851 рр.) економічний центр ключа був чітко структурований. Ядром маєтку виступав панський кам'яний двоповерховий будинок з відповідними господарськими службами, обведений кам'яною огорожею та палісадником, при якому функціонував плодovitий яблуневий сад [1, арк. 103–106 зв.]. Окрім того, інфраструктура ключа включала панську кам'яну пивоварню, що працювала на відкупі, та невеликий цегельний завод, який належав пану Красотському, що свідчить про диверсифікацію маєткового виробництва [13, с. 103–107].

Таким чином, напередодні скасування кріпацтва Деражнянський ключ репрезентував собою зрілий магнатський маєток з розвинутою внутрішньою інфраструктурою. Географічні переваги (наявність водних ресурсів для млинів та пивоварні, лісові угіддя) максимально експлуатувалися власниками для

отримання прибутку. Саме ця висока концентрація господарських об'єктів у руках приватного власника створювала об'єктивні передумови для гострих суперечок під час інвентаризації, оскільки імперська адміністрація намагалася чітко розмежувати «панську» землю та селянські наділи, обмежуючи тим самим економічну експансію економії за рахунок селянських угідь. Цей власницький та географічний базис став фундаментом, на якому в подальшому розгорталася складна соціально-економічна динаміка пореформеного періоду.

Інвентарна реформа 1847–1848 років на Правобережній Україні стала першою системною спробою імперської влади врегулювати земельні відносини та зафіксувати повинності селян на рівні державного законодавства. Для Деражнянського ключа, що перебував у володінні магнатського роду Радичевських, цей процес означав чітке юридичне розмежування «панської» (фільваркової) та «селянської» землі, що мало на меті унеможливити подальше свавільне скорочення селянських наділів [2, арк. 24]. Проте, як свідчить аналіз інвентарних описів, реформа фактично легалізувала вже існуючу структуру землеволодіння, де економія утримувала абсолютну більшість найродючіших та найбільш експлуатованих масивів.

Кількісний розподіл угідь у Деражнянському ключі чітко демонструє диспропорцію на користь фільварку. Згідно з інвентарними таблицями, ядром земельного фонду економії залишалися орні землі, які планувалося використовувати для вирощування товарного зерна. Окрему, критично важливу категорію панських угідь становили лісові масиви та сінокоси. Саме ліс і луки, які за правилами інвентарної реформи мали частково передаватися селянам для випасу худоби та заготівлі дров, фактично залишалися під жорстким контролем економії [2, арк. 5–12 зв.]. Така структура земельного фонду не була випадковою: утримуючи монополію на ліс та пасовища, поміщик штучно консервував економічну залежність селянського двору від панської економії, змушуючи селян відробляти додаткові дні панщини за право користування цими угіддями.

Селянські наділи в Деражнянському ключі формувалися за принципом тягловості, що відображало класичну структуру подільського села середини XIX століття. Інвентарні книги фіксують розподіл землі між «тяглими» селянами, які мали власних волів чи коней, та «пішими» (городниками). Для тяглих селян норма наділу зазвичай коливалася в межах від двох до трьох десятин орної землі на душу, тоді як піші отримували значно менші ділянки, часто непридатні для інтенсивного землеробства [2, арк. 8–19].

Історично земельні наділи на Правобережжі вимірювалися не площею, а часом, необхідним для їхнього обробітку (кількістю днів для оранки або кількістю косарів для збору сіна), проте інвентарна реформа 1847–1848 років остаточно закріпила

перехід на десятинну систему виміру, наближаючи її до загальноімперських стандартів [5, с. 144].

Формально інвентарна реформа мала на меті запобігти повному обезземеленню селянства, закріпивши мінімальні розміри наділів, необхідні для прожиття та виконання державних і поміщицьких повинностей. Проте аналіз інвентарних книг Деражнянського ключа свідчить, що адміністрація маетку майстерно використовувала лазівки в законодавстві. Зокрема, селянські наділи часто розташовувалися впереміш із панськими полями (чересполосиця), а найкращі ділянки ріллі, що межували з панським двором, залишалися у фільварку [2, арк. 9–18]. Така конфігурація земельного фонду унеможливлювала ефективне ведення власного господарства селянами та сприяла їхній інтеграції в орбіту панського виробництва.

Важливим аспектом структури земельного фонду була диспропорція у забезпеченні різними видами угідь. Якщо орна земля у певній, часто мінімальній кількості селянам належала, то пасовища (вигони) та лісові дачі майже повністю консолідувалися навколо панської економії. Це породжувало систему прихованих експлуатаційних механізмів: необхідність випасати худобу на панських луках або заготовляти дрова в панському лісі перетворювалося на додатковий інструмент тиску, який не завжди потрапляв у офіційні графі інвентарних таблиць як «панщина», але фактично збільшував час, відпрацьований селянином на користь поміщика [5, с. 145].

Таким чином, інвентарна реформа в Деражнянському ключі не створила рівноправної системи землеволодіння. Вона юридично закріпила домінування фільваркової системи, де селянські наділи виступали лише додатком до панського господарства, забезпечуючи його дешевою робочою силою. Ця структурна нерівність та штучне утримання селян у залежності від панських угідь заклали міну уповільненої дії, яка неминуче мала вибухнути масовими земельними конфліктами вже в пореформений період, коли питання доступу до лісу та сіножатей стало головним предметом судових та поземельних суперечок.

Інвентарна реформа 1847–1848 років на Правобережній Україні формально мала на меті встановити чіткі межі поміщицького свавілля, зафіксувавши розміри селянських наділів і відповідних повинностей у державних інвентарних книгах. Проте для селян Деражнянського ключа ці правила стали не стільки гарантією захисту, скільки юридичною фіксацією вже існуючої системи експлуатації. «Ціна» за отримані 2–3 десятини землі виявилася надмірно високою і складалася не лише з офіційно задекларованої панщини, а й з розгалуженої системи прихованих повинностей, які дозволяли економії максимізувати використання дешевої робочої сили [2, арк. 5–12].

Офіційна панщина в Деражнянському ключі, згідно з інвентарними правилами, зазвичай

становила два-три дні на тиждень для тяглих селян, які мали власний робочий інвентар. Проте цей норматив був лише базовим орієнтиром. У період найінтенсивніших сільськогосподарських робіт (від травня до вересня), особливо під час жнив та збирання цукрових буряків, економія вимагала від селян додаткових днів роботи, часто ігноруючи встановлені ліміти. Крім того, інвентарні описи фіксували обов'язок селян виконувати так звані «толоки» — колективні, часто неоплачувані роботи на користь маєтку під час критичних моментів сільськогосподарського циклу, таких як сінокосіння або обмолот зерна [5, с. 145].

Особливістю Деражнянського ключа була наявність розвинутої маєткової інфраструктури, що породжувало специфічні, непередбачені загальними правилами форми експлуатації. Наявність панської кам'яної пивоварні, цегельного заводу та водяних млинів змушувала економію залучати селян до промислових робіт. Селяни були зобов'язані виконувати підвідну повинність, доставляючи сировину до заводів або продукцію до ринків збуту, а також нести вартість утримання маєткової охорони. Нерідко адміністрація маєтку змушувала селян виконувати роботи в недільні та святкові дні або навіть відпрацьовувати повинності за місцевих священників, що грубо порушувало як інвентарні правила, так і канонічні норми [5, с. 146].

Для піших селян (городників), які не мали тяглової сили і отримували мізерні наділи, основним тягарем ставав чинш — грошовий або натуральний оброк. Хоча інвентарна реформа намагалася регламентувати розмір чиншу, на практиці економія часто довільно збільшувала його, вимагаючи від селян додаткової продукції (наприклад, пряжі, полотна або птиці) або грошових виплат за користування пасовищами та лісом, які формально вважалися панськими. Ця система створювала замкнене коло залежності: щоб сплатити чинш, селянин був змушений йти на заробітки до того ж поміщика, потрапляючи в боргову пастку ще до офіційного скасування кріпацтва [2, арк. 3–24 зв.].

Таким чином, інвентарні правила 1847–1848 років у Деражнянському ключі не стали інструментом емансипації селянства. Навпаки, вони легалізували складний механізм експлуатації, де офіційна панщина лише доповнювалася численними прихованими повинностями. Економія, контролюючи місцеву адміністрацію та процес інвентаризації, успішно маніпулювала класифікацією земель та робіт, зводячи нанівець спроби імперської влади обмежити поміщицьке свавілля. Ця накопичена соціальна напруга та економічна скривдженість стали тим вибухонебезпечним матеріалом, який неминуче прорвався назовні у формі масових протестів та судових позовів у пореформений період.

Інвентарні книги Деражнянського ключа переконливо деконструють поширений у старій

історіографії міф про монолітність та однорідність «кріпацької маси». Насправді селянська громада містечка та навколишніх сіл мала чітку внутрішню стратифікацію, яка фіксувалася не лише розміром земельного наділу, а й наявністю робочої худоби та характером виконуваних повинностей. Ця соціальна ієрархія, закладена інвентарною реформою 1847–1848 років, стала тим фундаментом, який визначив траєкторію економічної еволюції регіону в пореформений період.

Ядром селянської громади виступали тяглі селяни (або «тяглові»). Це була найбільш заможна та впливова верства в межах ключа, яка володіла робочою худобою — волами або кіньми. Згідно з інвентарними правилами, тяглі селяни отримували у своє користування відносно великі земельні наділи (зазвичай від двох до чотирьох десятин орної землі на двір, залежно від кількості тягла) [2, арк. 4–23]. Саме на цю категорію селянства лягав основний тягар класичної панщини: вони були зобов'язані відробляти на економії по два-три дні на тиждень, виходячи в поле з власним інвентарем. Проте їхня економічна стабільність була відносно високою, оскільки наявність тягла дозволяла їм самостійно обробляти власну землю, заготовляти сіно та утримувати господарство.

Протилежним полюсом соціальної структури виступали піші селяни, які в інвентарних описах часто фігурують під назвами «городники», «халупники» або «підсусідки». Ця категорія населення не мала робочої худоби і, відповідно, отримувала мізерні земельні наділи — часто лише невеличку присадибну ділянку та город для вирощування базових овочевих культур [5, с. 147]. Оскільки їхні наділи не могли забезпечити фізичне виживання родини, піші селяни були об'єктивно змушені шукати додаткові джерела доходу. Вони масово йшли в найми до панської економії, виконуючи найтяжчі та найменш оплачувані роботи: від догляду за панською худобою та робіт на цегельному заводі пана Красотського до обслуговування панської пивоварні.

Окрему, маргінальну групу становила дворова челядь (або «дворові люди»). Ці особи були повністю відірвані від сільськогосподарського виробництва та землеробства. Вони жили безпосередньо при панському дворі (у Деражні це був кам'яний двоповерховий будинок з господарськими службами) і виконували функції домашніх слуг, кухарів, садівників, кучерів та охоронців [1, арк. 103–106 зв.]. Їхнє утримання повністю залежало від безпосереднього розсуду економа або власника маєтку, що робило їхнє становище найбільш вразливим і наближеним до домашнього рабства.

Розуміння цієї внутрішньої стратифікації є критично важливим для аналізу подальших соціально-економічних трансформацій на Поділлі. Саме ця інвентарна нерівність стала тим «вибухонебезпечним матеріалом», який проявив себе після скасування

кріпацтва у 1861 році. Коли почався процес виділення селянських наділів, економії, прагнучи зберегти максимальні площі родючої землі, здійснили так звані «відрізки» на користь поміщиків. Внаслідок цього тяглі селяни, втративши частину своїх пасовищ та лісових угідь, почали стрімко деградувати економічно, перетворюючись на малоземельних селян-власників.

Натомість піші селяни та безземельні наймити, отримавши особисту свободу, але не отримавши достатнього земельного ресурсу для самостійного господарювання, поповнили лави вільної, але знедоленої пролетаризованої маси. Саме вони, а не вчорашні тяглі селяни, стали тією основною дешевою робочою силою, яку масово експлуатувала зароджуюча «індустрія» регіону. У 1860-х роках саме ці категорії колишніх піших селян Деражнянського та сусідніх ключів забезпечили працею ті самі 10 000 сезонних робітників, які щозими були зайняті на обмолоті зерна та прибиранні цукрових буряків на 51 цукровому заводі Подільської губернії [3, арк. 15–17]. Таким чином, соціальна стратифікація, зафіксована в інвентарних книгах 1845–1851 років, прямо детермінувала формування ринку найманої праці та механізмів боргової залежності селянства в пореформений період.

Просторова організація Деражнянського ключа, зафіксована в інвентарних описах 1845–1851 років, наочно демонструє глибоку інституційну асиметрію між поміщицьким фільварком та селянським землекористуванням. Інвентарна реформа, хоча й декларувала намір захистити селян від повного обезземелення шляхом встановлення мінімальних норм наділу, на практиці часто лише легалізувала вже сформовану диспропорцію, закріплюючи за економією найродючіші та найбільш зручні для експлуатації масиви [2, арк. 10–21].

Ядром поміщицького землеволодіння виступав компактний фільварковий масив, розташований безпосередньо навколо панського двору та вздовж річки Вовк. Саме тут концентрувалися найкращі орні землі, необхідні для товарного виробництва зерна, а також прирічкові луки, критично важливі для утримання панської худоби та забезпечення роботи млинів і пивоварні. Інвентарні таблиці свідчать, що економія залишила за собою абсолютну монополію на лісові дачі та вигони. Формально селянам могли надаватися права на збір сухостою або випас худоби, проте ці права часто обумовлювалися додатковими, не зафіксованими в основних графах інвентарю, відрібтками або грошовими зборами, що фактично перетворювало доступ до природних ресурсів на інструмент додаткового тиску [5, с. 148].

Селянське землекористування було жорстко диференційоване відповідно до соціальної стратифікації, про яку йшлося вище. Для тяглих селян, які становили економічний хребет громади та забезпечували основну частину панщини своїм інвентарем,

інвентарні правила передбачали найбільші наділи. Зазвичай вони отримували від 2,5 до 3 десятин орної землі на двір, а також частку в користуванні сінокосами. Цей розмір не був випадковим: він розраховувався державними інспекторами як мінімум, необхідний для того, щоб селянин міг прогодувати власних волів або коней, без яких виконання тяглової панщини було б неможливим [2, арк. 6–23 зв.]. Проте навіть ці наділи часто мали форму чересполосиці — розкиданих вузьких смуг, перемішаних із панськими полями, що унеможливлювало ефективне ведення власного товарного господарства та змушувало селянина постійно взаємодіяти з панською адміністрацією.

Піші селяни, які не мали власної тяглової сили, отримували значно менші ділянки — зазвичай від 1 до 1,5 десятини орної землі. Цього було недостатньо для повного забезпечення родини продовольством, особливо в неурожайні роки. Як наслідок, ця категорія була змушена компенсувати брак власної землі шляхом найму на роботи в панській економії, часто на найменш оплачуваних посадах, таких як догляд за худобою або робота на цегельному заводі пана Красотського. Таким чином, менший розмір наділу прямо корелював із більшою залежністю від поміщицької заробітної плати або натуральних видач [5, с. 149].

Найбільш маргіналізованою групою були городники та підсусідки. Їхній «наділ» фактично зводився до садибної ділянки та невеликого городу для вирощування овочів, без права на орну ріллю або сінокіс. Позбавлені можливості вести самостійне сільське господарство, вони повністю інтегрувалися в орбіту маєткового господарства як резервна армія дешевої робочої сили, виконуючи функції домашньої прислуги, охоронців або сезонних робітників на панській пивоварні [2, арк. 5–30].

Важливо також відзначити, що інвентарна реформа закріпила поділ не лише за площею, а й за якістю землі. Селянські наділи часто розташовувалися на периферії маєтку, на менш родючих ґрунтах або схилах ярів, тоді як рівнинні, чорноземні ділянки залишалися у фільварку. Така просторова сегрегація робила селянське господарство вразливим до кліматичних коливань і гарантувала, що в разі неврожаю селянин не зможе обійтися без позики зерном або грошима від того ж поміщика, потрапляючи в боргову пастку ще до офіційного скасування кріпацтва.

Отже, співвідношення поміщицького та селянського землекористування в Деражнянському ключі не було нейтральним адміністративним поділом. Це був ретельно вибудований механізм економічного контролю, де розмір і якість селянського наділу виступали не як гарантія незалежності, а як «гачок», що утримував різні категорії селянства в орбіті маєткового виробництва, забезпечуючи економію стабільною та дешевою робочою силою для її різноманітних галузей.

Для повного розуміння соціально-економічної природи Деражнянського ключа необхідно екстраполювати його інвентарну модель на ширший аграрний ландшафт Летичівського повіту. Подільська губернія у середині XIX століття являла собою складну мозаїку форм землеволодіння, де класичні магнатські латифундії межували з казенними (державними) маєтками та осередками дрібної шляхти. Порівняння Деражнянського ключа із сусідніми територіями — зокрема казенним селом Кальня та шляхетським анклавом у с. Попівці — дозволяє деконструювати уявлення про однорідність «кріпосного Поділля» та виявити унікальні риси саме приватновласницької економії Рациборовських.

Найбільш яскравий контраст Деражнянський ключ демонструє у порівнянні із сусіднім казенним селом Кальня. Якщо інвентарні книги Деражні фіксували жорстку залежність селян від розміру наділу та наявності тягла, то казенні селяни Кальні, згідно з правилами державного управління, перебували в зовсім інших правових та економічних умовах. Державні селяни Поділля зазвичай отримували земельні наділи, які за розмірами значно переважали (часто вдвічі) наділи поміщицьких селян Деражнянського ключа [3, арк. 15–17].

Замість виснажливої тяглової панщини, яка змушувала деражнянського селянина віддавати маєтності найкращі робочі дні, казенні селяни сплачували державний оброк. Ця різниця у системах експлуатації призводила до того, що казенні села, такі як Кальня, демонстрували вищий рівень господарської самостійності та заможності, тоді як селяни Деражнянського ключа були штучно законсервовані у стані хронічного дефіциту ресурсів, що робило їх абсолютно залежними від панського двору [14, арк. 1–12].

Інший тип контрасту відкривається при зіставленні монолітного Деражнянського ключа із сусідніми шляхетськими анклавами (гніздами дрібної шляхти), такими як село Попівці. Якщо економія Рациборовських у Деражні мала чіткі, юридично зафіксовані інвентарними правилами межі та беззаперечно підкоряла собі селянську масу, то шляхетські громади в Попівцях жили в умовах постійної правової нестабільності. Аналіз судових справ показує, що дрібні шляхтичі (Ставські, Липські) були змушені роками вести виснажливі межові процеси проти могутніх сусідів-поміщиків (Осовського), захищаючи свої мізерні наділи за допомогою старих польських архівів та інвентарів XVIII століття [14, арк. 1–40].

Деражнянський ключ у цьому контексті виступав як агресивний сусід, який прагнув поглинути або ізолювати ці шляхетські «острівці», використовуючи своє економічне та адміністративне домінування. Таким чином, інвентарна система Деражні була спрямована не лише на експлуатацію селян, а й на просторову експансію щодо сусідніх дрібних власників.

Важливим аспектом порівняння є також економічна диверсифікація. Казенні села та шляхетські анклави навколо Деражні залишалися суто аграрними, зосередженими на традиційному трипільному землеробстві. Натомість Деражнянський ключ, завдяки концентрації земель та капіталу в руках одного власника, функціонував як напівіндустріальний комплекс. Наявність у Деражні панської пивоварні, цегельного заводу, потужних водяних млинів та розвиненого гостинного двору з 30 кам'яними лавками створювало внутрішній ринок збуту та переробки, якого були позбавлені сусідні казенні та шляхетські поселення [1, арк. 103–106 зв.]. Селяни Деражні були вбудовані не лише в аграрний, а й у маєтковий промисловий цикл, що робило їхню експлуатацію багатомірною.

Отже, порівняльний аналіз переконливо доводить, що Деражнянський ключ не був просто «одним із маєтків» Поділля. Це була високоструктурована, агресивна економічна система, яка поєднувала в собі жорстку інвентарну регламентацію селянських наділів, просторовий тиск на сусідні шляхетські анклави та розвинену внутрішню інфраструктуру. Саме ця концентрація влади та ресурсів у руках магната робила Деражнянський ключ надзвичайно вразливим до будь-яких імперських реформ, які загрожували порушити цей ідеальний, з точки зору економа, механізм експлуатації.

Таблиця переконливо демонструє, що інвентарна система Деражнянського ключа не може бути зрозуміла ізолювано. Лише в порівнянні з казенним селом Кальня та шляхетським анклавом Попівців стає помітною її специфічна «над експлуататорська» логіка. Деражня тут постає як класичний магнатський фільварок, де інвентарі слугують інструментом максимального вичавлювання ренти з селян через тяглову панщину і штучне утримання їх у стані постійного дефіциту землі та ресурсів. Натомість казенні селяни Кальні, маючи більші наділи й грошовий оброк замість панщини, демонструють інший тип залежності, в якому держава залишає значно ширший простір для господарської ініціативи й накопичення, що, за логікою автора, конвертується у вищий рівень заможності та самостійності.

Шляхетський анклав у Попівцях вводить третю модель — дрібношляхетську мікросистему, вразливу не стільки через тип повинностей, скільки через хронічну правову нестабільність. Тут інвентарі й давні акти перетворюються на зброю в межових війнах із сильнішими сусідами, а сам простір постає як арена постійних юрисдикційних і територіальних конфліктів. У цьому контексті Деражнянський ключ постає вже не лише як «місце експлуатації селян», а як активний агент просторової експансії, що намагається поглинути або принаймні ізолювати дрібношляхетські «острівці», використовуючи перевагу капіталу й адміністративних зв'язків.

Особливістю даного краю була багатомірність експлуатації. На відміну від казенних і шляхетських

сіл, де господарство залишається переважно аграрним, магнатський ключ перетворюється на напівіндустріальний комплекс із пивоварнею, цегельнею, млинами та розвиненим гостинним двором. Це означає, що селянин тут включений одночасно в аграрний і промислово-торговельний цикл, а отже, інвентарна система фіксує не лише розміри наділу й панщину, а й доступ (або не доступ) до внутрішнього ринку, кредиту та зайнятості у маєткових підприємствах. У підсумку Деражнянський ключ з'являється як високоцентралізована економічна машина, особливо чутлива до будь-яких імперських реформ, що могли б порушити баланс між правовим режимом, структурою землеволодіння та інфраструктурною концентрацією.

Економічна ефективність Деражнянського ключа у середині XIX століття забезпечувалася не лише природними умовами чи розміром угідь, а й чітко вибудованою інституційною вертикаллю

управління, яка трансформувала розрізнені села та містечко в єдиний фінансово-господарський організм. На відміну від дрібних шляхетських володінь, де управління часто здійснювалося безпосередньо власником або його найближчими родичами, Деражнянський ключ належав до типу магнатських латифундій, які функціонували за принципом делегованої адміністрації. Рід Рациборовських, як і більшість великих землевласників Правобережжя, здійснював стратегічний контроль над маєтком дистанційно, покладаючи оперативне управління на професійних економістів та місцевих чиновників [2, арк. 4–12].

Ядром цієї адміністративної системи виступала посада головного економа (або «директора економії»), який призначався власником і ніс повну відповідальність за фінансові результати ключа. Економіст не лише координував посівні роботи, збір врожаю та виплату чиншу, а й виконував функції фінансового контролера: він вів суворі прибутково-видаткові

Таблиця 1

Інвентарні режими та соціально-економічні характеристики Деражнянського ключа, казенного села Кальня та шляхетського анклав Попівці (середина XIX ст.).

Параметр	Магнатський фільварок (Деражнянський ключ)	Казенне село (Кальня)	Шляхетський анклав (Попівці)
Форма власності	Приватна магнатська латифундія Рациборовських	Державна (казенна) власність	Дрібна шляхетська власність (родові гнізда)
Правовий статус селян	Поміщицькі кріпаки, підпорядковані інвентарним правилам маєтку	Державні селяни з окремим режимом управління	Залежні/напівзалежні від дрібних шляхтичів, часто в умовах правової невизначеності
Розміри селянських наділів	Менші, ніж у казенних селах; регламентовані інвентарями, прив'язані до тягла	Значно більші; часто приблизно удвічі перевищують наділи селян Деражні	Мізерні, роздроблені наділи, постійні межові конфлікти
Вид основних повинностей	Тяглова панщина з відбиранням «найкращих робочих днів» на фільварок	Грошовий оброк на користь держави, без обов'язкової тяглової панщини	Змішані повинності; значна частина часу йде на судові й межові справи
Господарська модель	Фільварково-напівіндустріальна економія з концентрацією землі й капіталу	Переважно дрібноселянське аграрне господарство з вищим рівнем самостійності	Дрібношляхетські господарства, фрагментовані й економічно вразливі
Економічна диверсифікація	Пивоварня, цегельня, великі водянні млини, гостинний двір із ~30 кам'яними лавками	Відсутність власної промислової інфраструктури; орієнтація на традиційне землеробство	Суто аграрний профіль без розвинutoї інфраструктури
Внутрішній ринок	Розвинений внутрішній ринок збуту й переробки в межах ключа	Обмежений локальний ринок, орієнтований на зовнішні центри	Локальний, слабо інтегрований у ширші ринкові мережі
Правова стабільність	Висока внутрішня керованість завдяки інвентарній регламентації	Відносно стабільний державний режим із чіткими нормами	Хронічні межові й судові конфлікти з сусідніми поміщиками, опора на старі польські акти
Просторові відносини із сусідами	Агресивна експансія, спроби поглинання або ізоляції шляхетських «острівців»	Територіальна стабільність без активної експансії	Оборонна стратегія, юридична боротьба за збереження дрібних наділів
Ступінь залежності селян	Максимальна: хронічний дефіцит ресурсів, багатовимірна (аграрна й промислова) експлуатація	Нижчий: більші наділи, грошовий оброк, вища господарська самостійність	Варіативний, але посилений правовою невизначеністю й тиском сусідніх маєтків

Джерело: таблиця складена на основі узагальнення матеріалу нашого дослідження, який спирається на такі архівні комплекси: Державний архів Хмельницької області (ДАХмО), ф. 244, оп. 1, спр. 2, арк. 15–17; ДАХмО, ф. 115, оп. 2, спр. 567, арк. 1–12; ДАХмО, ф. 115, оп. 1, спр. 4, арк. 1–40; ДАХмО, ф. 115, оп. 2, спр. 109, арк. 103–106 зв.

книги, фіксував кількість відпрацьованих панщинних днів, контролював роботу млинів, пивоварні та цегельного заводу, а також щорічно звітував перед власником або його повіреним у Санкт-Петербурзі чи Варшаві [5, с. 152]. Саме через економіста інвентарні правила 1847–1848 років впроваджувалися на місцях: він адаптував імперські норми до локальних умов, часто інтерпретуючи їх на користь економії, зокрема шляхом класифікації додаткових робіт (наприклад, підвезення дров, ремонту греблі чи обслуговування панських доріг) як «звичайних селянських повинностей», що не підлягали окремому обліку.

Безпосереднє управління селами, що входили до ключа, делегувалося місцевим старшинам, десятникам та двірським управителям. Ці особи формували нижчу ланку маноріальної адміністрації і виступали посередниками між економістом та селянською громадою. Їхня роль не зводилася лише до організації панщини: вони контролювали дотримання селянами інвентарних норм, запобігали самовільним порубкам лісу, фіксували випадки несплати чиншу та організовували «толоки» під час жнив. Важливо, що ці посади часто обіймали заможніші тяглі селяни або вихідці з міщан, які отримували за свою службу звільнення від частини повинностей або додаткові земельні наділи. Таким чином, адміністрація ключа штучно формувала прошарок лояльних посередників, які були економічно зацікавлені у підтримці існуючої системи експлуатації [2, арк. 8–21 зв.].

Особливу роль у функціонуванні Деражнянського ключа відігравала його взаємодія з імперською бюрократією. Після інвентарної реформи економіст був зобов'язаний регулярно звітувати перед повітовими комісіями та Подільською казенною палатою щодо виконання інвентарних правил. Проте на практиці ця звітність часто перетворювалася на формальність. Магнатська адміністрація використовувала імперське законодавство як інструмент легітимації своїх дій: звертаючись до судів у разі селянських скарг, економіст посилався на затверджені інвентарні книги як на «вищу правду», ігноруючи звичаєві норми чи усні домовленості, що існували в попередні десятиліття. Водночас власники ключа активно використовували свої зв'язки в губернських установах для отримання пільг, розстрочення податків або захисту майна від конкурентів, що перетворювало Деражнянський ключ на своєрідний «приватний інститут», інтегрований у державну фіскальну систему [5, с. 154].

Отже, інституційне управління Деражнянським ключем не було хаотичним або спонтанним. Це була раціоналізована, багаторівнева система, у якій магнат виступав архітектором економічної стратегії, економіст — її технічним виконавцем, а місцеві старшини — інструментом безпосереднього контролю над селянською масою. Саме ця адміністративна

вертикаль забезпечувала стабільність прибутків маєтку, мінімізувала ризики неврожайів або селянських непокори та дозволяла Деражнянському ключу функціонувати як замкнений, самодостатній господарський організм. Водночас саме жорсткість цієї системи, її орієнтація на максимізацію експлуатації та ігнорування звичаєвих прав селянства заклала підвалини для майбутньої інституційної кризи, яка проявилася вже в умовах пореформених трансформацій.

Висновки. Комплексний аналіз інвентарних описів Деражнянського ключа за 1845–1851 рр. дозволяє зробити низку узагальнень щодо соціально-економічної природи цього магнатського маєтку напередодні скасування кріпацтва. Дослідження засвідчило, що Деражнянський ключ не був ізольованим аграрним осередком, а являв собою високо структуровану економічну систему, органічно інтегровану в ширший регіональний контекст Лєтичівського повіту. Географічні переваги (наявність річки Вовк, лісових масивів та родючих ґрунтів) були максимально експлуатовані власниками (родом Рациборовських) для створення диверсифікованого господарства, що поєднувало традиційне трипільне землеробство з переробними виробництвами (пивоварня, цегельний завод, водяні млини) та розвинутою торговою інфраструктурою [1, арк. 103–106 зв.].

Інвентарна реформа 1847–1848 років, попри свої офіційні декларації про захист селян від повного обезземелення, фактично лише легалізувала існуючу глибоку асиметрію у землекористуванні. Просторовий аналіз засвідчив жорстку сегрегацію: найродючіші орні землі, сінокоси та лісові ділянки залишалися під монополією фільварку. Селянські наділи, диференційовані за тягловістю, були недостатніми для повної економічної самостійності. Це зумовило чітку соціальну стратифікацію: від заможних тяглих селян, що забезпечували основну панщину своїм інвентарем, до маргіналізованих піших селян та городників, які були об'єктивно змушені інтегруватися в орбіту маєткового господарства як резервна армія дешевої робочої сили [2, арк. 4–20 зв.].

Система повинностей у ключі виходила за межі формальної дворянної або трирядної панщини. Вона включала розгалужену мережу прихованих експлуатаційних механізмів: колективні толоки, підвідну повинність, грошовий чинш та примусову працю на панських промислових об'єктах. Ефективність цієї системи забезпечувалася чіткою інституційною вертикаллю: від дистанційного стратегічного контролю магната до оперативного управління головного економа та місцевих старшин, які виступали інструментом безпосереднього тиску на селянську громаду, штучно формуючи прошарок лояльних посередників [5, с. 152–154].

Наукова новизна проведеної мікроісторичної реконструкції полягає в деконструкції міфу про однорідність «кріпацької маси» та демонстрації того, як інвентарні правила стали не інструментом

емансипації, а механізмом легітимації поміщицького свавілля. Порівняльний аналіз із сусідніми казенними (с. Кальня) та шляхетськими (с. Попівці) володіннями переконливо довів, що Деражнянський ключ функціонував як агресивна економічна система, що чинила просторовий та економічний тиск на сусідні дрібні землеволодіння, прагнучи поглинути або ізолювати їхні ресурси [15, арк. 1–40; 14, арк. 1–12].

Таким чином, інвентарний період (1845–1851 рр.) у Деражнянському ключі характеризувався не стабілізацією, а максимальним загостренням внутрішніх

суперечностей маєткової системи. Штучне утримання селян у стані хронічного дефіциту ресурсів, просторова чересполосиця та жорстка адміністративна регламентація їхнього життя заклали підвалини для глибокої інституційної кризи. Ця накопичена соціальна напруга неминуче мала вилитися у масові земельні конфлікти та правові протистояння в умовах майбутніх пореформених трансформацій, коли питання доступу до лісу, сіножатей та межових знаків стане головним предметом боротьби між економією та селянською громадою.

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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MANAGEMENT OF STABILIZATION OF IT PROJECTS IN THE HEALTHCARE SECTOR

Summary. The article is devoted to means of stabilization of IT projects in the healthcare sector. The purpose of the study is to determine what prevents medical organizations from achieving sustainable effects from the implementation of software products. During the study, general scientific methods of cognition were used: analysis and synthesis, system approach, comparative analysis and structural-logical classification. According to the results of the study, it was found that after the technical launch, most organizations enter the phase of trial use of the system. During this period, a significant number of requests and clarifications accumulate that require elimination or refinement. This phase is the stabilization phase. Six factors that destroy the stability of IT projects in medicine were identified: the complexity of the system itself, problems with usability, staff overload with activities related to documentation, insufficient support from the implementation team, the lack of effective metrics of the current state of the system, as well as personnel risks associated with staff turnover during the adaptation period. It is significant that a significant part of these problems remains unnoticed by management as long as the staff copes with current duties. They become visible only when the load exceeds the team's adaptive resource. The practical significance of the study lies in the formation of mechanisms that allow accelerating the adaptation period and stabilizing IT projects of medical organizations undergoing automation or software updates.

Key words: stabilization management, IT projects, healthcare, EHR, change management.

Introduction. Healthcare organizations around the world are actively implementing digital solutions: electronic medical records, clinical decision support tools, telemedicine platforms. The market for medical information technologies is growing, and the volume of investments in the industry is increasing every year [4]. However, the success statistics of such projects remain disappointing: from 50 to 70% of EHR implementations do not achieve the planned results [8], and about 70% of pilot solutions in hospitals do not go into sustainable use [6]. The problem is often not whether the system was launched, but whether the organization was able to go through the difficult transition stage after this launch.

The classic project management model — deadlines, budget, scope — is poorly adapted to the realities of the healthcare environment. Clinical workflows are critical by nature, staff have a high level of autonomy and tend to form workarounds instead of adapting to new systems, and regulatory requirements significantly complicate any configuration changes after launch [12]. That is why a separate management concept has been formed in healthcare IT practice — stabilization

management. It covers the activities between technical go-live and achieving operational maturity and determines whether the implemented system will turn into a real clinical tool [10].

Literature Review. The issue of IT project management in healthcare is not sufficiently comprehensively covered in the scientific literature as an independent management category. Nevertheless, individual components of this topic are considered by scientists. In particular, the issue of general indicators of success and failure in EHR implementations was studied by such researchers as Anderson J., Beyer A. and Tate S. [2], as well as Anderson J. and Manzione L. [1]. The studies of these authors note that only 38% of organizations that have recently undergone large-scale EHR implementations reported that the result met their expectations, and the level of satisfaction of nurses with EHR support from organizations remains critically low.

As for the issue of EHR usability and its connection with clinical staff burnout, this issue is the subject of several independent studies. Among them, it is worth highlighting the work of Melnick E. R. et al. [13],

which showed that EHRs fall into the bottom 9% of all evaluated technologies on the System Usability Scale; Lohmann-Lafrenz S. et al. [11], who recorded even lower SUS scores after the implementation of Epic in a Norwegian university hospital; and Olakotan O. et al. [14], whose review confirms the systemic nature of usability problems in clinical EHRs.

The topic of documentation burden and its relationship to burnout has been investigated by Henry T. A. [5] and Budd J. [3]. According to the study cited by Henry T. A., physicians spend more than 5 hours in the EHR for every 8 hours of scheduled time with patients; Budd J. confirms that excessive documentation burden in primary care is one of the leading factors of burnout.

The issue of practical implementation and stabilization of EHRs after go-live is reflected in case studies. Kiepek W. and Sengstack P. P. [10] analyzed the experience of Vanderbilt University Medical Center and showed that even well-prepared organizations face the need for additional support in the first days after launch. Johnson K. B., Sternberg P. Jr. and Dubree M. [7] in their analysis note that the Vanderbilt team prematurely called the stabilization phase optimization, in effect confusing survival after launch with achieved success. Siwicki B. [17] describes the Health First support model, which involved emeritus-level physicians to provide "at-the-elbow" support during the transition to Epic. The problem of EHR optimization in a broader context is explored by Makhni S. et al. [12], as well as Restuccia M. [16], who, based on the experience of CIOs in large medical organizations, describes the practice of managing the backlog after launch. Tate S. [18] specifically examines the documentation workload of nurses and links it to reduction strategies through personalization and training. The issue of personnel and financial consequences of burnout and staff turnover is highlighted in the KLAS study presented by Pennic F. [15].

The financial dimension of ROI from digital investments is analyzed in the article by Kaltwasser J. [9] and the publication by Dyrda L. [4]. The general context of instability of IT projects in the healthcare sector, including the statistics of the Standish Group and the evaluations of pilot projects, is described in the publication Improvizations [6] and the materials of Topflight Apps by Kalinin K. [8].

Despite the wide coverage of individual aspects, a comprehensive approach to stabilization management as an independent phase of IT project management has not yet been formed in the scientific literature. The author of this study proposed his own systematization of destabilization factors and stabilization management tools in their interrelationships — this is the main contribution to the development of the topic. Analysis and synthesis, comparative analysis of practical cases, and structural-logical classification were used to process the material.

Problem Statement. The purpose of the article is to investigate stabilization management as a management category in healthcare IT projects and to systematize the means of its provision. To achieve the goal, the following tasks will be performed during the study: to reveal the content of the concept of stabilization management of IT projects in the healthcare sector; to analyze the factors of destabilization with a generalization of their evolution and classification by type; to systematize the means of stabilization management with a definition of their sphere of influence and characteristics.

Methods and materials. The study is based on the processing of scientific publications, practical cases and analytical reports in the field of IT project management in healthcare. The methods of analysis and synthesis, comparative analysis and structural-logical classification were used. Comparative analysis was used to compare the experience of different organizations, classification — to organize the identified factors and means of stabilization.

Results and Discussions. Standard approaches to the evaluation of IT projects take into account three parameters: timing, budget and compliance with the technical task. In most industries, this is sufficient. However, the study by Restuccia M. notes that the medical IT sphere requires a fundamentally different logic of evaluation, since the formal launch of the system and the actual receipt of benefits from it are different events, separated in time by months [16]. This difference constitutes the content of the stabilization phase.

Stabilization management as a category of IT project management encompasses a set of management actions aimed at ensuring the stable and effective functioning of the implemented information system after technical launch. In the context of IT projects in the healthcare sector, this category acquires particular importance due to three key circumstances:

- clinical criticality of the environment — medical systems directly affect treatment processes, therefore any instability carries not only operational, but also safety risks for patients [14];
- behavioral complexity of system adoption — clinical staff tend to form workarounds instead of adapting to the new system, especially when it does not correspond to the real rhythm of work. According to Olakotan O. et al., it is usability problems that are the leading factor in such behavior [14];
- regulatory and integration burden — EHR systems must meet data security, interoperability, and documentation requirements, which makes any configuration changes after launch significantly more difficult [12].

The stabilization phase is a separate stage between go-live and full-fledged operational optimization. Johnson K. B., Sternberg P. Jr., and Dubree M., describing the experience of Vanderbilt University Medical

Center, recorded a revealing situation: the team publicly declared the stabilization phase complete and renamed it optimization, but in reality the organization was still in survival mode after launch [7]. This is not an isolated case — it is a typical management error that leads to premature reduction of resources precisely when they are needed most.

In the operational dimension, stabilization management encompasses monitoring the clinical performance of the system, responding to critical issues, managing the backlog of user requests, training, and personalization. Makhni S. et al. emphasize that a few weeks of training without further support is fundamentally insufficient for complex medical platforms [12]. Stabilization management is a condition for the technology not to simply “stand” in the organization, but to actually support its clinical work.

Understanding what undermines the stability of IT projects is no less important than knowing the means of restoring it. The factors of destabilization in the medical IT sphere have changed significantly over time. At the initial stage of hospital computerization, in the 1980s and 1990s, projects failed mainly due to technical reasons: unreliable equipment, lack of integration standards, lack of specialists. It was believed that a properly configured system would work by itself [6]. In the 2000s and 2010s, along with the spread of

large EHR platforms, technical reliability increased — but organizational risks came to the fore. Staff resistance, the gap between designed and real workflows, insufficient involvement of clinicians in system design became the main reasons for failures. Today, according to Improvizations, from 50 to 70% of EHR projects do not achieve the planned results [6], and Kalinin K. notes that about 70% of pilot technological solutions in hospitals do not go into permanent use at all [8]. The leading destabilizers are currently usability, documentation load and personnel instability.

The systematization of current means of destabilization and their characteristics are presented in Table 1 (see Table 1).

As can be seen from Table 1, the means of destabilization cover both the system-technical and human-centric dimensions. Their common feature is that they mostly manifest themselves after the formal completion of the project and at the same time remain hidden from management. This situation confirms that destabilization is primarily a managerial, not a technical problem.

The response to the above destabilization factors is a set of management tools aimed at ensuring the operational stability of the system after launch. The principle is that these tools are not exclusively technical — they cover the organizational, human-centric and analytical dimensions of management.

Table 1

Means of destabilization of IT projects in the healthcare sector

Destabilizing factor	Characteristics and manifestations
Structural complexity of EHR systems [2]	EHR platforms serve dozens of staff categories simultaneously: physicians, nurses, pharmacists, administrators, laboratory specialists, and billing services. Each of these groups has different system configuration needs, which complicates even the most carefully designed rollout process. According to KLAS Research, only 38% of organizations that had recently completed a large-scale EHR implementation reported that the outcome met their initial expectations [2].
Low usability [13; 11]	The average SUS score for EHRs among physicians in the United States is 45.9/100, placing it in the bottom 9% of all technologies [13]. After Epic was implemented in one Norwegian university hospital, the median score fell to 25/100, and among physicians, to 15/100 [11].
Excessive documentation burden [5; 13]	For every 8 hours of scheduled patient appointments, physicians spend more than 5 hours in the EHR [5]. In addition, each hour of direct patient contact is accompanied by one to two hours of system-related work, some of which is performed outside working hours. When template and alert configurations are not reviewed after launch, these time costs become fixed as a permanent norm [13].
Insufficient post-launch support [16; 10]	After go-live, project teams are usually reduced, while managerial attention shifts to new initiatives. As a result, the accumulated backlog remains without dedicated personnel. The experience of Vanderbilt University Medical Center showed that, even with thorough preparation, the command center had to be expanded and additional staff had to be brought in on the second day after launch [10].
Weak operational metrics [9; 1]	Technical indicators, such as uptime and interface stability, are present in most organizations. Documentation time, the number of workarounds, and the level of engagement with system functions are measured much less often. A survey by Ernst & Young found that 70% of healthcare executives had not yet seen ROI from digital investments, with half of them linking this to fragmented metrics [9]. KLAS further notes that 46% of nurses disagree that their organization provides good EHR support [1].
Financial and workforce vulnerability [15]	Burnout is rarely cited as the sole reason for resignation, but it is a documented contributing factor. In 2024, nearly half of the nurses and physicians surveyed by KLAS said they were likely to leave their organization within two years, while the actual turnover rate among the at-risk group was 21% and 13%, respectively. Replacing one nurse costs approximately USD56,300, while replacing one physician costs between USD500,000 and USD1,000,000 [15].

Source: compiled by the author based on sources [1; 2; 3; 5; 6; 8; 9; 10; 11; 13; 15; 16]

The key principle of stabilization management is to change the criterion of success. According to Kiepek W. and Sengstack P.P., success is determined not by the fact of technical launch, but by the level of sustainable acceptance of the system and the actual operational result [10]. This means that stabilization requires a separately planned phase with its own resources and metrics. According to Anderson J. and Manzione L., nurses who personalized their EHR have 45 points higher satisfaction compared to those who did not [1]. Even a relatively simple means of personalizing the system can significantly affect the level of operational stability.

Stabilization management tools are systematized in Table 2, taking into account the scope of their influence and practical content (see Table 2).

As can be seen from Table 2, stabilization management tools cover different levels of management: from strategic (planning the stabilization phase, change management) to operational (rapid-response team, triage of problems, at-the-elbow support) and analytical (operational health metrics, backlog monitoring). Makhni S. et al. separately emphasize: measurement in the stabilization phase should not create a culture of surveillance. The question should not be “which clinicians are using the system incorrectly”, but “where is

the system failing the clinicians” [12]. Such a principle is important for maintaining staff trust and creating an environment in which feedback becomes a resource, not a source of anxiety.

Conclusions. In the medical IT sphere, the technical launch of a system and the moment when it actually starts working for all its users are separated by a time interval. It is this interval that determines the stability of the system and its practical value. It is technically incorrect to assess the implementation only by the fact of implementation.

Destabilization occurs from several sides at once. Different users have different levels of digital literacy, different experience with previous systems, and different rates of adaptation to new tools. Usability does not appear at the moment of launch — it is formed gradually, along with the acquired skills and habits of working in a new environment. Over time, the number of support requests naturally decreases, but by this point a specific list of requests from users has accumulated — things that interfere, do not work as expected, or need to be adjusted to real needs.

This list becomes the basis of stabilization management. A separate implementation phase is allocated for it with specific tasks: sorting problems by level of

Table 2

Stabilization management tools for IT projects in healthcare

Stabilization tool	Area of impact	Description
Formal planning of the stabilization phase [10; 7]	Project management	Stabilization is defined as a separate planned phase with resources, responsible teams, timelines, and success criteria. It does not replace the optimization phase but precedes it.
Maintaining support after technical go-live [12; 14]	Resource provision	The project team and managerial attention are maintained after go-live. The complexity of EHR systems increases the need for sustained support rather than reducing it.
Rapid-response team for critical issues [10]	Operational safety	A pre-established interdisciplinary rapid-response team is created to resolve critical issues related to safety, throughput, and clinical workflow.
At-the-elbow support [17]	User adoption	Physician champions and IT consultants are engaged directly at the workplace. Health First involved more than 50 support physicians, including emeritus-level physicians.
Prioritization of issues by criticality [17]	Backlog management	Issues are classified as patient-safety critical, throughput critical, and optimization-related. This prevents requests from accumulating chaotically.
Systematic handling of the optimization backlog [16]	System configuration	A formal mechanism is introduced for collecting, prioritizing, and addressing deferred requests related to templates, alerts, data entry sequences, and workflows.
Introduction of operational health metrics [9; 1; 18]	Monitoring and analytics	Documentation time, the prevalence of workarounds, feature use, satisfaction, and workload dynamics are measured instead of relying only on technical indicators.
EHR personalization and post-launch training [1]	User experience	Nurses who personalized the EHR reported satisfaction scores 45 points higher. Stabilization includes support in configuring the system around real workflows.
Optimization of the documentation burden [12; 3]	Clinical efficiency	Templates are reviewed, excessive alerts are reduced, and the EHR is adapted to clinical needs. A significant share of time loss is caused by configuration rather than regulatory requirements alone.
Early change management [10; 7]	Organizational culture	Communication, training, resistance management, and clinician engagement begin before launch and continue afterward. Change management is a building block of stabilization.

Source: compiled by the author based on sources [1; 3; 7; 9; 10; 12; 14; 16; 17; 18]

criticality, their sequential processing, introducing new metrics, personalized settings for key user groups, optimizing the documentation load. The implementation

of these measures allows to significantly increase the satisfaction of using the system — and this is the basis of stabilization management.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.

ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.

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REHABILITATION STRATEGIES FOR POST-SERVICE EYELASH DAMAGE: THE IMPACT OF INTEGRATED RESTORATION SYSTEMS

Summary. The article is devoted to the study of rehabilitation strategies for post-service eyelash damage and to determine the impact of integrated restoration systems on the condition of eyelashes, eyelid margin and ocular surface. The purpose of the study is to scientifically substantiate approaches to the correction of damage that occurs after cosmetic procedures with eyelashes and to determine the effectiveness of complex restoration protocols in normalizing the functional and aesthetic state of the ciliary apparatus. In the course of the scientific study, general scientific methods of cognition were used, in particular analysis, synthesis, generalization, systematization, comparison and classification. The results of the study show that post-service eyelash damage is multifactorial and may include allergic-inflammatory reactions, chemical irritation of the ocular surface, mechanical injury to the eyelashes themselves, impaired tear film stability, damage to the conjunctiva and corneal epithelium, infectious complications, as well as follicular changes and disruption of the eyelash growth cycle. It has been studied that such conditions are manifested by itching, redness, swelling, burning, tearing, dryness, photophobia, eyelash loss, thinning of the ciliary row and discomfort during blinking. It has been shown that effective rehabilitation should be based on a combination of elimination, anti-inflammatory, hygienic, antibacterial, regenerative, tear-stabilizing and preventive-educational strategies. It was concluded that the elimination of the irritating factor, restoration of eyelid margin hygiene, tear film support, inflammation control and stimulation of the restoration of natural eyelashes create conditions for the gradual normalization of the condition of eyelashes and adjacent structures. The value of the LRCA Method as an integrated restoration system was investigated, which includes an audit of injuries, primary diagnostics, decompression of natural eyelashes, removal of critical load, reconstruction of the ciliary row and safe modeling taking into account the bearing capacity of the own eyelashes. It was shown that such a technique makes it possible to combine aesthetic results with biological restoration, reduce the risk of re-injury and form a protective aesthetic framework. The practical significance of the study lies in the possibility of using the proposed strategies in professional practice for the safe correction of the consequences of post-service damage to the eyelashes.

Key words: eyelashes, rehabilitation, damage, eyelids, restoration.

Introduction. Post-service damage to eyelashes is a pressing problem of modern cosmetology and ophthalmology practice, since the procedures of eyelash extension, removal, coloring and modeling can be accompanied not only by aesthetic defects, but also by functional disorders of the eyelid margin and ocular surface. Excessive mechanical stress, contact with glues, removers, dyes or fixing materials can cause loss and weakening of natural eyelashes, irritation of the conjunctiva, inflammatory reactions of the eyelids, disruption of the stability of the tear film and damage to the corneal epithelium. In this regard, the restoration of eyelashes after aggressive or unqualified service exposure requires not only decorative correction, but also a comprehensive rehabilitation approach.

Of particular importance is the development and scientific understanding of integrated recovery systems that combine diagnostics of the degree of damage,

elimination of the traumatic factor, support of the follicular apparatus, stabilization of the eyelid margin and prevention of repeated damage. This approach allows us to consider natural eyelashes as a functional element of ocular surface protection, and not only as an object of aesthetic modeling. That is why the study of rehabilitation strategies for post-service eyelash damage is important for the formation of safe practices in the field of lash service and increasing the efficiency of restoring the natural resource of eyelashes.

Literature Review. The issue of rehabilitation strategies for post-service eyelash damage and the impact of integrated recovery systems is not sufficiently comprehensively covered in the scientific literature. Despite this, individual components of this topic are considered by scientists. In particular, the nature of post-service eyelash damage, its clinical manifestations and ophthalmological consequences

were studied by the following authors: Y. Amano, Y. Sugimoto, M. Sugita [1], S. Aumond, E. Bitton [2], M. Masud, M. Moshirfar, T.J. Shah and co-authors [7]. These authors studied the anatomical and functional significance of eyelashes, the features of ocular surface damage after cosmetic procedures, as well as the spectrum of side effects associated with eyelash extensions, in particular allergic blepharitis, keratoconjunctivitis, conjunctival irritation and other pathological conditions.

As for the factors of mechanical, chemical, allergic and infectious effects after cosmetic procedures with eyelashes, this issue was studied by several authors. Among them, it is appropriate to highlight F.K. Idu, A.D. Efosa, M. Mutali Jr. [6], who analyzed the prevalence of side effects among eyelash extension users, including itching, redness, pain, and loss of natural eyelashes; M. Moshirfar, M. Masud, T.J. Shah et al. [8], who described a clinical case of chemical conjunctivitis and diffuse lamellar keratitis after improper removal of eyelash extensions; K. Ullrich, N. Saha [9], who investigated a case of bacterial keratitis associated with semi-permanent eyelash extensions. Taken together, these works indicate that post-service complications can be not only cosmetic, but also clinically significant ophthalmological in nature.

The problem of restoration of eyelashes, eyelid margin and ocular surface after service exposure was considered by Y. Eom, K.S. Na, H.S. Hwang and co-authors [3], C.N. Grupcheva, D.I. Grupchev, N. Usheva, L.O. Grupcheva [4], J. Han, Z. Xie, X. Zhu and co-authors [5], D. Wirta, D.M. Pariser, S.G. Yoelin and co-authors [10]. A separate group of sources is made up of clinical, review and expert publications that allow us to summarize the ophthalmological risks of cosmetic procedures with eyelashes. In particular, the works of M. Masud, M. Moshirfar, T.J. Shah et al. [7], as well as S. Aumond and E. Bitton [2] are important for systematizing knowledge about the structure, functions and pathological changes of eyelashes, while the studies of C.N. Grupcheva et al. [4], J. Han et al. [5], F.K. Idu et al. [6] supplement the analysis with empirical data on dry eye, changes in the ocular surface and the frequency of adverse reactions after eyelash extensions. At the same time, the scientific literature does not sufficiently address the issue of integrated rehabilitation systems that combine diagnostics of post-service damage, reduction of traumatic load, reconstruction of the natural ciliary row and prevention of re-damage.

The scientific novelty of this article lies in the generalization of post-service eyelash damage as a complex condition that encompasses aesthetic, dermatological and ophthalmological manifestations, as well as in substantiating the feasibility of using integrated restoration systems, in particular the LRCA Method, as an applied model for the rehabilitation of natural eyelashes. To achieve the set goal, the methods of analysis, synthesis, systematization, comparison,

generalization of scientific sources and a structural-functional approach were used.

Problem Statement. The purpose of the article is to scientifically substantiate rehabilitation strategies for the correction of post-service eyelash damage and to determine the significance of integrated restoration systems in the normalization of the condition of eyelashes, eyelid margins and ocular surface. To achieve the goal, the following tasks will be performed during the study: to characterize the essence and clinical forms of post-service eyelash damage; to systematize the main factors of mechanical, chemical, allergic and infectious effects after cosmetic procedures; to generalize rehabilitation strategies for the restoration of eyelashes and adjacent structures; to analyze the potential of integrated proprietary techniques, in particular the LRCA Method, in preventing re-damage and maintaining the natural resource of eyelashes;

Methods and Materials. The materials of the study were scientific works devoted to ophthalmological complications after eyelash extensions, anatomical and functional features of the ciliary follicle, the effect of cosmetic procedures on the ocular surface, tear film stability disorders, eyelid margin hygiene, infectious and chemical lesions, as well as methods of eyelash restoration in hypotrichosis. The research used methods of analysis and synthesis to process scientific sources, systematization to group types of post-service damage and rehabilitation strategies, comparison to compare different mechanisms of damage and approaches to restoration, generalization to form conclusions regarding the effectiveness of comprehensive rehabilitation approaches, as well as a structural-functional approach that made it possible to consider eyelashes, eyelid margin and ocular surface as interconnected elements of a single protective system.

Results and Discussions. Post-service eyelash damage is a complex and comprehensive concept. In general, it can be defined as a complex of structural and functional changes that occur after cosmetic manipulations with eyelashes and the adjacent eyelid margin. Such damage is not limited to loss or fragility of eyelashes. It can include inflammatory reactions of the eyelids, irritation of the conjunctiva, disruption of tear film stability, damage to the corneal epithelium and changes in the condition of the eyelashes themselves. As noted by Y. Amano, Y. Sugimoto and M. Sugita, after eyelash extensions, patients may experience keratoconjunctivitis, allergic blepharitis, conjunctival erosion, reactions to fixing tapes and subconjunctival hemorrhage [1].

Within the framework of this study, post-service eyelash damage can be defined as a set of pathological changes in the eyelashes, eyelid margin and ocular surface that are formed after extension procedures, removal, staining or other cosmetic effects on the eyelashes due to mechanical, chemical, allergic or infectious factors. This definition is important because it

allows us to analyze the problem not only as an aesthetic defect, but as a condition that requires gradual recovery. The main types of such injuries are summarized in Table 1.

As can be seen from Table 1, post-service eyelash damage has various clinical forms. Some of them manifest themselves mainly aesthetically, in particular, thinning or weakening of the eyelashes. Other forms have ophthalmological significance, as they are associated with damage to the ocular surface, eyelid inflammation, tear film instability or infectious risk. All these disorders require correction, but the approach to recovery cannot be the same for all cases. For this purpose, various techniques are used, in particular,

eliminating the irritating factor, restoring eyelid margin hygiene, stabilizing the tear film, anti-inflammatory support and methods of stimulating the growth of natural eyelashes.

Strategies for resolving post-service eyelash damage should be formed not according to one universal algorithm, but according to the type of damage. This is important because eyelash loss, allergic blepharitis, chemical corneal irritation, and tear film disorders have different natures. Accordingly, they require different restorative actions. As shown by Y. Amano, Y. Sugimoto, and M. Sugita, most disorders after eyelash extensions were eliminated after adequate local treatment in the form of drops or ointments [1].

Table 1

Types of post-service injuries to eyelashes and related structures

Type of injury	Clinical meaning	Typical manifestations
Allergic-inflammatory injury after the use of adhesives or fixing materials [1; 4; 7]	Occurs as a reaction to components of adhesives, fixing tapes, or other materials that come into contact with the eyelids and the root zone of the eyelashes. In the study by Y. Amano, Y. Sugimoto, and M. Sugita, allergic blepharitis was specifically associated with the action of eyelash extension adhesives [1].	Itching, redness of the eyelid margin, swelling, irritation, burning sensation, discomfort during blinking.
Chemical injury to the ocular surface after exposure to adhesive or remover [1; 8; 7]	Develops when adhesive, solvent, or eyelash removal gel comes into contact with the conjunctiva or cornea. M. Moshirfar, M. Masud, T.J. Shah, and co-authors described a case of chemical conjunctivitis and diffuse lamellar keratitis after improper use of a product for removing eyelash extensions [8].	Sharp burning, lacrimation, photophobia, blurred vision, redness, corneal epithelial defects.
Mechanical injury to natural eyelashes [6]	Associated with the excessive weight of artificial eyelashes, frequent removal, tension, or traumatic detachment of the material. F.K. Idu, A. D. Efosa, and M. Mutali Jr. identify pulling out of lashes, that is, the pulling out or loss of natural eyelashes, among the common side effects after the use of eyelash extensions [6].	Loss of eyelashes, weakening of the root zone, uneven growth, thinning of eyelashes, changes in the growth direction of individual eyelashes.
Disruption of tear film stability and dry eye [5]	Occurs due to the effect of artificial eyelashes on blinking, tear evaporation, eyelid margin hygiene, and meibomian gland function. As shown in the study by J. Han, Z. Xie, X. Zhu, and co-authors, a decrease in tear break-up time was observed after eyelash extension, indicating impaired tear film stability [5].	Dryness sensation, foreign body sensation, unstable vision, irritation, redness, discomfort at the end of the day.
Damage to the conjunctiva and corneal epithelium [9]	May result from contact of adhesive, remover, fixing materials, or rigid elements of eyelash extensions with the ocular surface. In the study by K. Ullrich and N. Saha, bacterial keratitis was described in which the bonding agent of an eyelash extension was in contact with the cornea in the ulcer area [9].	Conjunctival erosion, corneal staining, superficial punctate keratitis, pain, photophobia, risk of infectious complication.
Infectious complication after wearing eyelash extensions [9]	Develops under conditions of insufficient eyelid margin hygiene, accumulation of debris near the eyelash roots, mechanical irritation, or microdamage to the ocular surface. K. Ullrich and N. Saha described a case of bacterial keratitis associated with semipermanent eyelash extensions [9].	Pain, marked redness, purulent or mucous discharge, photophobia, deterioration of vision, localized corneal infiltrate.
Follicular injury and disruption of the eyelash growth cycle [2]	Includes changes in the condition of the hair follicle, in particular disruption of the natural growth cycle, weakening of the eyelashes, or their loss. S. Aumond and E. Bitton emphasize that eyelashes are part of the functional system of the eyelid margin, and therefore their integrity is important for ocular surface stability [2].	Hypotrichosis, madarosis, milphosis, reduced density, length, or thickness of eyelashes, slow recovery after removal of artificial materials.

Source: compiled by the author based on sources [1; 2; 4; 5; 6; 7; 8; 9; 10]

However, in more complex cases, in particular after chemical damage, recovery may be long and require a combination of several methods, as demonstrated in the clinical case of M. Moshirfar, M. Masud, T.J. Shah et al. [8]. The general logic of recovery includes several sequential stages. First, it is necessary to eliminate the factor that caused the damage. This may be glue, remover, excessive weight of artificial eyelashes, dye, or residues of cosmetic materials at the roots of the eyelashes. Next, the condition of the eyelids, natural eyelashes, conjunctiva, cornea, and tear film is assessed. After that, the recovery technique is selected. In mild cases, hygiene of the eyelid margin, temporary refusal of re-extension and maintenance of the tear film are sufficient. In more complex cases, anti-inflammatory, antibacterial or regenerative agents are required. If the main problem is thinning of the eyelashes, the strategy shifts towards supporting the follicle and stimulating growth.

The main strategies for solving problems that arise after service procedures with eyelashes are presented in Table 2.

A special place among rehabilitation approaches is occupied by author's comprehensive methods that combine diagnostics, restoration and prevention of repeated damage. Such systems include Inna Bahriantseva's author's methodology LRCA Method, which is focused on the rehabilitation of natural eyelashes after aggressive, excessive or unqualified external influence. Its essence lies not only in the aesthetic correction of eyelashes, but in the restoration of their natural resource. This approach is conceptually consistent with the data of S. Aumond and E. Bitton, who consider eyelashes as a functional element of ocular surface protection, and not only as an aesthetic structure [8].

Within the LRCA Method, restoration occurs through several interconnected levels:

- damage audit and primary diagnosis. At this stage, the condition of natural eyelashes after previous procedures is assessed. The degree of mechanical overload, the presence of adhesions, breaks, thinning, signs of cuticle weakening and potential follicular depletion are determined. In fact, the procedure does

Table 2

Strategies for solving post-service injuries to the eyelashes and adjacent structures

Strategy	Implementation content	Expected result
Elimination strategy aimed at removing the irritating factor [4]	Involves stopping contact with the material that caused the injury. This may include removing eyelash extensions, avoiding repeated adhesive application, or discontinuing the use of a remover or dye [4].	Reduction of toxic, allergic, or mechanical effects. Conditions are created for the natural recovery of the eyelashes, eyelid margins, and ocular surface.
Anti-inflammatory strategy for blepharitis, irritation, and allergic reactions [1]	Used in cases of redness, itching, swelling, irritation of the eyelid margin, or allergic blepharitis.	Reduction of the inflammatory response, itching, swelling, and redness. Comfort in the eyelid area is restored, and the risk of the process becoming chronic is reduced.
Strategy for restoring eyelid margin hygiene [3]	Involves cleansing the eyelid margin of cosmetic residues, adhesive, meibomian gland secretions, and debris near the eyelash roots.	The bacterial load is reduced, the condition of the eyelid margin improves, and the risk of recurrent irritation and infectious complications decreases.
Strategy for tear film stabilization and dry eye correction [5; 8]	Used when dryness, foreign body sensation, visual instability, or reduced tear break-up time occurs after the procedure.	Improved tear film stability, with reduced dryness, irritation, and superficial corneal staining.
Antibacterial strategy when an infectious complication is suspected [9]	Used in cases of pain, photophobia, discharge, ulceration, or corneal infiltrate.	Prevention of infection progression, preservation of corneal transparency, and reduced risk of visual impairment.
Regenerative strategy for corneal epithelial injury [8]	Appropriate in cases of corneal staining, superficial punctate keratopathy, or epithelial defects.	Gradual epithelial healing, with reduced photophobia, pain, and superficial irritation. In complex cases, the outcome may take a long time to develop.
Strategy for restoring natural eyelashes and supporting the follicle [2; 6; 10]	Used in cases of eyelash loss, milphosis, madarosis, or hypotrichosis.	Gradual improvement in the density, length, and quality of natural eyelashes. Recovery should be monitored, as stimulating agents may cause local adverse reactions.
Preventive and educational strategy for avoiding recurrent injury [6]	Involves informing the client about the risks of repeated eyelash extension, the danger of low-quality adhesives, excessive length or weight of artificial eyelashes, and the importance of eyelid hygiene.	Reduction in the frequency of recurrent injuries. Safer behavior after the procedure is formed, and responsibility increases regarding the choice of materials, technique, and service frequency.

Source: compiled by the author based on sources [2; 4; 5; 6; 8; 9; 10]

not begin with modeling a new image, but with an analysis of defects from the previous intervention;

- reconstruction protocol and removal of critical load. The basis of the technique is decompression of natural eyelashes. This means reducing or completely eliminating excess weight that injures the own ciliary row. Then, restorative schemes are applied that allow eyelashes to gradually restore density, growth direction and structural integrity. Such logic corresponds to the clinical observations of C. N. Grupcheva, D. I. Grupchev, N. Usheva and L. O. Grupcheva, where an improvement in the condition of the ocular surface was recorded after removal of eyelash extensions [6];
- safe modeling as a prevention of repeated damage. At the final stage, parameters for further work with eyelashes are selected. This concerns the length, curvature, diameter, weight and density of the artificial material. The choice is not made according to the principle of fashionable form, but taking into account the bearing capacity of the natural eyelash. This approach reduces the risk of traction damage, excessive tension and repeated eyelash loss;
- forming a protective aesthetic framework. In practical terms, the technique is aimed at ensuring that the aesthetic result does not contradict biological restoration. Artificial material, if used, should not destroy the natural row, but create safe conditions for it. This is where the difference between the rehabilitation model and the standard decorative procedure is manifested.

Thus, the LRCA Method can be considered as an example of an integrated author's system in which work with eyelashes moves from a regular service to a controlled recovery process. Its practical value lies in the combination of expert diagnostics, reduction of traumatic load, reconstruction of the natural ciliary

row and prevention of repeated damage. It is these techniques that can be used as an example of the applied implementation of rehabilitation strategies in the field of post-service eyelash restoration.

Conclusions. The study found that post-service eyelash damage should be considered not only as an aesthetic defect, but as a complex of structural and functional changes involving natural eyelashes, eyelid margin, conjunctiva, corneal epithelium and tear film. The main clinical forms of such damage are mechanical loss or weakening of eyelashes, allergic-inflammatory reactions, chemical irritation of the ocular surface, tear film instability, follicular depletion and infectious complications.

Systematization of factors of post-service damage showed that the leading role is played by mechanical overload of natural eyelashes, contact with glues, removers, dyes and fixing materials, insufficient hygiene of the eyelid margin, as well as repeated or unqualified performance of cosmetic procedures. Accordingly, rehabilitation strategies should be approached in a differentiated manner: from eliminating the irritating factor, restoring eyelid hygiene and stabilizing the tear film to anti-inflammatory, antibacterial, regenerative support and stimulating the growth of natural eyelashes.

Integrated restoration systems, in particular the LRCA Method, have an applied value as a comprehensive approach to the rehabilitation of natural eyelashes after aggressive or unqualified service exposure. Their effectiveness lies in the combination of primary diagnostics, reducing traumatic load, reconstruction of the ciliary row, safe modeling and prevention of re-injury, which allows us to consider eyelash restoration as a guided rehabilitation process, and not just as a decorative procedure.

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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THE EFFICACY OF NON-INVASIVE AND MINIMALLY INVASIVE TREATMENTS FOR EARLY-STAGE CARIES

Summary. This article presents a clinical analysis of the effectiveness of non-invasive and minimally invasive methods for treating early-stage caries, based on structured longitudinal clinical observations within a practice-based clinical outcome analysis. The study included patients with non-cavitory enamel demineralization who underwent remineralization therapy, fluoridation, and resin infiltration or a combination thereof; follow-up examinations were conducted at 1, 3, and 6–12 months. According to the data obtained, early-stage caries accounted for 20–30% of all carious lesions; however, only 40–50% of patients sought treatment early enough for purely conservative management. According to the average clinical model, among 10 patients with non-cavitated lesions, complete stabilization was achieved in 6–7, partial stabilization in 2–3, and in 1–2 the process progressed to a cavitory defect. Remineralization resulted in stabilization in 70–80% of cases, infiltration in 80–90%, and a combined approach in 85–95% – but these figures apply to patients who followed recommendations. Among non-compliant patients, stabilization occurred in only 30–50% of cases, regardless of the method. In other words, how the patient behaved between visits had a more significant impact on the outcome than the choice of a specific technique.

The clinical logic developed through this analysis forms the basis of the Stoianov Early Caries Stabilization Protocol (SECSP) – a compliance-integrated, risk-stratified decision framework for managing non-cavitated lesions in minimally invasive dentistry.

Key words: early caries, enamel remineralization, resin infiltration, minimally invasive dentistry, non-cavitory demineralization, fluoride prophylaxis, compliance

Introduction. Early-stage caries rarely prompts a patient to seek medical attention. The lesion is painless and barely noticeable; if the patient notices anything on the tooth at all, they usually describe it as a “white spot” or a slight roughness. The vast majority of early-stage lesions are detected during routine preventive checkups. Global prevalence data indicate that more than 2.3 billion people have caries in their permanent teeth, and an additional 530 million children suffer from caries in their primary teeth [1]. Among this large population, a significant proportion of early-stage lesions could have been prevented from progressing to carious cavities with timely detection and proper management.

Initial caries corresponds to the stage of non-cavitory demineralization: the mineral composition of the enamel is disrupted, but the surface is anatomically intact, and there is no “depression” upon probing. At this stage, the process can still be halted without mechanical preparation [2; 3]. The possibility of conservative management remains until a structural defect appears.

Dental practice is gradually shifting from the “detect — drill — fill” approach to managing the carious

process. The concept of minimally invasive dentistry has shifted the focus: the goal of treatment for early caries is seen as halting demineralization and maintaining a balance between mineral loss and regeneration — without waiting for a carious lesion to form [3; 4]. In practice, this requires two conditions that are rarely met together: early diagnosis and the patient’s willingness to follow recommendations.

In the author’s own clinical practice, approximately 60–80% of patients with early-stage caries come in only after the process has progressed to a carious lesion. Those who come earlier mostly visit the dentist regularly. This determines the extent to which conservative management is fully implemented in practice.

This study evaluated the clinical outcomes of non-invasive and minimally invasive methods for early caries management. Outcomes were analyzed in relation to treatment method, lesion stage, patient age, and compliance level. The findings contributed to the development of a structured decision pathway — the Stoianov Early Caries Stabilization Protocol (SECSP) — integrating risk stratification, compliance assessment, and differential treatment selection for non-cavitated lesions.

Literature review

The Cariogenic Process as a Balance Between Demineralization and Remineralization.

In Featherstone's (2008) study, the cariogenic process is described as a dynamic equilibrium between mineral loss and remineralization, rather than linear tissue degradation [5]. Acids in microbial plaque leach calcium and phosphates from enamel; saliva, fluoride, and a reduction in the frequency of acid attacks can balance or even reverse this process. In the early stages, while there is no carious lesion, the chance of restoring balance is real, and this fundamentally distinguishes it from a carious lesion, where the question of preparation is no longer up for debate.

The consensus document by Schwendicke et al. (2016) established a shift from the principle of complete removal of affected tissues to differentiated criteria that take into account the depth and extent of the lesion [2]. For non-cavitory lesions limited to the enamel, the consensus confirms the priority of a non-invasive approach: the remineralization potential in non-cavitory lesions is preserved, and this opens up the possibility for non-invasive management.

Clinical presentation and diagnosis of early caries. According to the ICDAS system, which has become the standard for clinical classification, early caries corresponds to stages I and II: lesions visible only on a wet surface, and lesions that persist after drying [6]. Both stages encompass lesions without structural defects, where a conservative approach is appropriate and sufficient.

Clinically, early caries appears as a matte or chalky spot, sometimes with slight pigmentation in later stages. The lesion is localized primarily in the cervical region, on occlusal fissures, or on approximal surfaces. Upon probing, there is no "depression": the surface may be rough, but there is no structural destruction of the dentin yet. Symptoms are minimal or absent; occasionally, there is transient sensitivity to sweet or cold stimuli, which resolves after removal of the irritant. The absence of spontaneous pain distinguishes the initial stage from deeper lesions and forms the basis for a conservative treatment decision [7].

The decision regarding the reversibility of the process is based on a combination of signs: an intact surface without defects, the absence of a "depression" on probing, the absence of spontaneous pain, and localized damage without dentin involvement. Each sign on its own is insufficient; they are evaluated in combination, sometimes with confirmation via transillumination or a Bitewing radiograph for approximal locations. In the author's opinion, the combination of these signs as a whole allows for a well-founded choice of a conservative approach already during the initial examination.

Remineralization Therapy. Remineralization therapy saturates demineralized enamel with calcium, phosphate, and fluoride ions from the outside.

Fluorides interact with partially dissolved hydroxyapatite to form less soluble fluorapatite, reducing susceptibility to acid attacks [8]. Calcium-phosphate systems, particularly CPP-ACP and nanoforms of hydroxyapatite, increase the concentration of calcium ions in the pellicle, which enhances mineral deposition in the pores of the white spot. This restoration does not involve the growth of new tissue: the porous areas of the "white spot" are gradually filled with minerals, their permeability decreases, and optical homogeneity is restored.

A Cochrane review by Marinho et al. (2013), based on data from 22 randomized studies, confirmed that professional fluoridation statistically significantly reduces the incidence of caries in children and adolescents [9]. Walsh et al. (2019), in a systematic review of toothpastes with varying fluoride concentrations, demonstrated that higher concentrations are associated with a better preventive effect [10]. Twetman (2010) cautions: no single intervention will yield consistent results without concurrent correction of behavioral risk factors [11]. Where the patient makes no changes to diet or hygiene, a course of remineralizing therapy only temporarily slows the process.

Resin Infiltration. The infiltration method is based on the fact that low-molecular-weight resin, under the action of capillary forces, penetrates the porous structure of demineralized enamel and, after polymerization, blocks the diffusion pathway for acids and microbial substrates. No preparation is required. Paris et al. (2010) demonstrated in a randomized study that after 18 months, the progression of approximal lesions in infiltrated teeth was observed approximately three times less frequently compared to a watch-and-wait approach [12]. Martignon et al. (2012) confirmed these results in a three-year follow-up [15].

An additional advantage of the method lies in the alteration of the optical properties of the stain: the resin fills the pores with a refractive index close to that of healthy enamel, so the "white spot" becomes significantly less noticeable or completely invisible immediately after the procedure [7]. For patients with purely aesthetic concerns, such as spots following orthodontic treatment, this is often the sole reason for seeking treatment. The method is appropriate for approximal lesions, where remineralizing agents have limited access, and for aesthetically significant lesions of the anterior teeth.

The minimally invasive approach as a treatment strategy. Frencken et al. (2012) defined minimally invasive dentistry as a system encompassing early detection, risk assessment, remineralization at the preclinical stage, minimal tissue removal only when a defect has formed, and regular monitoring [4]. This approach finds its fullest practical application in early-stage caries: the disease is detected before it reaches the point of no return, and all conservative treatment options are still available.

Frencken et al. (2012) also emphasize that conservative management cannot be effective without the patient's active participation [4]. Explaining to the patient the connection between sugar intake frequency, hygiene quality, and lesion progression is no less important than the clinical procedures themselves. Terminological Clarification Innes et al. (2016) distinguish between non-cavitated and cavitated lesions primarily based on clinical and tactical principles: each stage dictates a different algorithm and a different extent of intervention [3].

Materials and methods. This study is based on a structured practice-based clinical outcome analysis — a retrospective observational treatment framework derived from the author's private dental practice. The sample included patients in whom, at the time of the initial examination, the lesion corresponded to ICDAS grades 1–2: a matte or chalky spot without surface disruption and without a "depression" upon probing, and without spontaneous pain. Patients with already established cavitation were not included.

The clinical examination included visual assessment, probing, and taking a history; sensitivity to cold and sweet stimuli was tested separately — if the reaction was brief and reversible, this confirmed pulp viability. When necessary, transillumination or a Bite-wing radiograph was performed. For the anterior teeth, which account for about a quarter to a third of all carious and non-carious cases, aesthetics were always taken into account when selecting a treatment method.

In the author's practice, several approaches were used in parallel. The main one was remineralization therapy: a course of applications of calcium- and fluoride-containing preparations (gels, varnishes) along with recommendations regarding hygiene and nutrition. Isolated fluoridation with varnishes served as a preventive adjunct. Resin infiltration was used for approximal and visible vestibular lesions. In cases of active or multiple lesions and increased caries risk, these methods were combined.

The remineralization course consisted of 3–5 procedures at 5–7-day intervals. The author deliberately chose this schedule: the tissues have time to gradually become saturated with minerals between sessions. Follow-up examinations were scheduled at 1 month, 3 months, and 6–12 months. The result was considered successful if the lesion did not increase in size, no cavitation defect appeared, and no new complaints arose. The criterion for failure was progression or symptoms requiring a switch to invasive treatment.

The Stoianov Early Caries Stabilization Protocol (SECSP). Based on the clinical decision logic developed through this analysis, the author proposes a structured approach to managing non-cavitated carious lesions: the Stoianov Early Caries Stabilization Protocol (SECSP).

The first component is lesion risk stratification. Each non-cavitated lesion is assessed by activity,

anatomical location, depth within ICDAS grades 1–2, and salivary factors. This stratification determines whether the lesion is managed as low-, moderate-, or high-risk, and directly informs the intensity of the treatment pathway.

The second component is compliance-adjusted treatment planning. Patient adherence is evaluated at the initial visit and reassessed at each follow-up. Where adherence is poor, the treatment plan is adjusted toward more mechanically reliable options — resin infiltration or a combined approach — rather than depending on remineralization alone, which requires consistent home care to be effective.

The third component is differential method selection based on lesion characteristics. Smooth-surface lesions detected at an early active stage are managed with remineralization therapy. Approximal lesions and aesthetically significant lesions of the anterior teeth are treated with resin infiltration. Active, multiple, or high-risk lesions are addressed with a combined approach, supported by scheduled follow-up at one month, three months, and six to twelve months.

In clinical practice, this framework has been associated with a reduction in unnecessary invasive treatment, earlier stabilization of non-cavitated lesions, and better conditions for long-term preventive management through preserved tooth hard tissue.

Results

Patient Presentation. Early-stage caries in the non-cavitated demineralization stage accounted for approximately 20–30% of all carious lesions. Fewer than half of this group sought treatment early enough to qualify for exclusively conservative management. In the remaining cases (50–60%), cavitation or a transitional stage was already observed during the initial examination, which limited the possibilities for non-invasive treatment.

Initial lesions were detected primarily during routine preventive examinations. Where complaints were present, patients mostly reported an aesthetic concern ("noticed a white spot") or mild, transient sensitivity to sweet foods. Patients had no spontaneous pain, nocturnal pain, or prolonged sensitivity to cold. This suggested that the pulp remained vital and allowed a conservative approach to be considered. However, most patients who came because of discomfort were already at the cavitated stage.

Effectiveness of Methods. The results showed a clear difference between the two groups. In patients who followed clinical recommendations and attended follow-up visits, initial lesions stabilized in 70–90% of cases. Among those with poor adherence, stabilization was observed much less often, in about 30–50% of cases.

Remineralization therapy on smooth surfaces resulted in stabilization in 70–80% of cases with proper hygiene. It worked best on fresh lesions without pigmentation. Within 2–4 weeks, the spot became less dull and a sheen appeared; after 1–3 months, the process

either stabilized completely or the lesion became practically invisible. It is important to understand that restoration involves saturating the existing porous structure with minerals, not the growth of new tissue.

Resin infiltration proved to be a more predictable method for approximal lesions and achieved stabilization in 80–90% of cases. Immediately after the procedure, the spot became significantly less noticeable or disappeared within the enamel structure, which often proved to be a decisive factor for patients with anterior teeth and aesthetic concerns. After 3–6 months, the aesthetic effect persisted, and the lesion did not progress. In this case, infiltration blocks the diffusion pathway, halting progression without restoring the damaged tissue.

The combined approach yielded the highest stabilization rate: 85–95%. The difference between isolated remineralization and the combined approach was approximately 10–15%. Mechanical sealing of the lesion with resin and biological restoration of the mineral balance complement each other. The author prefers the combined approach for active or multiple lesions and considers it the most reliable option in cases of increased cariogenic risk.

Average distribution of clinical outcomes. According to clinical observations, out of 10 patients with

similar non-cavitory lesions, 6–7 achieve complete stabilization of the process, 2–3 achieve partial stabilization without progression, and 1–2 experience caries progression requiring invasive treatment. Progression in most cases was attributed to non-compliance with recommendations and the absence of follow-up examinations, or to the fact that the depth of the lesion was underestimated during the initial examination.

Recurrence and Transition to Invasive Treatment. Recurrence or progression of caries was observed in 15–25% of patients, primarily within 6–12 months after completion of the active treatment course. Approximately 20–40% of patients eventually required a transition to restorative treatment: either due to the formation of a cavity or because the depth of the lesion at the outset was greater than clinically apparent.

In patients without conservative treatment and without control of risk factors, progression to carious cavities was observed in 40–70% of cases within 1–2 years. Some lesions remained stable or progressed very slowly, especially with a low overall cariogenic load. However, it was not always possible to predict in advance which lesion belonged to which group based solely on clinical data.

Results in children and adults. Children usually showed a faster response to conservative treatment.

Clinical Algorithms for Early Caries Management

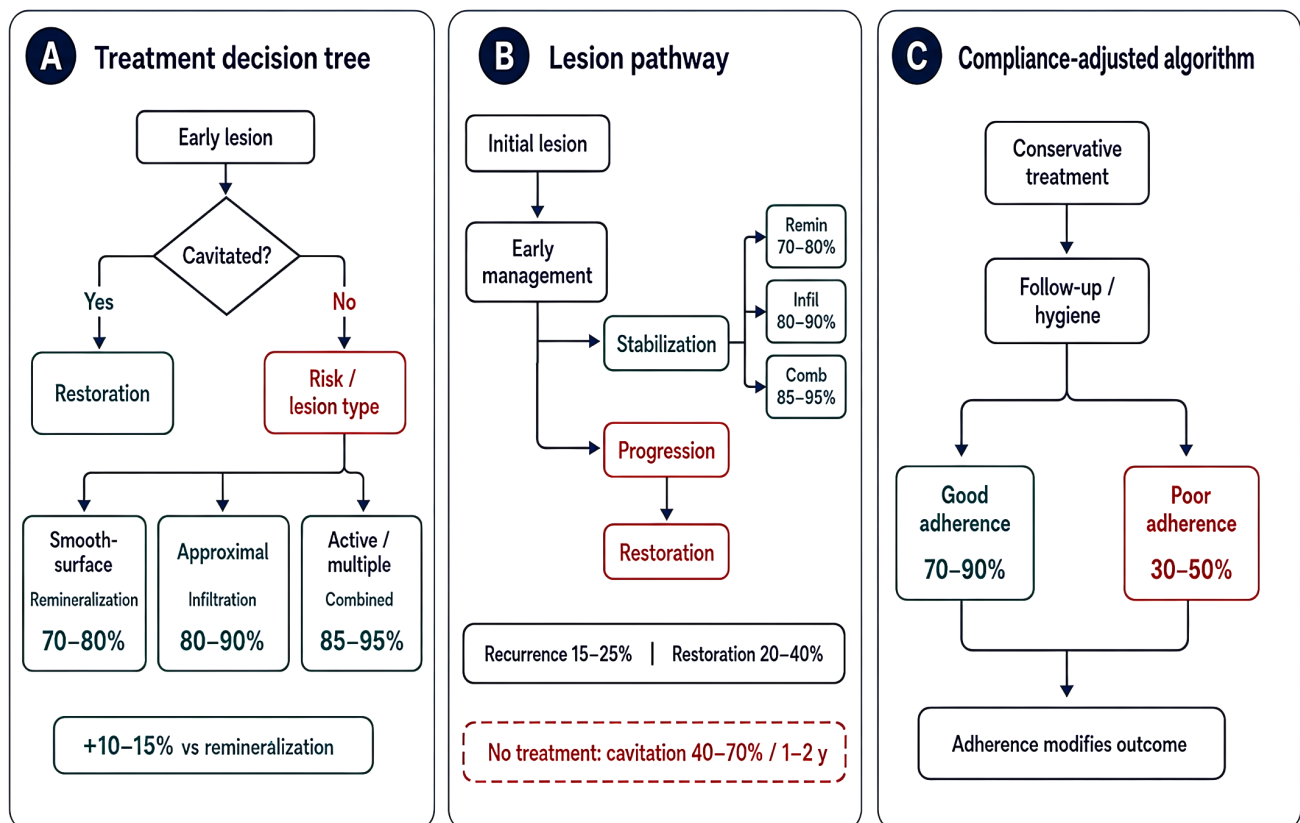


Fig. 1. Effectiveness of Conservative Methods in Early Caries Management

Initial lesions stabilized in 80–90% of cases, while recurrence was relatively uncommon. The first changes were often visible after 2–4 weeks, and stabilization was usually reached within 2–3 months. Parental support was important here: when parents monitored daily hygiene and helped maintain the routine, adherence was comparatively high.

In adults, the results were more modest: stabilization in 60–75% of cases, recurrence in 20–30%, and a compliance was noticeably lower. Tissues responded more slowly — the first changes appeared after 3–4 weeks, and complete stabilization took 3 to 6 months. A combined approach was more often required. The difference between the groups is easily explained: children have higher enamel mineral activity and better buffering capacity of saliva; in adults, these mechanisms are weaker, so the outcome depends even more on behavior between visits.

The Impact of Timely Treatment. When patients sought treatment at the non-cavitory stage, stabilization was achieved in 80–90% of cases, and in a significant portion of these, remineralization therapy and hygiene correction were sufficient. In cases of late presentation, when a carious lesion had already formed or the process was approaching the dentin, the effectiveness of the conservative approach decreased to 40–60%, and in 50–70% of cases, preparation was already required.

Discussion

Clinical results compared to study data. Stabilization rates of 70–90% in compliant patients and

30–50% in non-compliant patients correspond to the range described in randomized trials, although direct comparison is complicated by differences in inclusion criteria. Paris et al. (2010) reported a reduction in the progression of proximal lesions by approximately threefold 18 months after infiltration [12]; Martignon et al. (2012) confirmed these results in a three-year follow-up [15]. The stabilization rate with infiltration in the author's own practice (80–90%) corresponds to the upper limit of these data, which likely reflects the selection of patients with regular follow-up.

The fact that 50–60% of patients with initial caries present after cavitation has already occurred implies that the actual potential for conservative management is significantly higher than what is currently achieved in practice. A significant portion of the lesions that required preparation and filling could have been stabilized earlier. Preventive examinations, in this context, allow for the detection of non-cavitated lesions before they progress to a carious form, which defines their clinical role.

Patient Compliance and Behavior. After treatment, daily patient behavior often determined whether the lesion remained stable. Adherence explained approximately 50–60% of the differences in outcomes. This finding positions compliance not merely as a confounding variable, but as a primary prognostic factor within a behavior-integrated preventive dentistry model — a compliance-based prognostic system embedded in the SECSP framework. The most common problems were frequent sweet snacks, missed evening brushing, lack of interdental cleaning, and unfinished

Recurrence and Transition to Invasive Treatment

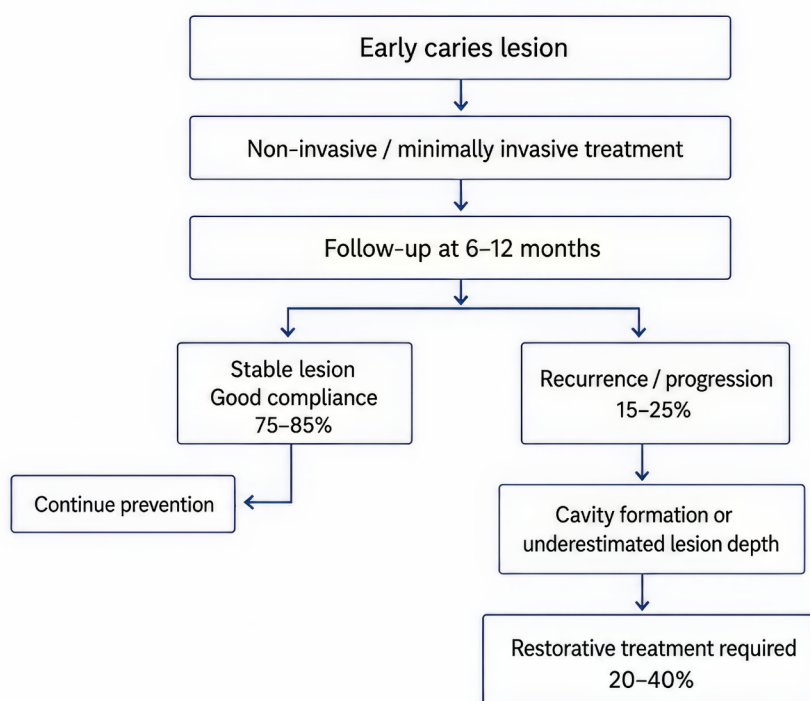
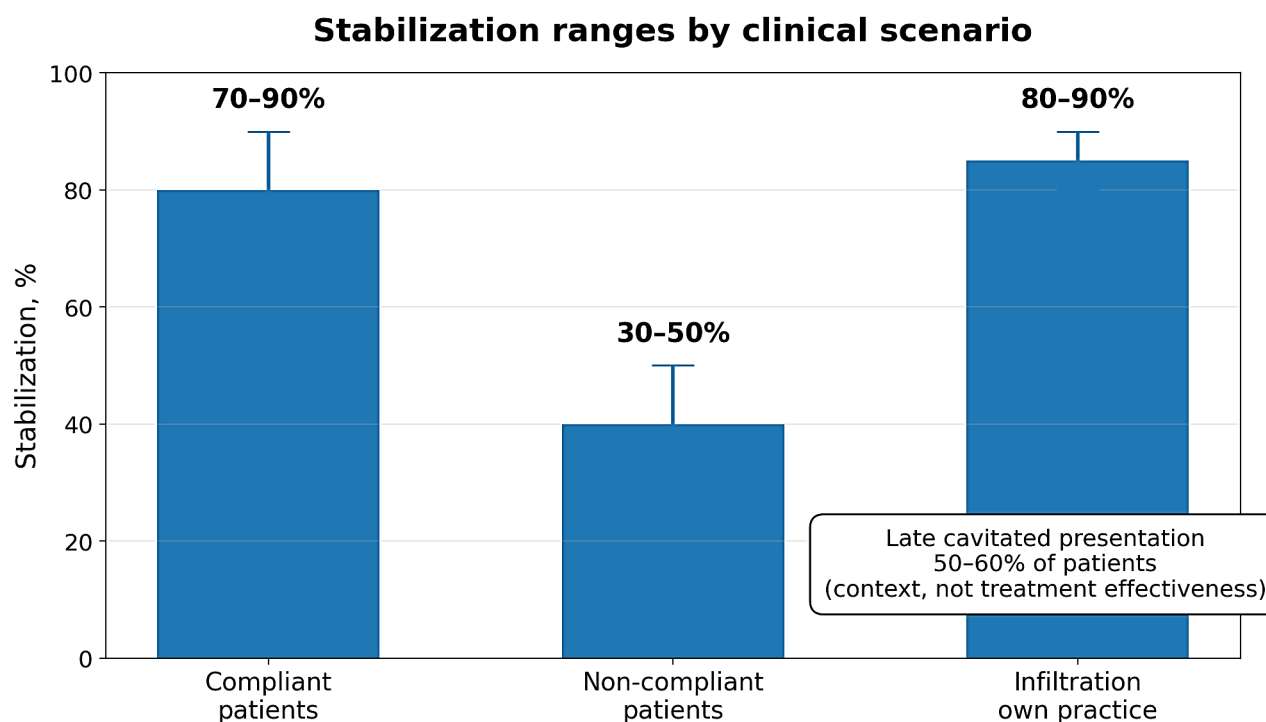


Fig. 2. Compliance-adjusted pathway of recurrence and transition to restorative treatment



Late cavitated presentation is shown separately because it reflects diagnostic timing, not treatment effectiveness.

Fig. 3. Stabilization Ranges and Preventive Potential in Early Caries

fluoride courses. When there was no pain, patients often assumed that the lesion was no longer a problem. Without follow-up, early progression could remain unnoticed for several months.

Frencken et al. (2012) emphasize that a minimally invasive approach requires active patient participation [4]. In the author's clinical practice: approximately 30–50% of patients significantly improve their oral hygiene after the cause-and-effect relationships are explained; another 20–30% consistently follow the recommendations; the rest revert to their previous habits. About half of the patients willingly choose “treatment without drilling,” but are not always ready to fulfill the part of the agreement regarding dietary habits and regular checkups.

Specifics and visual aids worked better than any general advice: showing a photo of the lesion, explaining that the problem isn't the amount of sugar, but how often it comes into contact with the enamel. The author often told patients directly: “If you don't change your habits, this spot will turn into a cavity in a few months.” Those who understood this and returned for follow-up visits had significantly better results.

Biological and Clinical Factors. Even with good hygiene, some lesions stabilize more slowly. This may be related to low salivary buffering capacity, reduced remineralizing potential, xerostomia, or systemic disorders of mineral metabolism. In these situations, the clinician may choose resin infiltration or schedule follow-up visits at shorter intervals.

Anatomy and access also matter. Orthodontic appliances, deep fissures, and approximal surfaces can prevent remineralizing agents from reaching the lesion properly. Because of this, standard remineralization is not always enough, and the treatment approach may need to be adjusted.

A separate source of failure: underestimation of lesion depth during the initial examination. In approximately 30% of unfavorable cases, the lesion was found to be closer to the dentin than expected based on clinical data. Where the clinical picture is ambiguous, a bitewing radiograph or transillumination reduces the risk of error.

Dynamics of Results. Comparing his own practice over time, the author notes an increase in the stabilization rate from approximately 65–70% to 80–85%, while the frequency of progression to preparation decreased from 25–30% to 15–20%. Several changes in approach explain this result. The transition to the principles of selective caries removal has allowed for the preservation of dense dentin over the pulp even in cases of deeper lesions. Infiltration has begun to be used more widely for approximal and aesthetically sensitive lesions, which has affected the number of teeth preserved without preparation. Finally, follow-up examinations have become more systematic — progress is now recorded in a timely manner, and treatment strategies are adjusted before the situation worsens.

Among those who returned for follow-up (about 50–60%), stable results were recorded in 80–90%

of cases; among those who did not return, only in 50–60%. There are two explanations for this: timely detection of deterioration allows for adjustments to treatment strategy before complications arise, and regular contact with the doctor prevents the patient from “forgetting” about treatment between visits.

Study Limitations. The retrospective nature of the analysis and the single-center sample limit the external validity of the conclusions. These indicators should be interpreted as clinical observations, not as results of a randomized study. The enamel condition was not verified histologically, and the assessment did not include microbiological monitoring or standardized saliva testing. Although these data are less controlled, they are based on real clinical practice. Patients differed in adherence: some followed the recommendations, some did so only partly, and some did not return for follow-up. For this reason, the observations show not only the potential of conservative treatment, but also its limits in everyday work.

Conclusions. Conservative management of early-stage caries is effective when the lesion is detected before cavitation occurs and the patient returns regularly for follow-up. Under these conditions, stabilization becomes the typical clinical outcome rather than the exception. Of 10 patients with non-cavitated lesions, in 6–7 the process stabilizes completely, in 2–3 partially, and in 1–2 progresses to the cavitation stage and requires preparation.

The choice of method depends on the location, activity, and clinical characteristics of the lesion. Remineralization therapy is appropriate for smooth surfaces and fresh lesions; resin infiltration provides better predictability for approximal and aesthetically significant lesions; a combined approach yields the highest stabilization rate (85–95%) and is indicated for active or multiple lesions. The author prefers the combined approach in cases of increased caries risk and gives it priority in such cases.

Patient adherence explained approximately 50–60% of the differences in treatment outcomes. In practice, the main risk was often the patient’s attitude to early lesions. If there was no pain, follow-up visits and fluoride treatment were easily postponed or ignored.

Therefore, the final result depended not only on the chosen method, but also on whether the patient understood the risk and continued daily hygiene control.

Early detection changed the prognosis considerably. When non-cavitated lesions were diagnosed in time, stabilization without invasive treatment was achieved in 80–90% of cases. With delayed diagnosis, this rate decreased to 40–60%. Preventive examinations were therefore important because they allowed clinicians to detect lesions before cavitation, while conservative management was still likely to work.

The use of selective caries removal, resin infiltration, and systematic recall was associated with a reduction in progression to invasive treatment from 25–30% to 15–20%, demonstrating the practical impact of a structured minimally invasive approach on preservation of tooth hard tissue and reduction of unnecessary drilling. These outcomes informed the Stoianov Early Caries Stabilization Protocol (SECSP): a compliance-integrated minimally invasive treatment framework combining risk stratification, differential lesion management, and a behavior-integrated preventive dentistry model.

The stepwise structure of the SECSP makes it reproducible across different clinical settings, clinically transferable to general and preventive dentistry practice, and directly applicable within standard preventive dentistry workflows. As these findings remain observational, prospective randomized validation with standardized adherence assessment is indicated.

Author’s contribution. This study introduces:

- a structured prognostic approach for early-stage caries management based on longitudinal practice-based clinical outcome analysis;
- the Stoianov Early Caries Stabilization Protocol (SECSP): a compliance-integrated minimally invasive treatment framework;
- a differential decision pathway for non-cavitated lesions incorporating risk stratification, compliance-adjusted planning, and method selection;
- a behavior-integrated preventive dentistry model identifying patient adherence as the primary prognostic determinant in conservative caries management.

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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ПЕДАГОГІЧНІ НАУКИ

CONTEMPORARY PEDAGOGICAL PARADIGMS IN TYPEFACE DESIGN EDUCATION

Summary. The article examines the current modification of pedagogical systems in the field of typeface design, necessitated by the cognitive turn in visual communications and total digital integration. The author substantiates the transition from craft-oriented instruction to the concept of systemic “meta-design”, integrating profound humanitarian reflection and high-tech engineering. The study verifies a trialectic model of education (history – theory – applied praxis) and analyzes the experience of leading international design programs, including institutions in the United States and Europe, within the framework of STEAM, Critical Design and Problem-Solving strategies. Particular attention is paid to the methods of deconstructing historical forms as “generative matrices” and the overcoming of “algorithmic conformism” through heuristic search. The research defines a new professional identity – the type engineer, whose activity is directed toward the creation of adaptive sign systems within the context of cognitive ecology. The crystallization of an individual authorial idiom is recognized as the culmination of the educational trajectory, serving as a manifesto of professional subjectivity and the designer’s ethical responsibility toward the visual culture of post-industrial society.

Key words: typeface design, typography, typeface engineering, STEAM, variable fonts, deconstruction of historical letterforms, Critical Design.

Introduction. Within the epistemological field of visual communications, typeface design is a category of an autonomous sign system determining the modalities of production and transmission of meanings. Being a veritable architectonics of thought, typography today acts as a complex cognitive interface where sign morphology is inextricably linked with the mechanisms of perception and data interpretation [1]. Thus, a necessity for a scrupulous revision of existing pedagogical strategies is logically formed, requiring the formation of a complex meta-design that unites humanitarian reflection and high-tech engineering [2].

In this subject matter, contemporary type design education operates as an internationally interconnected network of shared methodologies rather than a set of isolated national traditions [3]. Programs such as the Master Type and Media at the Royal Academy of Art in The Hague (KABK), the MA Typeface Design at the University of Reading, and graduate programs at RISD, Yale and Cooper Union share pedagogical DNA through faculty exchange, alumni networks and collaborative research. The principles of Critical Design and interdisciplinary integration (within the STEAM strategy) have become common currency across these institutions. In this interconnected landscape, typeface design is conceptualized not as a mediocre mastery of a set of software presets, but as a study of the

boundaries between linguistic structure and visual form. The cross-pollination between academic programs and global IT ecosystems facilitates the implementation of algorithmic and generative methods in design pedagogy, while maintaining a commitment to philosophical and calligraphic heritage as an axiological foundation.

Consequently, the educational trajectory in the field of typeface design is constructed as a process of sequential deconstruction and subsequent synthesis of professional competencies. The historical typeface in this coordinate system ceases to be an object of passive retrospection. Finally, it transforms into a generative matrix, allowing the student to realize the genesis of form and develop deep project thinking.

Parallel to this, digital instrumentation is realized as an active co-author — that is, an extension of the designer’s cognitive abilities, changing the very logic of form-making. The result of such a multi-level pedagogical impact is the crystallization of the authorial idiom — an individual visual language that is not a product of an accidental heuristic search, as one might erroneously assume, but a logical result of in-depth analytical work at the intersection of history, theory and technology.

It is interesting to note that in conditions of excessive semiotic noise and information entropy, the role

of typeface design and typography itself is viewed as a tool of cognitive ecology — a discipline aimed at minimizing cognitive load and structuring visual space. Typeface design education in this context becomes an interdisciplinary study at the junction of perception psychology and ergonomics, where the primary task of the designer is the creation of adaptive sign systems capable of ordering global data flows without loss of semantic transparency. Particular value in the context of professional training is represented by the Problem-Solving approach, a methodology that has gained broad adoption across type design programs internationally, from KABK and ECAL to RISD and the Type@Cooper program.

The rapid digitalization of the type design industry has dramatically lowered the barriers to entry through accessible software such as RoboFont, Glyphs and FontLab. As a result, the field has experienced a substantial increase in the number of typeface creators, which has fostered wider participation, but has also brought renewed attention to issues of originality, authorship and quality in contemporary type production. In this regard, the concept of an ethical imperative and the designer's responsibility for the visual landscape is introduced into academic discourse. The contemporary educational concept focuses on the cultivation of critical thinking, in which the mastery of technology is accompanied by an awareness of copyright, intellectual honesty and the cultural significance of each created symbol. The authorial style in this case acts as a manifesto of professional responsibility.

In addition, the educational process today is forced to overcome digital determinism — a situation where software capabilities begin to dictate the logic of form-making. A relevant methodological model involves a return to analog intuition as a source of vital plasticity, where manual practice serves as a tool for understanding the physics of the sign, which is subsequently translated into a high-tech digital product.

Materials and methods. The relevance of this study is conditioned by the ongoing transformation of typeface design in response to changes in its technological medium. While typography has historically functioned as a cognitive interface shaping the perception of written information, the shift from print to digital environments has significantly redefined the conditions of its production, distribution, and use.

Amid global digitalization and the exponential growth of semiotic noise, traditional craft-based instructional methodologies prove insufficient to address the expanded scope of contemporary practice. This necessitates a revision of pedagogical strategies and a transition toward an interdisciplinary STEAM-oriented framework that integrates humanitarian reflection, historical analysis, and advanced technological competencies. The experience of leading international institutions, demonstrating the synergy between design education and the technology sector, becomes

an essential benchmark for bridging the gap between academic theory and dynamic technological praxis.

The scientific novelty of the research lies in the conceptualization of typeface education as a system of comprehensive meta-design, operating at the intersection of linguistics, programming and neuroaesthetics. The study proposes a trialectic model of instruction, wherein the history of writing is viewed as a generative matrix for professional reverse-engineering. The author substantiates the concept of analog shadows in the digital environment and formulates the role of the typeface as a tool for cognitive ecology. The research defines a new professional identity — the type engineer, whose authorial idiom is the result of disciplined heuristic search rather than an accidental creative act.

The methodological foundation of this research is based on interdisciplinary convergence, uniting the principles of art historical analysis, cognitive psychology, typeface engineering and contemporary pedagogical anthropology [4]. The study is grounded in a trialectic model of professional consciousness development, presupposing an inextricable synthesis of historical reflection, normative typographic theory and applied praxis. The research draws upon the critical analysis of educational strategies developed across the international type design community (specifically, the STEAM and Critical Design paradigms), viewing them as catalysts for the transformation of typeface design from a craft discipline into high-tech meta-design [5].

The analytical tool of the work is the method of visual hermeneutics and the profound deconstruction of historical typeface forms. The research process includes the visual archaeology of primary sources — incunabula, punches and archival sketches (based on the collections of the Letterform Archive and the Plantin-Moretus Museum) [6]. This approach enables the verification of the hypothesis of the typeface as the genetic code of culture and the identification of invariant morphological structures that retain their functionality amidst shifts in technological regimes. The reverse-engineering of the professional mindset of past masters is utilized here to form the epistemological matrix necessary for the design of contemporary sign systems.

The practice-oriented component of the research relies on the methodology of analog modeling and tactile diagnostics through calligraphic practices. The use of the broad-edged pen and the study of the ductus are defined as propaedeutic methods that prevent digital determinism and establish the foundation for a conscious understanding of the physics of the sign. Subsequently, the methodology expands to the principles of parametric design within multidimensional design spaces. Work with variable fonts and the algorithmic automation of processes (including Python scripting) are regarded as means of developing systemic engineering thinking, enabling the manipulation of the typeface as a dynamic structure rather than a static graphic object.

An important layer of the methodology is the integration of cognitive science and neuroaesthetics into the design process. The research includes the analysis of the physiology of visual perception and the design of optical sizes as a method for compensating for visual distortions. In this context, typeface design is conceptualized as a tool of cognitive ecology aimed at structuring the information space and minimizing entropy. The Problem-Solving method serves as the primary vector here, shifting the educational process from the plane of abstract creativity to the plane of searching for functionally relevant technological and social solutions.

The concluding methodological cycle is based on iterative heuristic practices and the culture of design critique (The Crit). The process of forming an authorial idiom is investigated through the lens of intellectual maieutics — a Socratic dialogue between mentor and student aimed at decoding individual graphic intentions. The evaluative criteria for final results encompass not only aesthetic authenticity, but also technological efficiency, systemic stability and the author's ethical responsibility. Such a comprehensive approach allows for an objective assessment of the effectiveness of contemporary pedagogical paradigms in the context of training specialists capable of meeting the challenges of post-industrial society.

The limitations of this work are related to the predominant focus on academic models within the Latin typographic tradition, which may impose a certain cultural and technological filter on the universality of the presented conclusions. Given the high volatility

of the contemporary digital environment, the rapid development of generative AI and immersive technologies (AR/VR) creates a risk of partial obsolescence of specific instrumental cases. Furthermore, the research is primarily theoretical and methodological in nature. For the final verification of the proposed paradigms, further longitudinal empirical observations regarding the effectiveness of their implementation in various sociocultural and educational contexts are required.

Instructional methodologies for typeface engineering within the design education framework. In its entirety, the methodology of typeface design instruction is based on a systemic engineering approach. Within the academic discourse, typeface engineering is defined as a complex iterative process combining morphological analysis, mathematical precision in contour construction and a deep understanding of the typeface file's software architecture [7]. The key task of pedagogy in this context is the formation of systems thinking, wherein the student perceives the typeface not as a set of disparate glyphs, but as a holistic dynamic structure capable of adaptation across diverse technological environments (see: Figure 1. The iterative engineering cycle).

The initial stage of instruction traditionally relies on the methodology of analog modeling through the practice of calligraphy and the use of the broad-edged pen [8]. This approach, deeply integrated into leading design schools worldwide, serves as a tool for the deconstruction of the logic of typographic form-making. Manual mastery of the ductus, contrast distribution

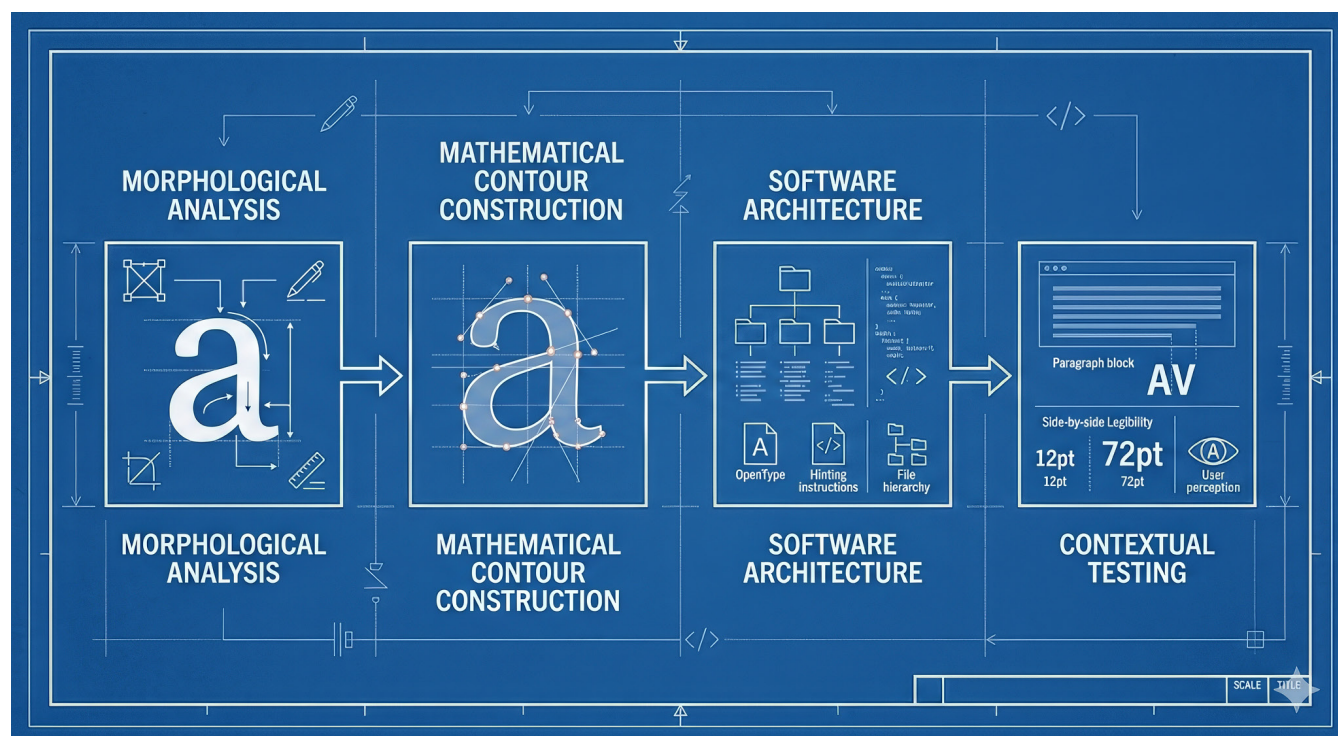


Fig. 1. The iterative engineering cycle
 Source: compiled by the author

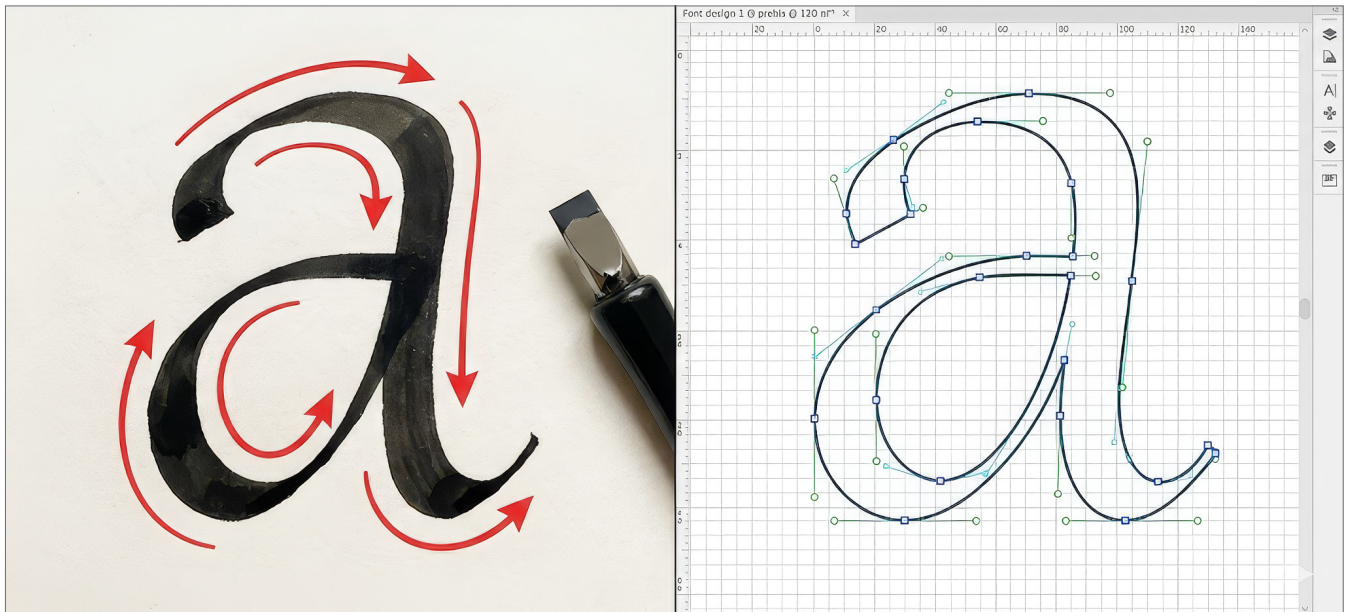


Fig. 2. From ductus to vector

Source: compiled by the author

and stroke dynamics allows the learner to physically sense the sign's architectonics (see: Figure 2. From ductus to vector).

Further development of the methodology presupposes the integration of algorithmic design methods, including work with interpolation and variable font masters. In the contemporary educational environment, the learning process is inextricably linked with the mastery of parametric design logic, where the typeface is viewed as a flexible system existing within a multidimensional space of weights, widths and optical sizes.

Here, the pedagogical strategy shifts toward exploratory research. Students solve engineering problems regarding the optimization of inter-character spacing (kerning and sidebearings) and hinting, which requires aesthetic reflection and an analytical approach to the perception of micro- and macro-typography.

Separately, within the structure of the educational process, the Problem-Solving methodology, adopted across a broad range of international type design programs, should be noted. According to the tenets of this approach, typeface design is conceptualized as a search for a solution to a specific communicative or technological problem. Educational tasks are formulated through the prism of functional relevance — addressing challenges that reflect the genuine complexity of contemporary typographic practice. Such challenges include the adaptation of typefaces across heterogeneous display environments, from low-resolution screens to high-density panels, where maintaining legibility and visual consistency constitutes a significant technical undertaking. Similarly, the design of multi-script systems, variable fonts for dynamic interfaces, and typographic solutions for dense information environments — such

as navigation systems and data visualization — represent paradigmatic problem spaces within current professional discourse. Accessibility, too, figures as a relevant dimension: while research does not support the claim that specific letterforms can remediate conditions such as dyslexia, well-designed typefaces demonstrably contribute to broader readability, cognitive comfort, and inclusive communication. A paramount methodological element, established as a standard pedagogical tool across leading type design programs from The Hague and Reading to New York and Basel,

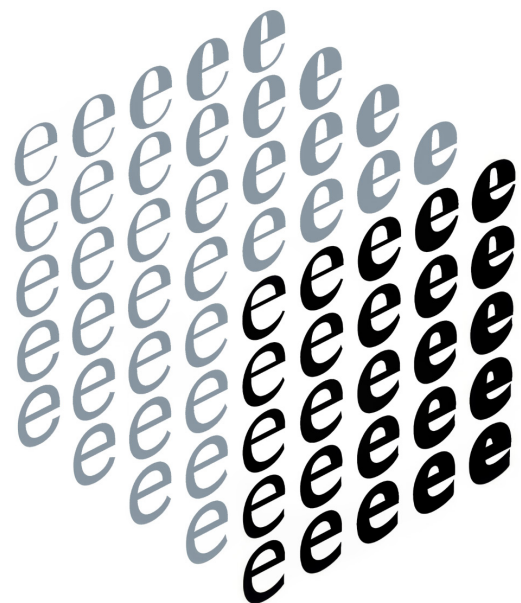


Fig. 3. 3D design space cube

Source: compiled by the author

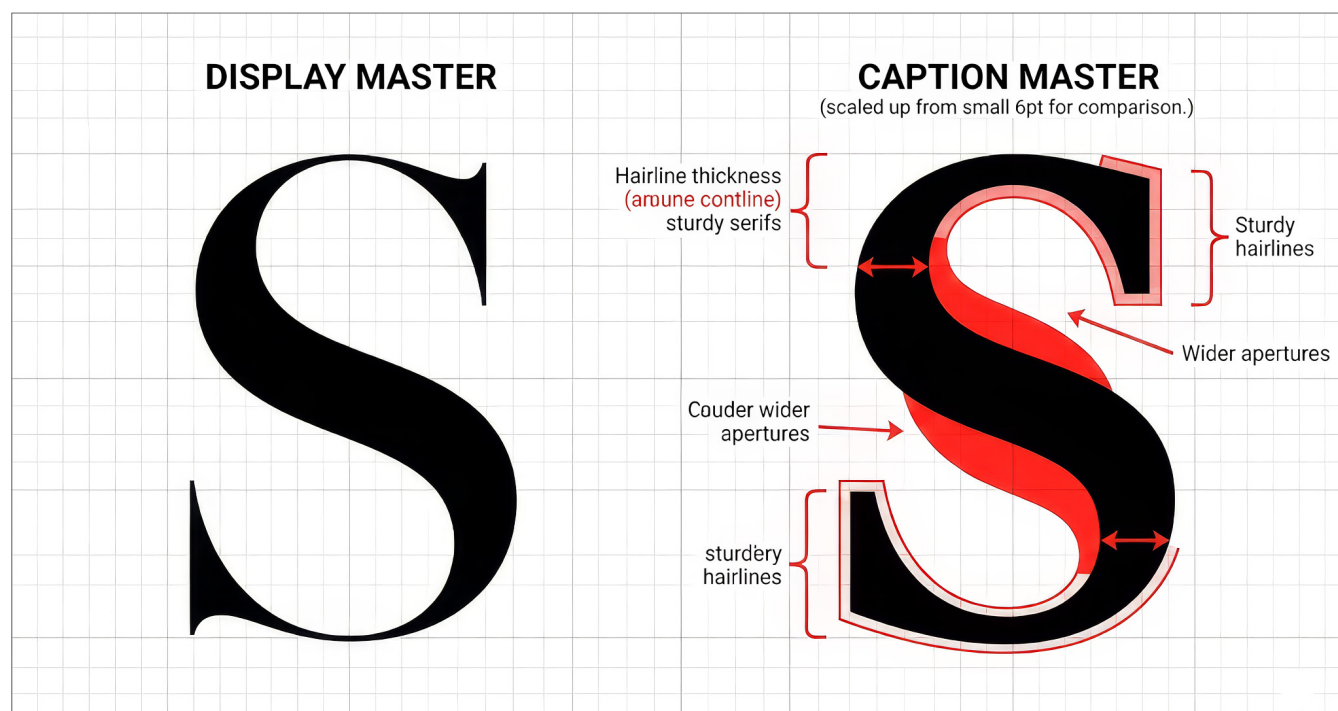


Fig. 4. Optical size compensation
 Source: compiled by the author

is the design critique format. Within the educational framework, this is a tool for the profound analytical deconstruction of the project. Collective review of the typeface system trains the student to provide an argumentative defense of their engineering decisions

and to distinguish subjective aesthetic preferences from objective criteria of legibility and systemic logic. This iterative feedback loop forms a critical distance between the author and their product, which is crucial for professional growth.

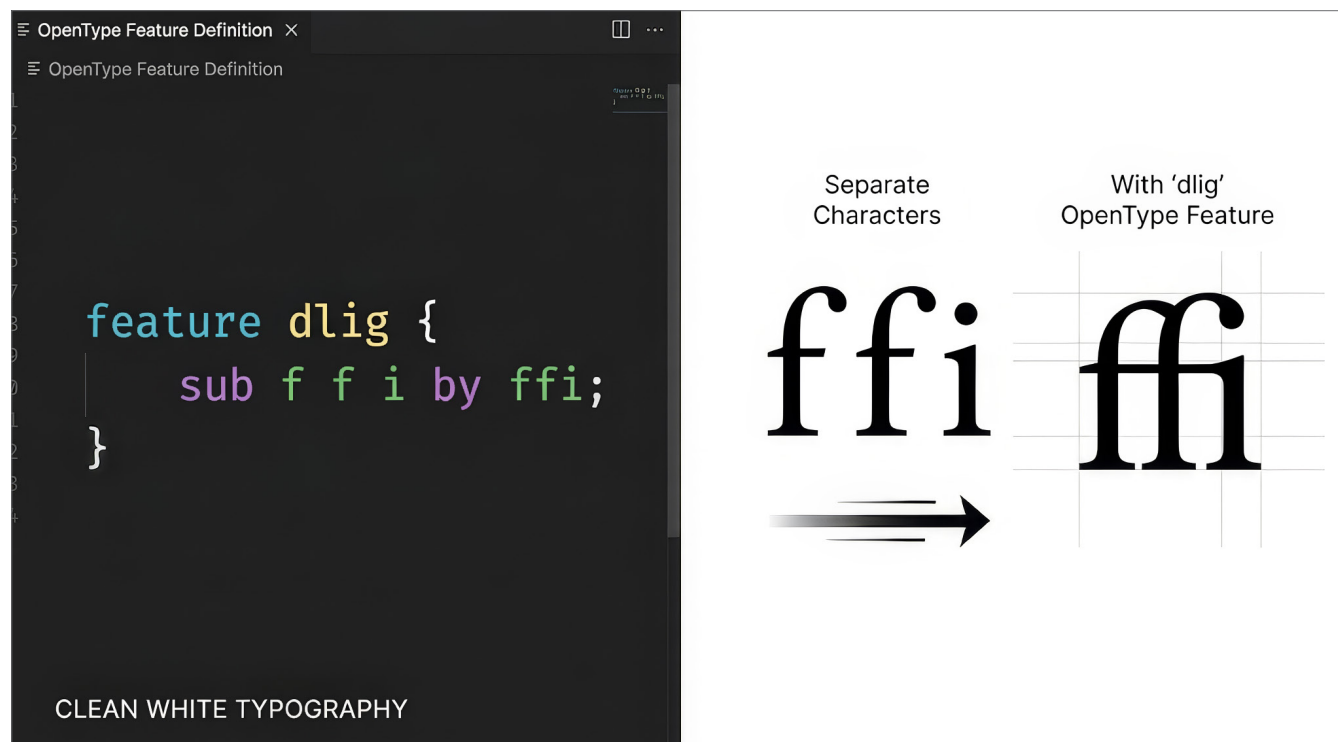


Fig. 5. OpenType logic (the bridge)
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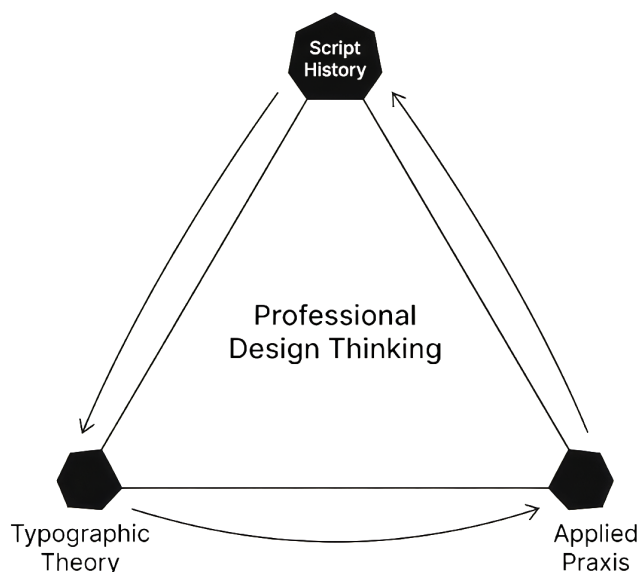


Fig. 6. The trialectic model diagram

Source: compiled by the author

The concluding element of the methodological framework is the principle of critical analysis and self-reflection. In the process of creating a typeface project, the student undergoes stages of testing in real-world contexts of use, which allows for the verification of the adopted engineering solutions. This iterative cycle from historical analysis and calligraphic sketching to software assembly and contextual approbation forms the professional competence of

a specialist capable of reproducing existing canons and constructing new visual languages that respond to the challenges of post-industrial society.

It is necessary to integrate the study of the physiology of vision into the methodology of modern typeface engineering. The instructional process includes the analysis of how the human eye interprets sign form under various point sizes and lighting conditions [9].

Students master the creation of “optical sizes”, where the engineering task lies in the subtle compensation of visual distortions: widening sidebearings, increasing counters and accentuating serifs for small point sizes. This transforms design from a purely graphic task into an applied research project at the intersection of neuroaesthetics and optics (see: Figure 4. Optical size compensation) [10].

It is also noteworthy that typeface design in the academic context is increasingly viewed as a bridge between linguistics and programming. Students study not only the form of the letter, but also the logic of OpenType features — the programming of ligatures, contextual alternates and diacritic systems (see: Figure 5. OpenType logic (the bridge). This requires an understanding of the grammatical structures of various linguistic groups and the ability to translate linguistic rules into the language of algorithms.

As a result, the educational process becomes a truly interdisciplinary research endeavor, where the designer acts simultaneously as a philologist, a researcher of visual culture and a developer of software architecture.

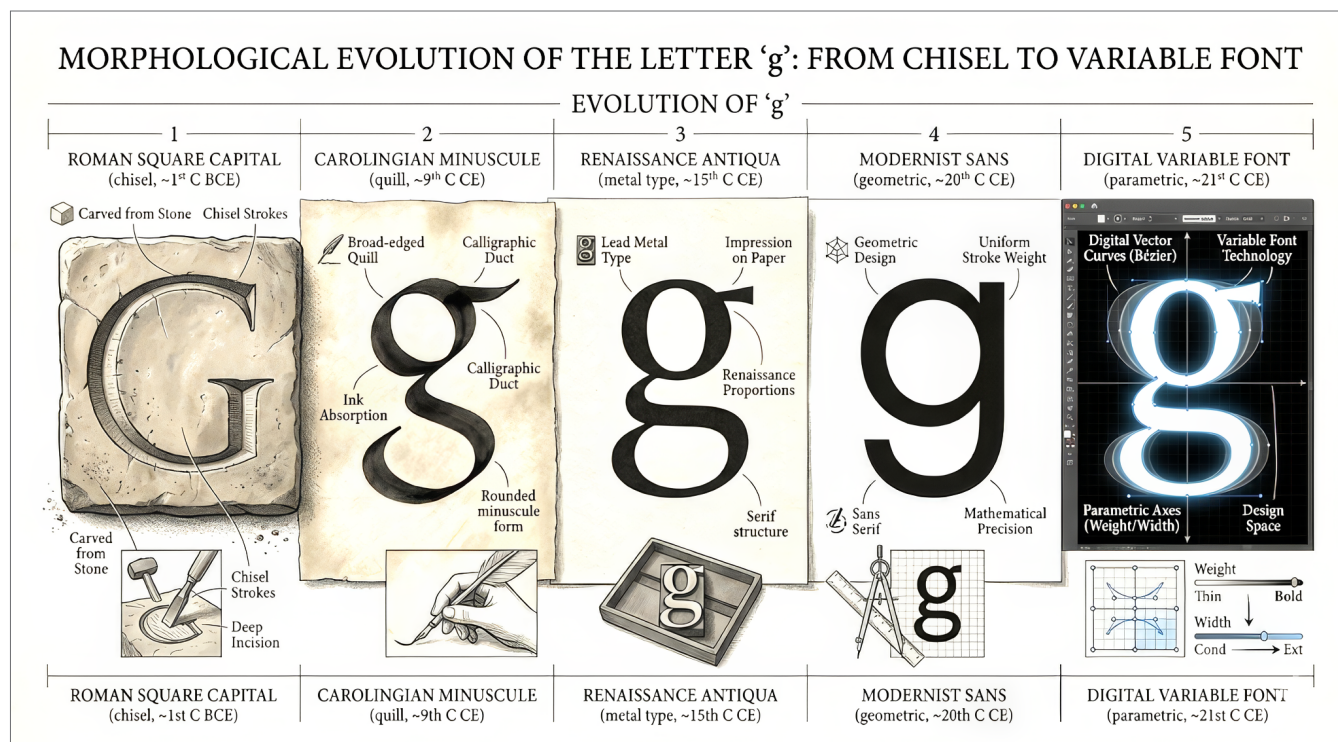


Fig. 7. The morphological genetic code

Source: compiled by the author

The synthesis of script history, typographic theory and applied praxis. The integration of historical heritage, theoretical basis, and practical implementation represents a trialectic model determining the maturity of professional design thinking [11]. In this coordinate system, the history of writing acts as a true genetic code of visual form (see: Figure 6. The trialectic model diagram).

Understanding the evolution of the grapheme, including epigraphy, medieval manuscripts and Renaissance masterpieces, allows the designer to comprehend the logic of the ductus, weight distribution and the dynamics of swells as a result of centuries-long morphological adaptation of the tool to the material [12]. Historiosophical reflection thus transforms into an active tool of deconstruction, allowing for the extraction of fundamental principles of sign construction and their adaptation to the challenges of the digital environment (see: Figure 7. The morphological genetic code).

Typographic theory in this synthesis serves as a normative framework ensuring the structural integrity of the visual message. It operates with categories of systematicity, hierarchy and proportion, translating an intuitive artistic gesture into the language of verified regularities. Contemporary theoretical discourse includes not only the rules of micro- and macrotypography, but also the semiotic analysis of the interaction between form and content [13]. As mentioned above, theory serves as a bridge between historical experience and modern cognitive requirements. It explains why the classical proportions of antiqua remain

the benchmark of legibility and how these parameters can be mathematically interpreted in variable font algorithms. Without a solid theoretical foundation, practical work risks degenerating into superficial stylization, devoid of systemic logic (see: Figure 8. The normative theoretical framework).

Applied praxis is the point of crystallization where historical knowledge and theoretical concepts acquire physical (or digital) embodiment. Today, praxis is defined as research through design. The design process becomes an iterative cycle in which hypotheses formulated on the basis of theory and history are verified in real technological conditions. It is at the implementation stage that the critical collision of canonical forms with the limitations of modern screen technologies and software interfaces occurs. Successful synthesis in this vein signifies the designer's ability to preserve the humanistic spark of calligraphic heritage by subordinating it to the rigorous discipline of program code and functional client requirements.

A defining pedagogical model in this branch is the concept of intellectual craftsmanship, cultivated across leading programs internationally. At institutions such as KABK, Reading, ECAL, Type@Cooper and Yale, the synthesis of history, theory and practice is realized through interdisciplinary projects where students deconstruct historical specimens drawn from diverse typographic traditions to create innovative interface solutions. Such an approach eliminates the gap between academic theory and industrial praxis, transforming the designer into an architect of meanings

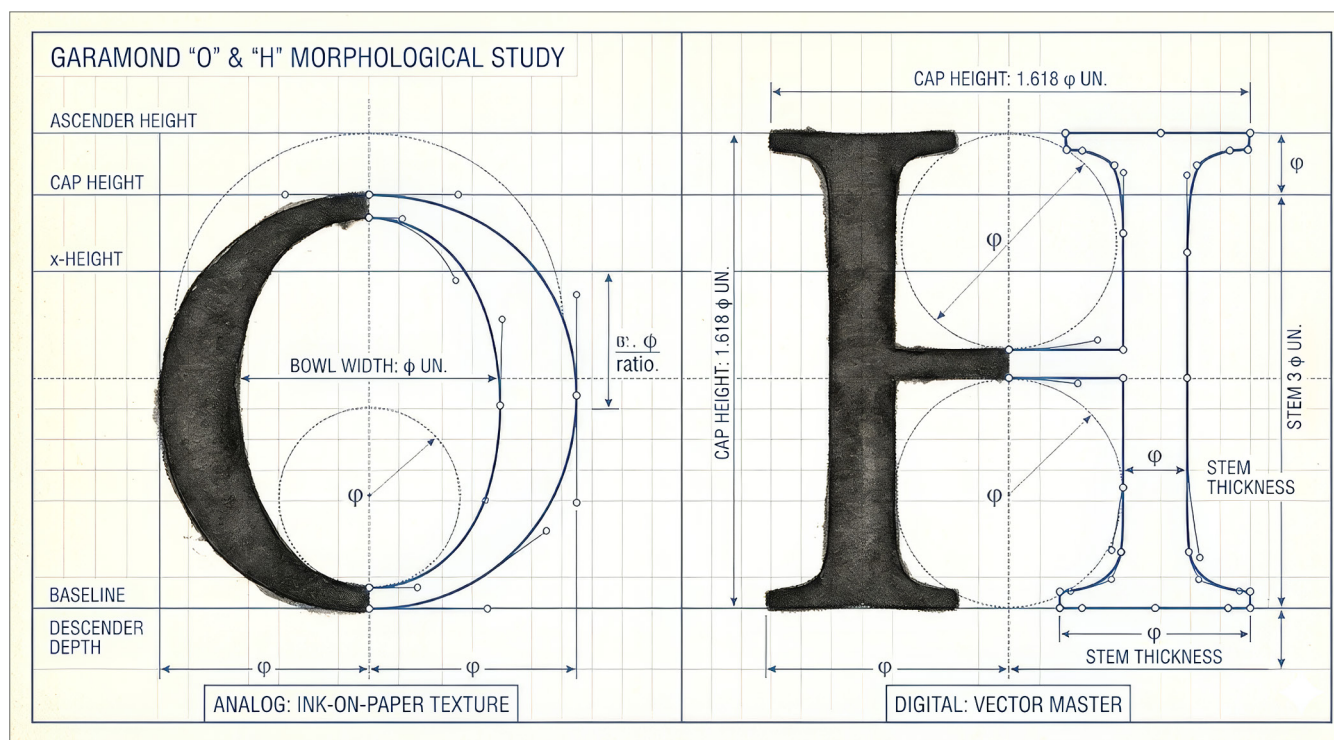


Fig. 8. The normative theoretical framework

Source: compiled by the author

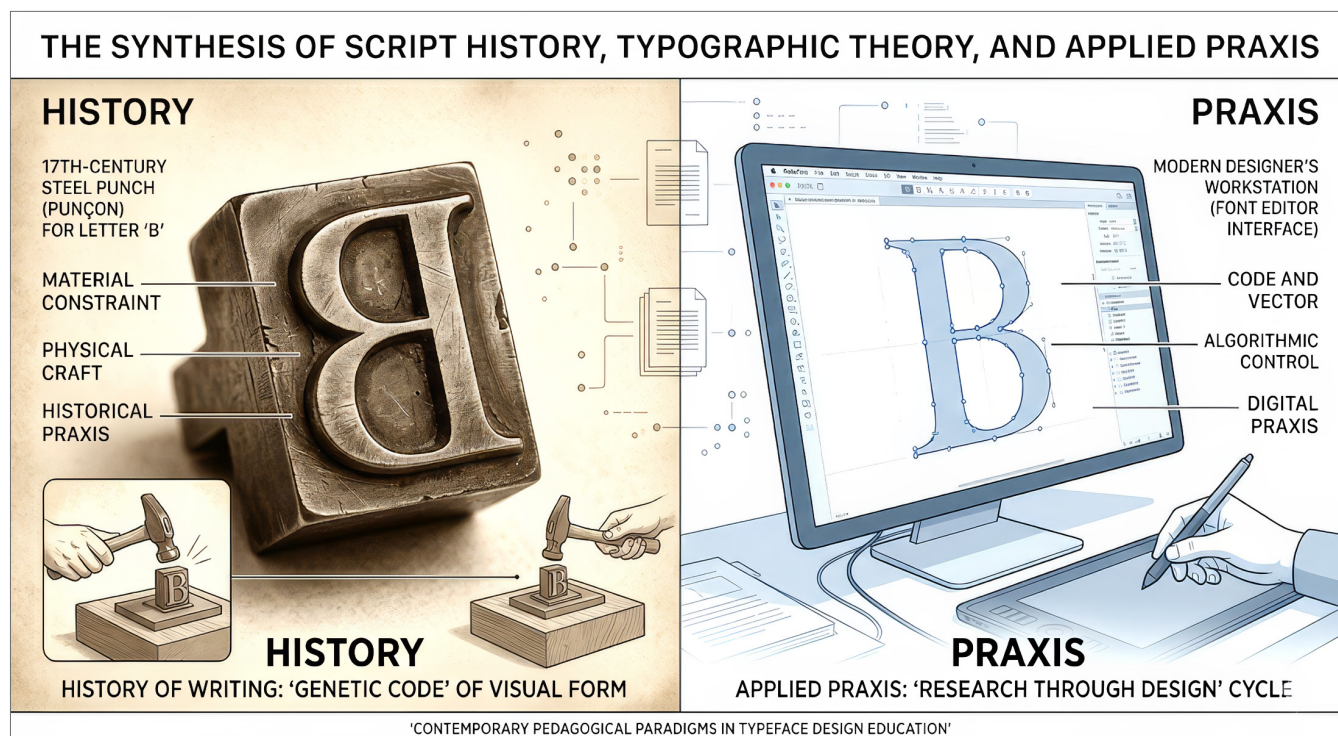


Fig. 9. Visual archaeology: the archive lab

Source: compiled by the author

capable of justifying every decision from the stroke's angle of inclination to the hinting strategy through the prism of cultural context and technological expediency. The global interconnectedness of these programs, reinforced by shared alumni networks and faculty mobility,

ensures that pedagogical innovations circulate rapidly across institutional boundaries.

Furthermore, the importance of the archive should be mentioned, which also occupies its own special place and serves as an active research laboratory.

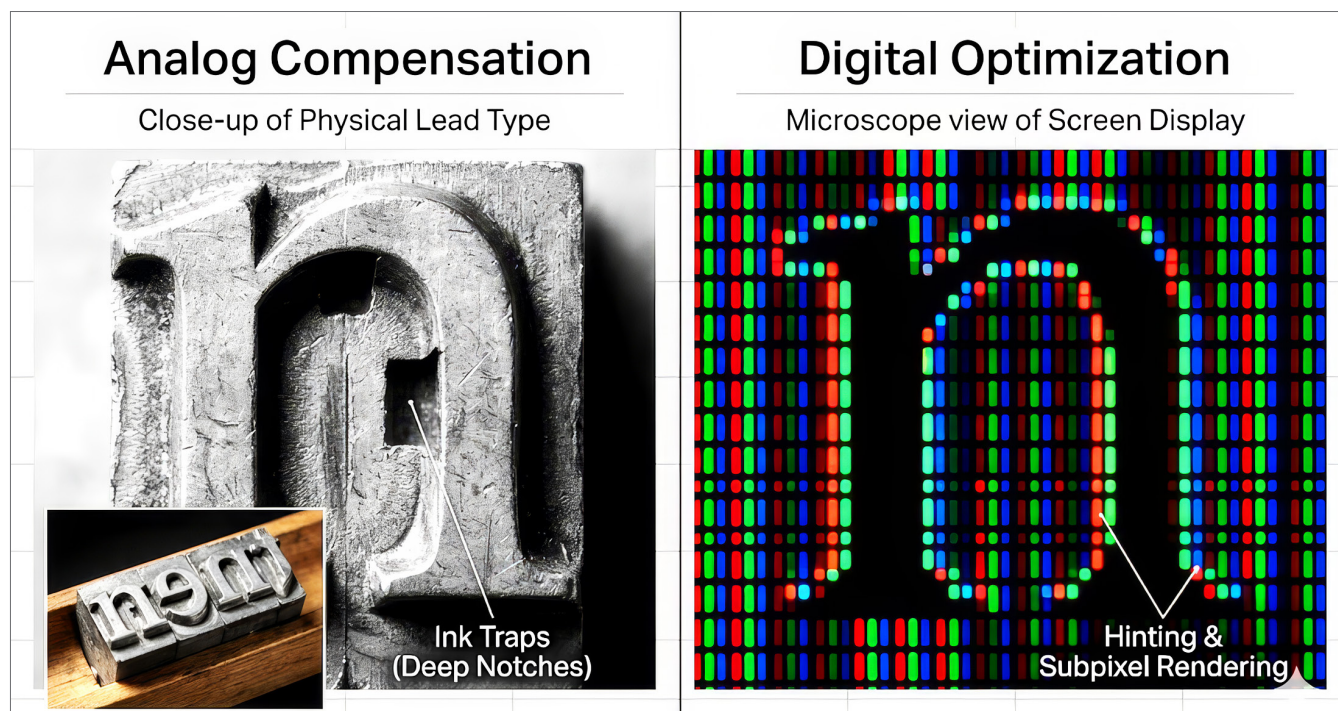


Fig. 10. Technological adaptation: ink traps to pixels

Source: compiled by the author

Turning to primary sources, such as incunabula, punches and authorial sketches by great typefounders, allows the student to implement the method of visual archaeology.

Working with physical or digitized archives (such as the collections of the Letterform Archive in San Francisco or the Plantin-Moretus archives in Antwerp) teaches the future designer to read contextual nuances. Among these are the influence of paper quality, the chemical composition of ink and the wear of printing plates on the final morphology of the sign. This forms a critical understanding that a typeface is not a static idealized form, but a living result of the interaction between creative will and material limitations (see: Figure 9. Visual archaeology: the archive lab).

An important layer of synthesis is understanding how replication technologies determined the development of typographic styles. Within the academic discourse, the phenomenon of technological adaptation is investigated. For example, how the need to compensate for ink spread on porous paper led to the emergence of ink traps, which in the digital era were reinterpreted as an aesthetic device or a functional solution for micro-screens. The study of these transformations allows students to recognize the continuity of engineering tasks. Modern hinting and subpixel rendering are direct conceptual heirs to the craft techniques of the past, aimed at preserving legibility in an aggressive technological environment.

Historical letterforms as a locus for professional deconstruction and design cognition. Within the epistemological field of contemporary

design education, historical typeface forms function as a dynamic substrate for profound analytical deconstruction [14]. By examining palaeographic and typographic heritage through the prism of visual hermeneutics, the student becomes accustomed to perceiving the letter as the result of a complex morphogenesis. The process of professional deconstruction here involves an intellectual operation to identify the genetic code of the sign — the discovery of those invariant structures that retain their identity amidst shifts in technological regimes. Here, the historical locus becomes a space where critical reflection on the boundaries between the canonical norm and innovative deviation occurs (see: Figure 11. The morphogenesis: genetic code of the sign) [15].

Design cognition in this context evolves through the method of structural empathy and reverse engineering. Investigating, for example, the transition from humanist script to Old Style antiqua, the learner reconstructs the movement of the pen and the very logic of the engineering mindset of past typefounders.

This fosters the capacity for an architectural vision of the typeface — that is, an understanding of how micro-parameters (the angle of axis inclination, curve tension, the logic of mass distribution) determine the macro-characteristics of the entire sign system. Consequently, the historical form acts as a cognitive simulator, developing the capacity for abstraction and predictive modeling [16]. The designer learns to anticipate how certain morphological changes will affect the systemic stability and legibility of a typeface in radically different media environments.

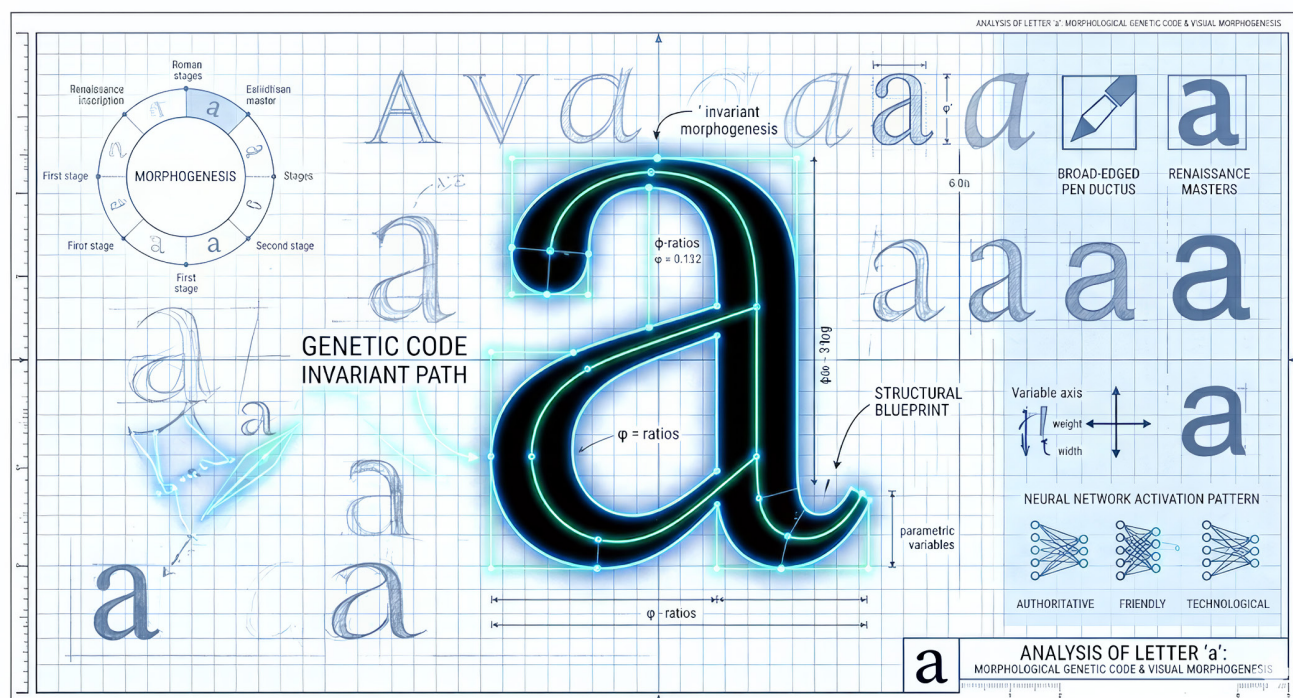


Fig. 11. The morphogenesis: genetic code of the sign
 Source: compiled by the author

It is worth emphasizing the significance within the contemporary international tradition of type design education (specifically within the framework of the Critical Design concept) of overcoming decorative automatism. The historical typeface is deconstructed as a manifesto of the technological pragmatism of its time. The student analyzes how the constraints of manual typesetting or the specific properties of paper became catalysts for the search for new visual solutions. Such an archaeology of meanings allows for the shift of instruction from the plane of formal imitation to the plane of strategic design. Mastery of this method enables the future specialist to utilize history as a tool of speculative design not for the restoration of the past, but for the construction of authentic visual languages of the future possessing internal logic and cultural legitimacy.

Profound deconstruction enables the identification of so-called analog shadows — elements of historical morphology that have lost their original technical function while retaining cognitive and semiotic significance. A representative example is the ink trap: originally introduced as a compensatory measure to counteract ink spread in print, it persists in digital typefaces as a marker of technical precision, a stylistic device, and a tool for micro-typographic control. Education in this vein is directed toward developing the ability to consciously manipulate these vestigial elements, transforming skeuomorphic details into functional components of contemporary interface design. A vital aspect of professional analysis is the question of

cultural legitimization. The project thinking of the contemporary designer includes ethical responsibility for the interpretation of historical heritage. Deconstruction helps to delineate the boundary between the superficial exploitation of historical styles and profound, intellectual revival. The student learns to decipher the ideological context behind a specific historical form (for example, the imperial pathos of Roman Square Capitals or the utopianism of modernist sans-serifs), which allows for the creation of new typeface systems that resonate with the contemporary context while maintaining respect for the primary source.

Consequently, the integration of historical analysis into the structure of project thinking ensures the transition from craft intuition to methodologically substantiated praxis. Within this coordinate system, the historical typeface is a fundamental matrix providing continuity of intellectual efforts in design. A specialist capable of conducting a profound deconstruction of a classical form attains professional subjectivity. Henceforth, their creative search ceases to be chaotic and transforms into a conscious process of managing visual meanings, where every decision, from the structure of a serif to the logic of variative axes, is the result of deep intellectual reflection.

It is also interesting to note neuro-psychological patterns of archetype recognition. The integration of cognitive science into the analysis of historical forms allows for the investigation of the typeface as a system of visual archetypes. The deconstruction of classical specimens helps to understand which formal attributes

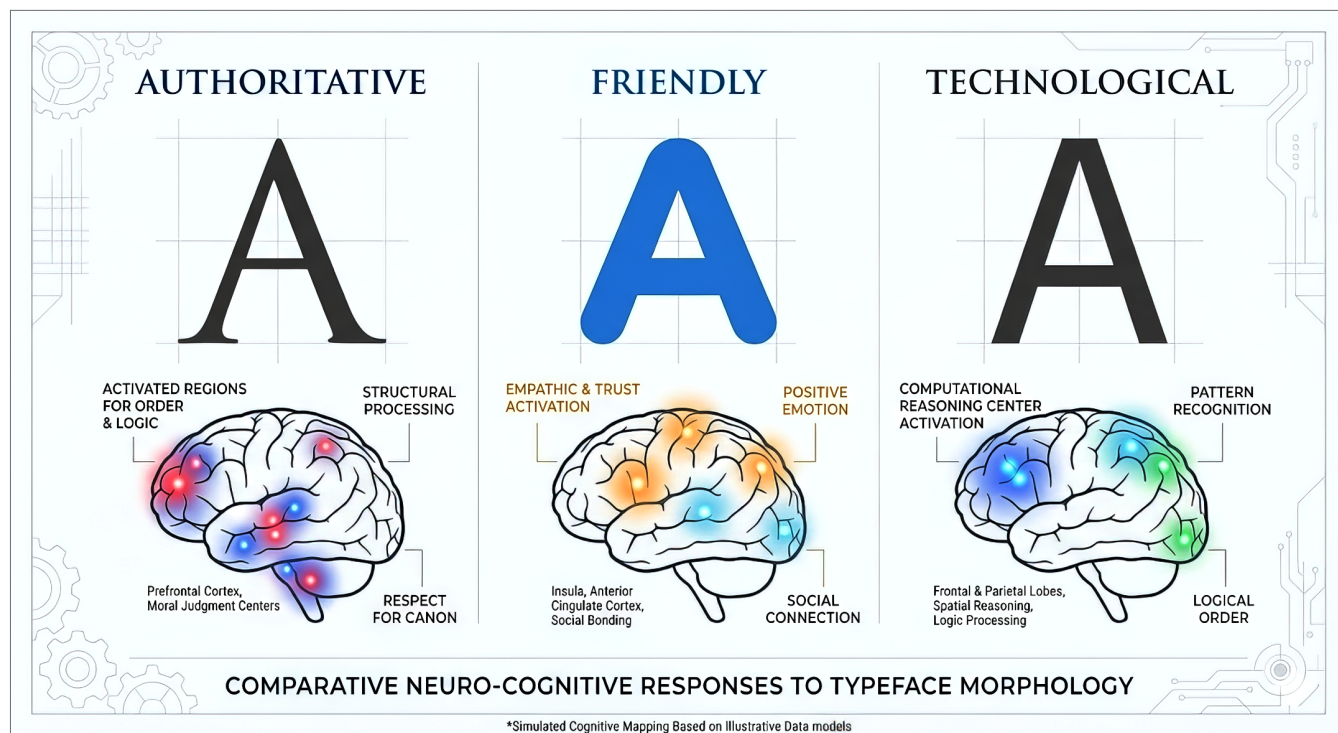


Fig. 12. Neuro-psychological archetypes

Source: compiled by the author

are perceived by the human brain as authoritative, friendly or technological. The historical typeface in this context acts as a database of time-tested cognitive triggers. Mastery of this toolkit allows the designer to project not just beautiful letters, but highly effective systems of visual communication that subconsciously manage perception and recipient trust (see: Figure 12. Neuro-psychological archetypes).

Digital instrumentation as a transformative vector in type design pedagogy. The integration of digital instrumentation into the academic discourse of typeface design has marked an unprecedented transition from manipulations with fixed form to the design of dynamic systems [17]. In today's pedagogical concept, the software environment is viewed as an active agent and a catalyst for epistemological shifts. The transformation of education in this vein presupposes the abandonment of the linear sketch-realization process in favor of non-linear modeling, where the digital tool acts as a cognitive extension of the designer, allowing for operation with mathematical abstractions and algorithmic regularities at all stages of form-making [18].

A key factor in these modifications has been the emergence and development of variable fonts technology, which has radically altered the architecture of the learning process [19].

Typeface engineering instruction is now centered around the concept of design space, where the student projects multidimensional continuums.

This approach requires the development of a specific algorithmic thinking, as the future specialist must perceive the typeface as a set of parameters and axes of

interpolation (see: Figure 13. The variable design space continuum). Thus, digital instrumentation shifts the focus from the aesthetics of a single glyph to the systemic stability of the entire typeface under conditions of infinite metadata variability. A particular influence on this process is exerted by the growing convergence between design education and the technology sector globally. Programs at KABK, where students work with Python-based font production tools, and at institutions in the San Francisco Bay Area, where proximity to the technology industry has fostered the standard of the designer-developer, exemplify this trend [20]. Across leading international programs, typeface instruction is increasingly integrated into the STEAM strategy, where writing Python scripts for automating routine tasks or generating complex structures becomes an integral part of professional competence. The digital tool here is understood as an instrument for the democratization of innovation [21]. Access to complex software for mastering and hinting allows students to solve tasks that were previously the prerogative of large type foundries, thereby shifting the focus in education toward investigative and experimental design.

At the current stage of technological development, generative neural networks cannot yet be considered reliable tools for automating core type design tasks such as glyph construction or kerning refinement. Their practical value lies primarily in supporting auxiliary processes — including the expansion of character sets, the extension of language coverage, assistance in kerning generation, and the creation of intermediate interpolation masters within variable font workflows.

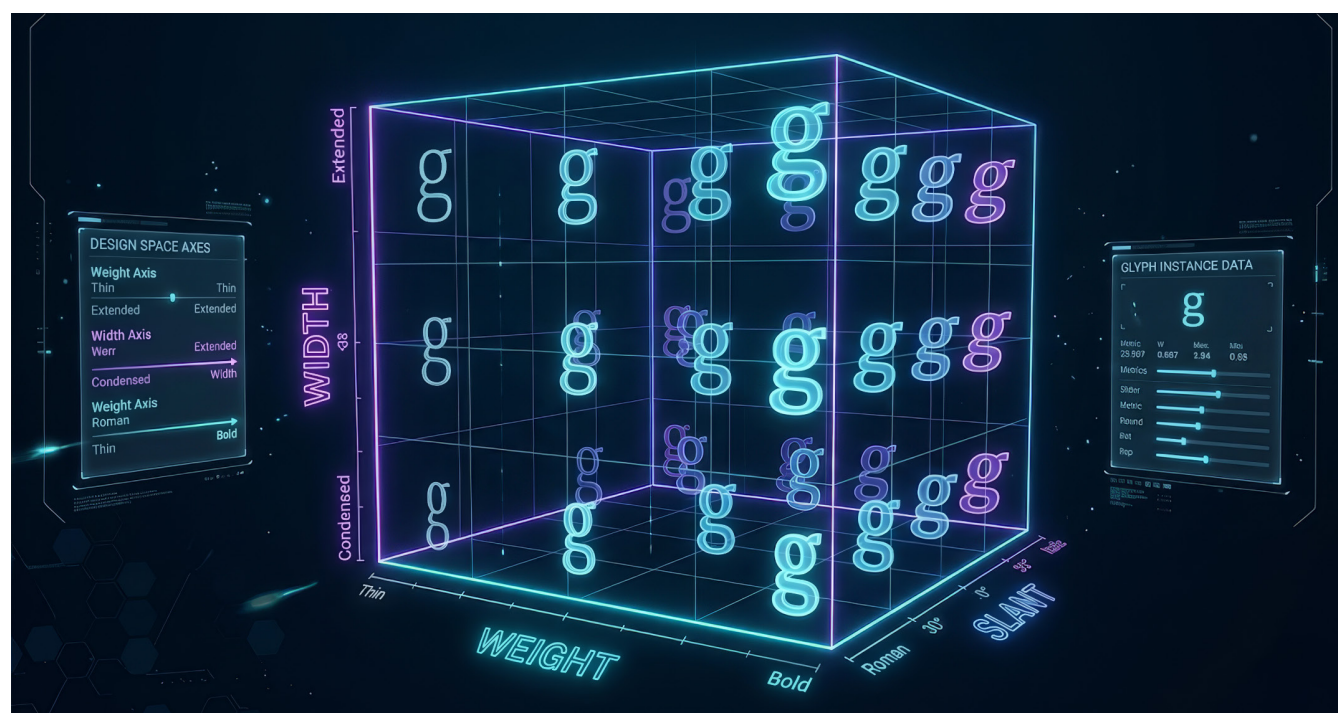


Fig. 13. The variable design space continuum
 Source: compiled by the author

In this context, the primary pedagogical objective is not the delegation of authorship, but the cultivation of critical judgment. Students must develop the ability to evaluate, filter, and refine AI-assisted outputs, repositioning these systems from autonomous generators into instruments that extend and amplify the designer's intent.

The modification of typeface education is inextricably linked with the expansion of Open Source culture and the use of collaborative development platforms (such as GitHub). Digital instrumentation ceases to be a closed proprietary product, transforming into a shared knowledge base. Including students in global repositories of typeface projects allows them to analyze the live code of existing font families, participate in collective bug fixing and script development. This methodology forms skills of interdisciplinary collaboration characteristic of the contemporary global technology sector and breaks the barrier between academic learning and the real production cycle. The typeface in this system is perceived as an evolving ecosystem, open to infinite improvement and adaptation.

Ultimately, the digitalization of pedagogy leads to the formation of a new professional identity — the type engineer, for whom code and vector are equal means of expression. Instrumentation changes the very nature of heuristic search — the possibility of instant testing of hypotheses in various software environments and on different devices reduces the distance between concept and approbation. However, the main task of modern education remains the preservation of a critical distance toward technology, so that the digital

environment remains a conduit for the author's intent rather than a constraint determining the visual result through the standard functions of software.

Autorial idiom as the culmination of pedagogical and heuristic processes. Within the coordinate system of higher design education, the formation of an autorial idiom is defined by the final crystallization of professional subjectivity [22]. Authorial style in typeface design is a complex semiotic construct emerging at the intersection of profound knowledge of the canon and its conscious transcendence. This process represents the zenith of integration of all preceding educational stages: from the morphological analysis of history to the mastery of high-tech code. The pedagogical task here entails the creation of conditions for intellectual inquiry, where the idiom becomes a visual manifesto of the designer's unique analytical approach.

The heuristic component of this process is based on the guided discovery method, where digital and analog environments serve as spaces for experimentation [23]. Authorial style is born in moments of heuristic insights arising during the process of iterative design, when the student consciously takes the risk of deviating from standard parameters. In this vein, an error or a technological limitation is recontextualized as a catalyst for innovation.

Heuristics in typeface design is a disciplined investigation of formal boundaries, where every original solution be it the specific plasticity of a serif or a non-trivial logic of variability is underpinned by a profound understanding of typographic theory.

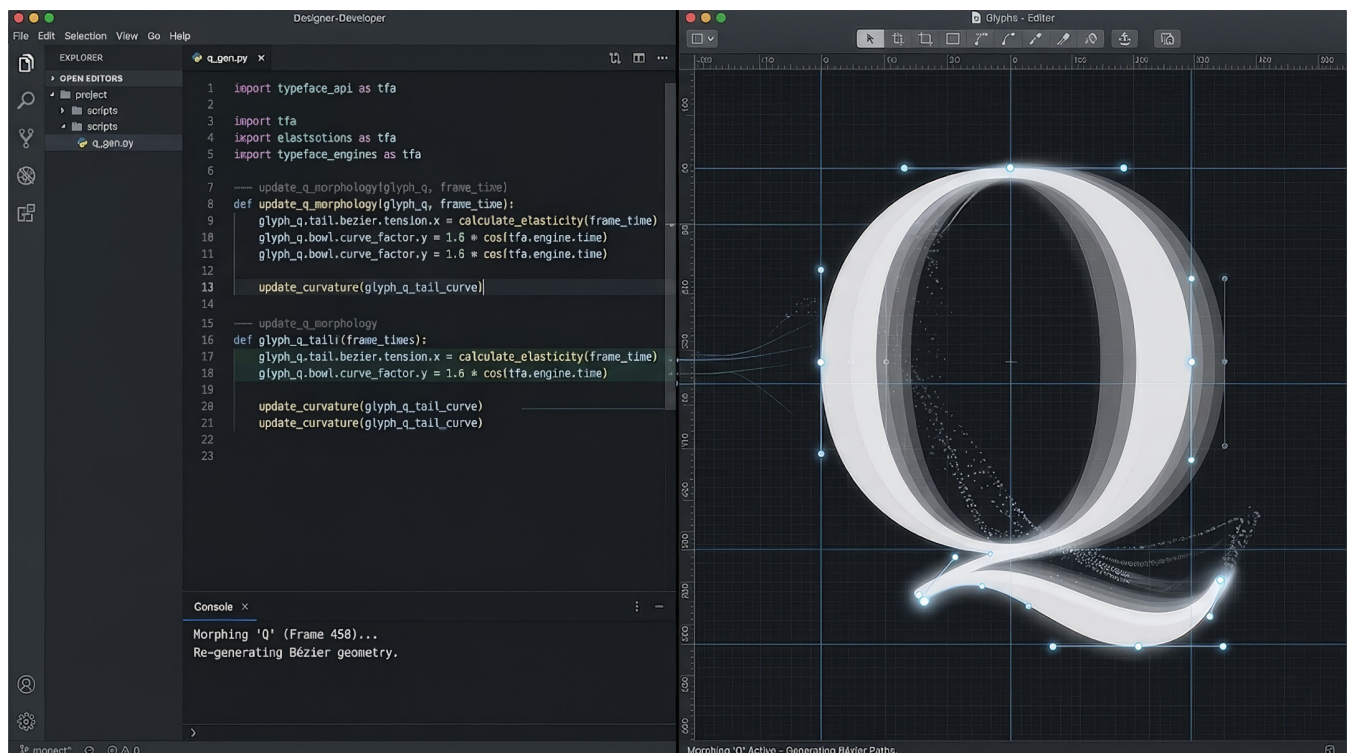


Fig. 14. The STEAM strategy: code as a brush
Source: compiled by the author

Contemporary type design pedagogy contributes significantly to the understanding of this process through the critical voice concept. Across leading programs, from KABK and Reading to Cooper Union and ECAL, the emphasis shifts from copying visual trends to developing critical reflection. The student is encouraged to find their own position within the global professional discourse, where the authorial idiom is viewed as a response to current socio-cultural challenges. Here, pedagogy is directed at the deconstruction of the concept of taste and its replacement with the category of informed choice. As a result, the designer's personal style acquires cultural legitimacy and intellectual weight, transforming from an aesthetic preference into a tool of professional expression.

In the era of total digitalization of education, a risk of algorithmic conformism arises, where software tools impose specific aesthetic standards on the student. The formation of an authorial idiom in this context is regarded as an act of conscious resistance to digital unification. The pedagogical strategy is aimed at encouraging idiosyncrasy — individual graphic deviations that constitute the foundation of a unique authorial hand. Authorial style here acts as intellectual friction between the designer's will and software logic, where precisely the non-linear solutions, incorrect from an algorithmic standpoint, become markers of high artistic value [24]. The process of forming authorial style is inextricably linked with ethical reflection and the awareness of one's own cultural DNA. Under the globalization of educational models and the increasing interconnection of design programs worldwide, it is essential that the authorial idiom does not turn into a superficial appropriation of foreign visual codes. The pedagogical process stimulates the student toward a profound search for authenticity, where personal style becomes the result of a synthesis between local visual traditions and global technological standards. This transforms design from a commodity into a tool for preserving and developing cultural identity.

Despite a high level of automation, the culmination of the pedagogical process continues to rely on the dialectical interaction between mentor and student. The formation of the authorial idiom occurs within the space of intellectual maieutics (Socratic dialogue), where the educator does not dictate rules, but helps the student decipher their own intuitive findings. This process of intellectual mentorship, characteristic of leading international master's programs (MA/MFA), allows for the translation of disparate heuristic insights into a system of conscious creative principles. Style, thus, is recognized as the product of collective intellectual work aimed at uncovering the individual subjectivity of the author.

Ultimately, the authorial idiom as the culmination of the educational cycle marks the designer's transition from the status of a translator of external meanings to that of an architect of visual culture. The process of its formation does not end within the university walls,

but it is specifically the academic environment that lays the axiological foundation for this development.

The synthesis of pedagogical strategies and heuristic practices enables the future specialist to synthesize their own visual language, which harmoniously combines the universality of the typeface system with the authenticity of authorial vision. Thus, the completion of the educational process in the field of typeface design becomes the beginning of the formation of a mature master, capable of enriching the global visual landscape with new semantic and aesthetic codes.

Conclusions. The conducted research allows for the constation of existing epistemological modifications in the field of typeface education — the formation of a complex meta-design. In the contemporary media environment, the typeface has ceased to be a passive graphic attribute, becoming a complex cognitive interface, which demands from the designer a deep synergy of humanitarian reflection and high-tech engineering.

The key result of the work was the verification of a trialectic model of instruction, integrating the history of writing as the genetic code of form, typographic theory as a normative framework and applied praxis as research through design. It has been proven that the professional deconstruction of historical heritage through the method of reverse engineering serves as a necessary basis for the development of innovative project thinking, allowing for the avoidance of decorative automatism and algorithmic conformism.

Digital instrumentation (Variable Fonts, generative AI models, scripting) is defined in the work as a cognitive extension of the author, altering the very logic of form-making. The transformation of pedagogy toward the STEAM strategy and the Problem-Solving approach, as evidenced by the convergence of methodologies across leading international programs, facilitates the emergence of a new professional identity — the type engineer. This specialist is capable not only of generating visual symbols, but also of designing adaptive sign systems that respond to the challenges of cognitive ecology and information entropy.

The crystallization of the authorial idiom is recognized as the final stage of the educational process, acting as a manifesto of the designer's professional responsibility and subjectivity. It has been established that a unique visual style is a logical outcome of a disciplined heuristic search at the intersection of ethics, technology, and cultural identity. Thus, the contemporary educational trajectory must be directed toward the cultivation of the author's critical voice, capable of harmonizing technological pragmatism with the anthropocentric values of visual culture.

Prospects for further research lie in the field of integrating immersive technologies (AR/VR) and directive curatorship in working with generative algorithms, which will continue to alter the architecture of typeface education toward even greater interdisciplinarity and social relevance.

ДОДАТКОВА ІНФОРМАЦІЯ

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THE DEVELOPMENT OF SOCIAL SKILLS IN PRESCHOOL-AGED CHILDREN AS THE FOUNDATION FOR SUCCESSFUL ADAPTATION TO SCHOOL EDUCATION

Summary. This article addresses an issue that practicing educators are well aware of but which is rarely discussed in academic discourse: why one child adapts easily to the school environment, while another, who is just as well-prepared, struggles from the very first weeks. The author examines the social skills of 5–6-year-old children as an independent and equally important dimension of school readiness alongside cognitive preparation. The article reports findings from a qualitative longitudinal observational study ($n = 28$; two groups of 14 children aged 5–6; November 2021 – January 2022) conducted in a preschool setting in Lviv, Ukraine. The article describes pedagogical work with a group of older preschoolers: which difficulties in social interaction were most common, which pedagogical approaches proved effective, and what dynamics were observed in the children's behavior and emotional reactions from September to May. The influence of the family environment and the child's prior social experience on the pace of adaptation within the group is examined separately. The theoretical framework of the article is based on scientific research in the field of social-emotional learning, particularly on meta-analytic data confirming the long-term impact of preschool socialization on subsequent academic success.

Key words: social skills, preschool education, school adaptation, role-playing, fairy tale therapy, empathy, school readiness, social-emotional learning.

Introduction. In the public consciousness, a child's readiness for school is usually associated with the ability to count, read, and write. These skills are indeed important and easy to assess. However, educational practice regularly reveals situations where a child who is well-prepared academically experiences serious difficulties in the first months of school: they cannot wait their turn to answer, react painfully to the teacher's comments, and struggle to get along with classmates. Conversely, a child who knew little but was able to negotiate and get along with others enters the school environment without significant difficulties. This pattern reflects the real significance of the social-emotional dimension of school readiness, which is often overlooked in the practice of preparing children for school [1; 2].

The age of 5–6 is a sensitive period for the development of basic social competencies. It is precisely at this time that a child begins to realize that another person may think and feel differently; that rules are a prerequisite for joint activity; and that it is possible to negotiate and compromise without feeling like a loser. These discoveries occur primarily through play-based

interaction with peers, rather than in sessions with adults [3; 4].

A preschool setting is an environment where a child first finds themselves among socially equal partners. Parents may make concessions, a younger sibling gets used to obeying, but twenty peers in a group have their own needs and interests, and this must be accounted for every day. This experience is an important pedagogical resource, the utilization of which requires the teacher's focused effort [3].

The purpose of this article is to substantiate, based on theoretical analysis and personal pedagogical experience, the importance of social skills for a preschooler's successful adaptation to school and to describe approaches that have proven effective in practical work with a group of 5–6-year-old children. To achieve this aim, the following tasks have been identified: to elucidate the content of social skills as a component of school readiness; to analyze the role of group interaction in the development of communication skills; to describe pedagogical approaches to fostering cooperation and empathy; to determine the influence of the social

environment on child development; and to outline the long-term consequences of preschool socialization.

Literature Review. The issue of preschoolers' social development occupies a prominent place in pedagogy and child psychology. Burns et al. demonstrated that children's development occurs through collaboration with peers and more experienced partners: joint activity in early educational settings creates conditions under which children achieve more than they could independently [4]. E. Erikson, in describing a stage-based model of psychosocial development, defined the preschool age as the stage of initiative, when, through play and social roles, a child develops the basic ability to actively participate in community life [5].

In Ukrainian scholarship, significant attention is devoted to the social-emotional development of preschoolers. O. L. Kononko views social competence as an independent and equally important dimension of a child's personal growth, rather than as a derivative of cognitive achievements [6]. T. O. Pirozhenko and her colleagues investigated the structure of school readiness and convincingly demonstrated that communicative-linguistic and social-emotional components play no less important a role in it than the cognitive component [1; 2]. The research team also developed and tested a diagnostic tool for assessing the level of a preschooler's socio-psychological maturity, which allows for the construction of an individual developmental trajectory [8]. N. V. Gavrysh investigated the role of literary texts and fairy tales in the development of speech and the emotional sphere, demonstrating that through identification with a character, a child gains the opportunity to safely make sense of complex emotional states [9].

Among foreign studies, the meta-analysis by J. Durlak and colleagues [10], published in the journal *Child Development*, holds a significant place. The authors synthesized the results of 213 social-emotional learning (SEL) programs and found that participants demonstrated academic performance 11 percentage points higher than their peers who did not participate in such programs. The observed reduction in aggressive behavior and improvement in attitudes toward learning persisted several months after the program's completion, indicating the durability of the acquired skills.

In her study [11], S. Denham found that social-emotional competence, as measured in a five-year-old child, is a significant predictor of their academic success and social adjustment in elementary school. This association persists even after controlling for intelligence and family socioeconomic status, indicating the independent contribution of social-emotional development to the child's future achievements.

Scientific research in this field focuses primarily on general patterns and large samples. Less attention is paid to how a specific educator's pedagogical work with a specific group of children is linked to changes

in their social behavior over the course of a year. It is precisely this level of description that forms the basis of this article.

Materials and Methods. This study employed a qualitative longitudinal observational design. The sample comprised 28 preschool-aged children ($n = 28$; 14 boys, 14 girls; age range 5–6 years), divided into two groups of 14. Of these, 18 children had prior experience attending an early childhood setting, while 10 had no previous peer interaction experience. Data were collected from November 2021 to January 2022 across three assessment points: baseline (November 2021), midpoint (December 2021), and endpoint (January 2022). Observations were conducted 2–3 times per week, with each session lasting 30–40 minutes, yielding systematic weekly records throughout the study period. Four situational contexts were observed: free play, structured activities, conflict episodes, and daily routines. Data were recorded in a pedagogical journal and supplemented by conversations with children and parents, analysis of children's responses in social interaction situations, and follow-up feedback from receiving elementary school teachers. The theoretical framework draws on structural-functional analysis of the pedagogical process and the principles of person-centered early childhood education. Observations continued informally throughout the academic year (September 2021 — May 2022), providing additional context for the interpretation of findings.

Results and Discussion.

3.1. Social Skills as a Component of a Child's School Readiness. School readiness encompasses at least four interrelated components: intellectual, motivational, volitional, and social. The social component is often overlooked when preparing a child for school, although without its development, the other components are realized only partially. Classroom learning is primarily a group activity: the child receives a task, performs it alongside others, and interacts with the teacher in a situation of public assessment. All of this places demands on social skills that must be developed in advance [1; 3].

The social component of school readiness includes several groups of skills. The first group covers communication skills: the ability to clearly express one's own needs, listen to the interlocutor, and ask for help in an appropriate manner. The second group concerns cooperation: the willingness to work together with others, distribute roles and responsibilities, and take responsibility for the joint outcome. The third group is related to regulating one's own emotions: the ability not to give in to the first impulse, to respond appropriately to comments, and to cope with disappointment due to failure. The fourth group encompasses empathic skills: the ability to understand that another person may feel differently and to take this into account in joint activities. Without a basic level of development of these skills, a child finds themselves in a situation of

constant discomfort in the classroom, even with good cognitive preparation [6; 11].

In children aged 5–6, these skills are in the active development stage, and certain difficulties in this process are inevitable. Pedagogical observations of a group of older preschoolers allow us to identify several problems that arise regularly. Conflicts most often arise during the distribution of roles in role-playing games: every child strives to take the central role and is reluctant to accept secondary characters. Along with this, there is an impulsive reaction to failure or rejection: pushing, shouting, crying, and only then realizing what has happened. Some children exhibit the opposite pattern: excessive shyness and prolonged avoidance of active participation in group games. Such children play alongside others, but not together. This parallel play is normal for early preschool age, but by age 5–6, it indicates difficulties requiring pedagogical attention [3].

Educational observations conducted at the beginning of the school year showed that about a quarter of the children in the group exhibited pronounced signs of difficulty adapting. Some cried when parting with their parents and did not want to stay at the facility; others, from the very first day, got into conflicts with their peers or, conversely, kept to themselves. Most of them had no experience of regular interaction with peers prior to entering the facility. These findings are consistent with studies indicating a link between prior social experience and the nature of adaptation [1; 11].

3.2. The Role of Group Interaction in the Development of Communication Skills. A peer group in a childcare facility is an environment that cannot be replaced by home education or individual lessons. Here, the child interacts with socially equal partners: there are no hierarchies, no automatic authority. The needs and desires of each participant in the interaction are equal, so they literally have to negotiate. This situation provides a productive environment for the development of communication skills [4; 6].

Observations of the group over the course of a year show that children change more during free play than during organized activities. During a lesson, a child mostly responds to the teacher. In play, they negotiate with an equal: they stand their ground, compromise, and seek a solution. These situations are different

every time, and it is through them that communication skills gradually develop.

An example of such development is an observation recorded in the teacher's journal. At the beginning of the school year, two boys in the group regularly fought over a toy car: one would grab it, the other would scream, and both would turn to the teacher. A few months later, the same pair of children independently reached an agreement: one plays for five minutes, then they switch. Neither of them realized this as a mastered skill, yet the very fact that they reached an agreement without adult assistance indicates a qualitative change in their social development.

An important factor is the diversity of temperaments and personalities within the group. An active child and a quiet child, when paired together during a game or a shared task, gain an experience that cannot be replicated in a homogeneous environment. The first learns to restrain themselves and wait; the second gradually finds the courage to express their opinion. In these situations, the teacher acts as an observer and, if necessary, helps children find the words to describe what they are experiencing, without resolving the conflict for them [6].

For shy or socially immature children, parallel play is an important intermediate step before full inclusion in group interaction. By observing others, such a child gradually learns the game strategies and community rules, and this process requires time and respect from the teacher [3].

3.3. Pedagogical Approaches to Fostering Cooperation and Empathy. Experience with children aged 5–6 shows that results depend on how different methods are combined and function together as a unified system in supporting social development.

Role-playing. In the game, the child takes on a social role and learns to think from the character's perspective. A child playing the role of a doctor treats the "patient" with a certain degree of attentiveness, because otherwise the game does not work; a child playing the role of a teacher discovers that they must explain things in a way that the other person can understand. These small experiments in taking on other people's roles gradually develop the ability to understand another person's perspective [4; 6].

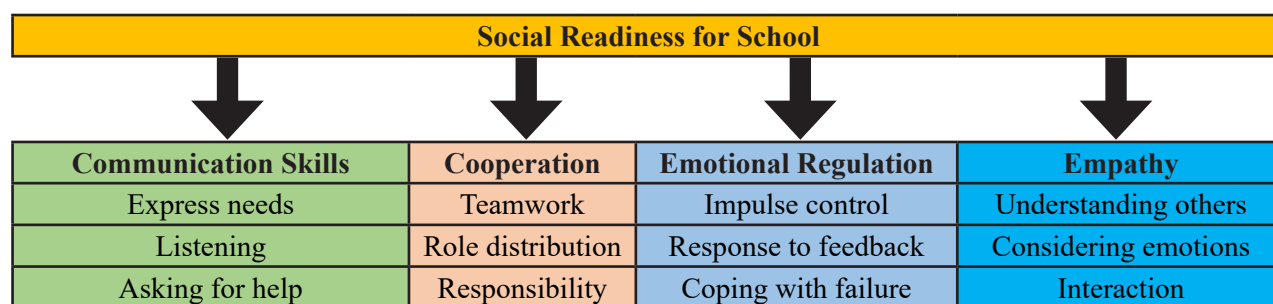


Fig. 1. Structure of the Social Component of School Readiness

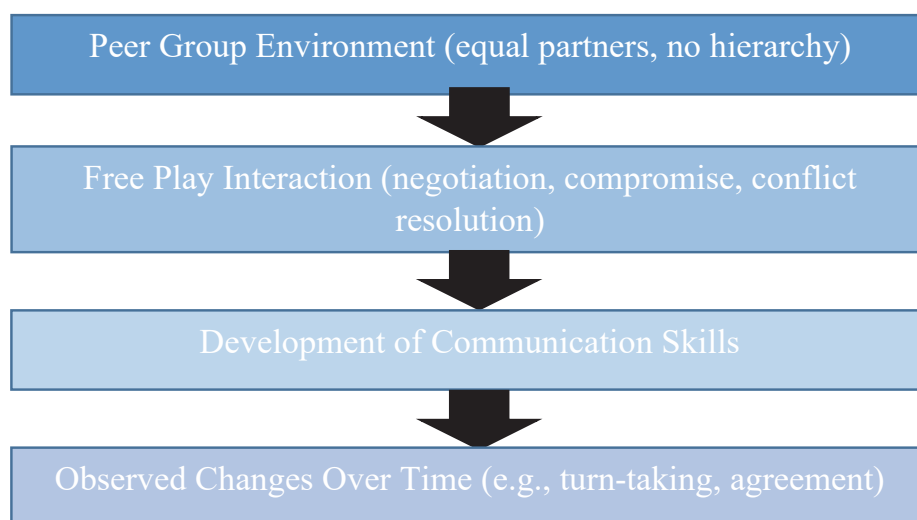


Fig. 2. Peer Interaction as a Context for the Development of Social Skill

Throughout the school year, the games “Hospital,” “School,” “Family,” “Builders,” and “Store” were systematically used in group work. The fundamental pedagogical approach here was to refrain from excessive interference in the course of the game. When a conflict arose among the children over the distribution of roles, the teacher did not resolve it authoritatively but asked, “How can we make it interesting for everyone?” and waited. At first, the children could not answer. By the end of the school year, situations where children resolved role conflicts on their own before the teacher even had a chance to intervene became increasingly common.

Fairy-tale therapy. A fictional text gives a child the opportunity to experience someone else’s situation through identification with the protagonist in a safe environment. Preschoolers still struggle to discuss their own feelings directly, but they do so willingly through a fairy tale [9]. During discussions of a fairy tale or cartoon, questions were posed not in the format of “who behaved badly,” but rather “what might he have felt,” “why did he do that,” and “what would you do in his place.” The children genuinely reflected on these questions, offered various explanations, and sometimes debated among themselves. A notable result was that by the end of the first semester, children began to use words denoting emotional states more frequently in everyday communication: “he was offended,” “she was scared,” “I’m upset.” The expansion of emotional vocabulary is a direct indicator of the development of reflective and empathic abilities.

Fairy tale therapy was applied in two formats. The first, a group format, involved a joint discussion after reading or watching a story. The second format focused on individual or small-group work with children who had particular difficulties in social interaction: fairy tale situations in which the characters experienced similar challenges were discussed with them separately.

Morning Circles. This daily practice took 10–15 minutes at the start of each day. Each child could share what was important to them that day and be heard without judgment or commentary. Over time, the children began to speak for themselves and respond to others’ words: asking questions, offering support. While at the start of the school year most children responded briefly with “fine” or “I don’t know” and looked away, by November they were making detailed comments and, most importantly, reacting to their peers’ words: “I think so too,” “Why are you sad?” This change occurred without special exercises, as a result of regular practice in a predictable, safe setting.

The method of collaborative tasks. Pairing or grouping children into trios to complete a shared task (assembling a puzzle, drawing an illustration for a fairy tale, or coming up with an ending to a story) forced them to negotiate. The key condition was that there must be a single result for everyone, which made it impossible to work in parallel. After completing the task, the teacher discussed with the children not the result, but the process: “How did you decide who would do what?” “What was difficult?” These questions prompted reflection on their interactions and reinforced the experience of cooperation [10].

Teaching independent conflict resolution. When a dispute arose in the group, the teacher resisted the initial urge to resolve the situation for the children and instead asked both participants: “What do you want? What does he want? How can we make it work for both of you?” At first, these questions caused confusion: the children were used to an adult telling them who was right. Gradually, the approach became familiar. By the end of the school year, there were instances where two children argued over a toy, and a few minutes later, one of them suggested: “Let’s do this: you first, then me.” Without the teacher’s intervention. The ability to reach such agreements is an indicator of social maturity, which cannot be achieved through a single explanation or rule.

Encouraging prosocial behavior. The system of positive reinforcement through the "tree of good deeds" and verbal praise in front of the group served as feedback: it made social norms visible and meaningful. When a teacher acknowledges academic achievements alongside the ability to compromise or support someone, children develop an understanding that these skills are valued. According to social learning theory [12], reinforcement is one of the key mechanisms for the acquisition of social norms in childhood.

3.4. The Influence of the Social Environment on Children's Behavior and Emotional Development. A child enters a childcare facility with a set of social interaction experiences already formed, shaped primarily by the conditions of family upbringing. The family's communication style, the availability of emotional contact with parents, the consistency of adult expectations, and how the family typically responds to conflict all influence how a child behaves in a group and how quickly they acquire new social skills.

Differences in children's social behavior within the group were linked to observable patterns in family communication styles. Children from households characterized by dialogue-based parenting — where decisions were explained and the child's perspective acknowledged — demonstrated more adaptive negotiation strategies with peers. In contrast, children from directive parenting environments more frequently reproduced authoritarian interaction patterns toward peers. The former is more likely to find common ground with peers and less likely to get stuck in conflict. A child from an overprotective family, where everything is decided for them in advance, often feels

lost when there is no adult nearby to tell them what to do. This is not a rule without exceptions, but this pattern is observed quite consistently. Those who were rarely given explanations at home for refusals and prohibitions often replicated a similar pattern of behavior toward peers in the group.

At the same time, the family environment is significant, but not the only or decisive factor. A teacher who consistently models attentive and respectful communication, responds to children's feelings, and explains their own decisions gradually becomes a model of social behavior for the children. Provided it is consistent and predictable, the pedagogical atmosphere in the group can compensate for certain deficits in home upbringing [6].

The child's prior social experience is also a notable factor. Those who, prior to entering the institution, had regular contact with peers in clubs or other settings adapted to the group noticeably faster. The first signs of adjustment appeared in most of these children after 10–14 days: they parted more calmly from their parents and began to join in group games. Children without prior experience interacting with peers required more time; in some cases, full adaptation took up to two months. The overall average adaptation period in the group ranged from two to four weeks, which corresponds to data in the scientific literature [1; 11].

The pedagogical atmosphere in the group is a distinct and significant factor in children's social development. An environment where a child feels safe, where the teacher is equally attentive to everyone, and where a mistake does not become a cause for shame, is a necessary condition for a child to be able to take risks in

Table 1

Influence of the Social Environment on Children's Behavior and Emotional Development

Factor of Social Environment	Observed Behavioral Patterns in Children	Impact on Social Interaction and Adaptation	Pedagogical Implications
Family communication style (dialogue vs. directive)	Dialogue-based children express opinions calmly; directive upbringing leads to rigid statements	Better negotiation vs. higher conflict risk	Model respectful communication and encourage dialogue
Emotional contact with parents	Secure children show confidence; others may be anxious or withdrawn	Faster inclusion vs. avoidance	Ensure emotional safety and individual support
Consistency of expectations	Predictable upbringing → better rule understanding; inconsistency → confusion	Easier adaptation vs. incorrect behavior	Maintain clear and consistent rules
Family response to conflict	Children reproduce negotiation or aggression patterns	Constructive vs. impulsive reactions	Support conflict resolution skills
Overprotective upbringing	Dependence on adults, low autonomy	Slower adaptation	Encourage independence gradually
Lack of explanations at home	Authoritarian behavior toward peers	Low empathy, rigid interaction	Explain decisions and model alternatives
Prior peer experience	Faster engagement in group activities	Adaptation in 10–14 days vs. up to 2 months	Provide structured interaction opportunities
Pedagogical atmosphere	Children take social risks in safe environments	Active participation vs. withdrawal	Create supportive, non-judgmental climate

Source: developed by the author based on pedagogical observations

a social sense at all: to try to approach someone, to propose an idea, to admit that they were wrong. Without this condition, any specific methods and techniques will have a significantly lower effect.

3.5. Long-term effects of socialization in early childhood. A key question in early childhood education is how preschool affects later development. Both research and practice show that the strongest effects are seen in social-emotional development.

A meta-analysis by Durlak and colleagues [10], covering the results of 213 SEL programs with a total sample of over 270,000 children and adolescents, documented a lasting effect on academic achievement (an 11-point increase), prosocial behavior, anxiety levels, and attitudes toward school. Crucially, this effect persisted several months after the program ended, indicating the formation of lasting skills rather than temporary behavioral changes.

S. Denham [11] proposed and empirically confirmed a model according to which social-emotional competence, measured at age five, is a significant predictor of academic achievement. This association persists after controlling for intelligence and family socioeconomic status, indicating an independent influence of social-emotional development on the child's future achievements.

Elementary school teachers who later worked with this group describe similar patterns. The children are familiar with school routines, take part in group tasks, and rarely have serious conflicts. Many are able to resolve minor disagreements on their own, without adult help.

These assessments aligned with pedagogical observations conducted in the older group throughout the school year. By the end of the year, the number of conflicts among the children had noticeably decreased. The way they were resolved also changed: while in September disputes almost always ended in shouting, tears, or physical contact, by May most situations were resolved through conversation. Someone would suggest a solution, someone would agree, and the children would return to playing.

Children's responses to others' emotions changed over time. At the beginning of the year, many reacted with indifference or irritation. By the end, they were

more likely to approach a crying peer, ask what had happened, offer help, or simply stay nearby.

These changes developed gradually through everyday activities such as reading, discussion, and conversations about feelings. Progress varied: some children adapted quickly, while others needed more time and individual support. A few continued to experience difficulties by the end of the year, which highlights the need for ongoing work with both children and their parents.

3.6. Limitations. Several limitations of this study should be acknowledged. First, the sample was small ($n = 28$) and drawn from a single preschool institution in Lviv, Ukraine, which constrains the generalizability of the findings. Second, the study relied only on naturalistic observation and practitioner notes, without independent verification from other observers. This creates a risk of subjective bias in how the data were interpreted. Third, the lack of a standardized measurement tool means that the reported changes in social behavior are based on professional judgment rather than validated metrics. Fourth, the three-month study period (November 2021 — January 2022) is relatively short and does not allow firm conclusions about long-term developmental effects. Future research should include larger and more diverse samples, use validated assessment tools, and extend the observation period to confirm whether these findings remain consistent over time.

Conclusions. Social skills are an integral part of a child's readiness for school. A child who is able to listen to others, negotiate, and manage their own emotions adapts much better to the school environment than one who lacks these skills, even if they have a high level of cognitive development.

These skills develop gradually through regular educational practice. Role-play allows children to explore social roles and negotiation in a safe environment. Fairy tale therapy facilitates understanding of another person's emotional state through identification with a character. Morning circles foster the habit of expressing one's own feelings and listening to others. Tasks in small groups develop skills in responsible cooperation. Targeted training in independent conflict resolution fosters social autonomy. None of these

Table 2

Long-term Effects of Socialization in Early Childhood

Source / Evidence	Key Findings	Implications for Child Development
Durlak et al. meta-analysis (213 SEL programs)	Improvement in academic performance (+11%), prosocial behavior, reduced anxiety; effects persisted over time	Social-emotional learning leads to stable, long-term developmental outcomes
Denham's model (age 5 social-emotional competence)	Predicts academic achievement independently of IQ and socioeconomic status	Social-emotional skills function as an independent factor of future success
Teacher observations (longitudinal practice)	Children adapt to routines, participate in group work, resolve conflicts independently	Early socialization supports smoother school adjustment and autonomy

Source: developed by the author based on research and pedagogical observations

methods is sufficient on its own, but when combined, they yield lasting results.

The family environment plays an important role in a child's social development, but it is not the only influence. Preschool settings can help balance differences in home experience, especially when children feel safe, understand daily routines, and interact in a respectful environment. In this context, the teacher acts both as a guide and as a model of behaviour.

Research, classroom observations, and feedback from elementary schools all point to a connection

between social-emotional development in late preschool years and later academic and social outcomes. This suggests that these skills should be treated as seriously as academic preparation.

Prospects for further research include the development and testing of structured social-emotional learning programs for preschool institutions in Ukraine, as well as longitudinal studies of the relationship between the level of social skills in late preschool age and academic and social success in elementary school.

ДОДАТКОВА ІНФОРМАЦІЯ

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ФОРМУВАННЯ ІНФОРМАЦІЙНОЇ КУЛЬТУРИ ЗДОБУВАЧІВ ОСВІТИ В УМОВАХ ГІБРИДНИХ ЗАГРОЗ

DEVELOPING INFORMATION LITERACY OF HIGHER EDUCATION STUDENTS IN THE CONTEXT OF HYBRID THREATS

Анотація. У статті розкрито функціональне значення інформаційної культури у системі фахової підготовки майбутніх бакалаврів бібліотечної, інформаційної та архівної справи в умовах гібридних загроз. На основі структурно-функціонального та порівняльного аналізу досліджено сукупність національних стратегій та стандартів інформаційної кібербезпеки. Розкрито ефективність включення регламентуючих безпекових настанов, основ кібергігієни у навчальні матеріали для формування здатності здобувачів освіти розпізнавати когнітивні маніпуляції та інформаційну експансію. Особливу увагу приділено інтерактивним методам навчання, спрямованим на формування інформаційної культури здобувачів освіти. Фахівець, здатний розпізнавати інформаційні загрози та протидіяти їм, відповідає актуальним запитам бібліотечних та архівних установ як стратегічних суб'єктів національної пам'яті.

Ключові слова: інформаційна культура, гібридна загроза, здобувач освіти, архівні установи, освітній компонент, освітній процес, кібербезпека.

Summary. The article reveals the functional role of information culture within the professional training system of future Bachelors in Information, Library and Archival Studies under hybrid threats. Based on structural-functional and comparative analyses, a complex of national strategies as well as information and cybersecurity standards is investigated. The study demonstrates the effectiveness of incorporating regulatory security guidelines and core elements of cyber hygiene into educational components to develop students' capacity to recognize cognitive manipulations and information expansion. Special attention is paid to interactive teaching methods aimed at shaping the information culture of higher education students. A specialist capable of identifying and counteracting information threats meets the current demands of libraries and archives as strategic entities of national memory.

Key words: information culture, hybrid threat, higher education student, archival institutions, educational component, educational process, cybersecurity.

Постановка проблеми. У сучасному суспільстві інформація посилює конкурентну боротьбу за сфери впливу між суб'єктами економічних, політичних відносин, як на регіональному, так і міжнародному рівнях. Цифрові технології стають потужним

інструментом маніпуляцій у суперництві підприємств, фінансових організацій, корпорацій, політичних партій, держав. Система освіти має оперативно реагувати на нові соціальні виклики, тому що наша країна перебуває під тиском інформаційних атак,

які прагнуть підсилити воєнну інтервенцію. Важливим виміром цієї проблеми є стрімкий розвиток інформаційно-комунікаційних технологій, що підвищує рівень потенційних загроз та небезпек.

У останні роки відбулось переоцінювання проблем кібербезпеки та інформаційної грамотності державному рівні, що в подальшому вплинуло на змістовне наповнення навчального матеріалу освітніх компонентів, переорієнтувало тематику модулів на формування у здобувачів критичного мислення, здатності розпізнавати фейки під час проведення лекційних та практичних занять з інформаційної культури. Здобувачі освіти активно споживають цифровий контент, але поява принципово нових безпекових викликів та штучних тригерів вимагає від системи освіти їх ретельного аналізу для впровадження відповідних змістових блоків для викладання, щоб озброїти майбутніх фахівців інструментами захисту та протидії інформаційним викликам. Захист від дезінформації стає пріоритетним умінням за ступенем важливості, оскільки в обставинах сьогодення інформаційна культура молоді є гарантом збереження культурної спадщини, національної ідентичності.

Аналіз останніх досліджень і публікацій. Проблема формування інформаційної культури майбутніх бакалаврів бібліотечної, інформаційної та архівної справи в умовах гібридних загроз перебуває на стику двох наукових напрямів, фахової підготовки здобувачів освіти та державної безпеки. Теоретичні основи дослідження національної безпеки детально проаналізовано в працях О. Данільяна, О. Дзьобаня та М. Панова. Європейський контекст та особливості реалізації національної інформаційної політики висвітлено у колективній монографії за редакцією Л. Губерського, Є. Камінського, Є. Макаренка. Водночас соціальний аспект кібербезпеки для розуміння ролі людського фактора в умовах гібридних загроз досліджено в розвідках В. Бурачка, В. Толубка, В. Хорошка, С. Толюпи. Концептуальним підґрунтям для визначення безпекових вимог до підготовки кадрів є чинна нормативна база України. Пріоритети захисту національних інтересів в інформаційній сфері та протидії маніпуляціям окреслені у Стратегії інформаційної безпеки та Стратегії кібербезпеки України «Безпечний кіберпростір — запорука успішного розвитку країни», в якій також висвітлено орієнтири розбудови захищеного віртуального простору. Окреме місце у формування професійних компетентностей посідають національні стандарти побудови систем керування інформаційною безпекою: ДСТУ ISO/IEC 27001:2023, ДСТУ ISO/IEC 27005:2023, ДСТУ ISO/IEC 27701:2022.

Проблемам адаптації системи освіти до викликів цифрового суспільства, трансформації професійного профілю інформаційного працівника присвячено наукові розвідки О. Матвієнко та М. Цивіна [1].

Особливості формування цифрової компетентності у здобувачів освіти бібліотечної, інформаційної та архівної справи розкрито у статті О. Мудрохи [2]. Загальні принципи та інструменти інтеграції цифрових технологій в освітній процес узагальнено О. Сахно [3]. Попри значну кількість публікацій, питання формування інформаційної культури майбутніх фахівців в умовах гібридних загроз залишається актуальним та потребує подальшого комплексного дослідження.

Мета статті полягає в теоретико-методологічному обґрунтуванні ключових аспектів та принципів формування інформаційної культури у здобувачів освіти як основи протидії дезінформації в умовах гібридних загроз.

Для реалізації мети в ході дослідження було застосовано метод структурно-функціонального аналізу для деталізації трансформації викладання змістових модулів з інформаційної культури; компаративний аналіз та систематизація нормативно-правових актів, стратегій кібербезпеки та останніх наукових розвідок за тематикою статті сприяли зіставленню моделей державної інформаційної політики в Україні та міжнародного досвіду. Інституційний та системний підходи стали підґрунтям розроблення методичних засад вдосконалення інформаційної грамотності здобувачів освіти.

Виклад основного матеріалу дослідження. В умовах розбудови цифрового суспільства інформація змінюється на визначальний чинник більшості соціальних, політичних та економічних процесів, що призводить до масштабування концепту інформаційної війни як несилового інструментарію досягнення поставлених завдань. Пришвидшений розвиток технологій суттєво збільшує аудиторію споживачів цифрового контенту, експоненційно посилює потужність ресурсів деструктивного впливу, мета якого полягає у когнітивній дезорієнтації та спрямована на маніпулювання громадською думкою, що актуалізує потребу в підготовці фахівців бібліотечної, інформаційної та архівної справи. Їх майбутня професійна діяльність буде пов'язана зі стратегічним управлінням інформаційними потоками, формуванням цифрової грамотності користувачів бібліотек та архівів, перевіркою документних джерел на валідність, пошуком фальсифікацій.

У науковому дискурсі інформаційну війну розглянуто як процес використання інформації та управління нею задля набуття переваг над конкурентом, як засіб ідеологічного та психологічного тиску, легітимізації та обґрунтуванні справедливості власних через обмеження прав опонента [4]. В широкому розумінні інформаційна війна — це протистояння з активним залученням цифрових технологій, дослідження якого є критично важливим для здобувачів освіти, оскільки їх професійні обов'язки будуть безпосередньо пов'язані з адмініструванням, захистом та збереженням електронних документів. Оскільки

віртуальний простір стає головним майданчиком розгортання маніпулятивних кампаній, навчальні матеріали курсу «Інформаційна культура» мають включати методи аналізу медіапотоків, основи кібергігієни у межах організаційних та соціальних комунікацій.

Інформація є фундаментальним атрибутом управління, її використання в межах інформаційно-комунікаційної діяльності простежується на всіх етапах історичного поступу людства. Проте, якщо в попередні епохи інформаційне протистояння редукувалося до конспірації власних даних та розвідувальної діяльності з її викриття, то сучасність вирізняється протистоянням різних технологій, «які використовуються для широкомасштабного, цілеспрямованого, швидкого і прихованого впливу на військові і цивільні інформаційні системи противника» [5, с. 90].

В умовах активної фази воєнного конфлікту в нашій країні здобувачам освіти варто пояснювати, що зіткнення в інформаційному просторі спостерігаються також в економічній сфері, для формування об'єктивного бачення глобального інформаційного суспільства. Методи виробників товарів та послуг вплинути на смаки та уподобання потенційних споживачів також належать до маніпулятивних, пошук та посилення позицій на нових ринках збуту, зміцнення національних економік за рахунок непрямих інвестицій, це також засоби протистояння на рівні корпорацій та держав. В інформаційній боротьбі держав, так само як корпорацій, інноваційним різновидом зброї вважають різноманітні комп'ютерні віруси та несанкціоновані вторгнення, що несуть пряму загрозу цілісності електронних архівів та баз даних.

Актуальною темою для вивчення та обговорення здобувачами спеціальності бібліотечна, інформаційна та архівна справа є інформаційна експансія, пролонгована в часі, цілі та методи якої передбачають варіативність та комплексність, можливість залучення зовнішніх ресурсів та союзників. Інформаційна експансія окреслюється прагненням домінувати в інформаційному просторі, на державному та локальному рівнях. Зазначена тактика передбачає активну роботу зі створення іміджу успіху, легітимності, дотримання норм моралі та гуманних цінностей. Зворотний бік такої діяльності полягає у побіжному нівелюванні опозиційної точки зору, дискредитації супротивників або конкурентів. Справжньою ареною інформаційних протистоянь є соціально-психологічна сфера, яку складно прогнозувати. Тому подання достовірної інформації на противагу фейкам та дезінформації буде недостатньо. Для протидії інформаційній експансії на рівні держави розробляються нормативно-правові документи, стратегії та стандарти інформаційної безпеки, вивченню яких необхідно приділити окремий змістовий модуль.

Система протидії гібридним загрозам та інформаційній експансії в нашій країні спирається на Закон України «Про національну безпеку України», Стратегію інформаційної безпеки та Стратегію кібербезпеки України «Безпечний кіберпростір — запорука успішного розвитку країни», прийняті в 2021 році. У Стратегії інформаційної безпеки пріоритетним визначено забезпечення конституційних прав і свобод кожного громадянина «на збирання, зберігання, використання та поширення інформації, доступ до достовірної та об'єктивної інформації» [6], також констатується на відповідальності держави щодо забезпечення захисту в цифровому просторі, «існує ефективна система захисту і протидії нанесенню шкоди через поширення негативних інформаційних впливів, у тому числі скоординоване поширення недостовірної інформації, деструктивної пропаганди, інших інформаційних операцій, несанкціоноване розповсюдження, використання й порушення цілісності інформації з обмеженим доступом» [6].

У Стратегії кібербезпеки України акцентується увага на захисті критичної інформаційної інфраструктури, безпеці цифрових реєстрів та мінімізації ризиків втручання в комп'ютерні мережі [7]. Оскільки архіви та бібліотеки інтегровані у цифровий простір, захист хмарових сховищ та електронного документообігу покладається в тому числі на працівників зазначених установ, тому процес формування кібергігієни у здобувачів освіти має бути невід'ємним складником під час вивчення майже всіх дисциплін. Здобувачам освіти необхідно набути навичок розпізнавання кіберзагроз, спричинених комп'ютерними вірусами та хакерськими атаками, вміти адмініструвати бази даних, забезпечувати цілісність електронних документів.

У контексті протидії гібридним загрозам та задля реалізації Стратегії інформаційної безпеки та Стратегії кібербезпеки України «Безпечний кіберпростір — запорука успішного розвитку країни» до аналізу на лекційних заняттях рекомендовано три взаємопов'язані стандарти, які формують базис для інформаційних установ: ДСТУ ISO/IEC 27001:2023 (ISO/IEC 27001:2022, IDT) Інформаційна безпека, кібербезпека та захист конфіденційності. Системи керування інформаційною безпекою. Вимоги; ДСТУ ISO/IEC 27005:2023 (ISO/IEC 27005:2022, IDT) Інформаційна безпека, кібербезпека та захист конфіденційності. Настанова керування ризиками інформаційної безпеки; ДСТУ ISO/IEC 27701:2022 (ISO/IEC 27701:2019, IDT) Методи безпеки. Розширення до ISO/IEC 27001 та ISO/IEC 27002 для керування конфіденційною інформацією. Вимоги та настанови.

Стандарт ДСТУ ISO/IEC 27001:2023 є генеральною методологічною рамкою, що забезпечує триаду інформаційної безпеки, а саме, конфіденційність, цілісність та доступність цифрових реєстрів, баз даних та електронного документообігу, гармонізований з міжнародними вимогами та враховує

динаміку кіберзагроз [8]. ДСТУ ISO/IEC 27005:2023 обґрунтовує інструменти ідентифікації, оцінювання та мінімізації ризиків втручання в цифрові мережі та хмарні сховища, що дає змогу моделювати загрози та прогнозувати їх наслідки [9]. ДСТУ ISO/IEC 27701:2022 регулює недопущення витоків масивів даних, що є критично важливим при оцифруванні документів, містить вимоги щодо захисту персональних даних [10].

Для здобувачів освіти спеціальності бібліотечна, інформаційна та архівна справа важливим результатом вивчення проблематики інформаційного протистояння має бути розуміння того, як захистити інформаційні ресурси; яким чином дезінформація впливає на професійну сферу; як здійснюється планомірний тиск на свідомість; як відбувається зміна тактики, від раптових фейків до планомірного приховування новин. Навички протидії маніпуляціям, адекватна реакція на загрози формуються на практичних заняттях для закріплення теоретичного матеріалу. Наприклад, аналіз реальних фейків, що транслюються через новини та соціальні мережі, дослідження випадків створення штучного інформаційного хаосу, або на лабораторних заняттях здобувачі обирають роль детективів та шукають ферми ботів, перевіряють приховані дані. Під час проведення круглих столів тестуються ділові ігри-маніпуляції, що викликають сильні емоції, страх, злість, радість, а потім у групі обговорюються засоби протидії таким інформаційним атакам. Здобувачам освіти також пропонується створити власні короткі курси чи пам'ятки з інформаційної безпеки для бібліотек або архівів.

Дієвим інструментом протидії інформаційним впливам, на думку вітчизняних дослідників, визначено освіту та самоосвіту, просвітницьку діяльність та активну громадянську позицію, а саме: «захистити себе людина може тільки шляхом використання системи внутрішньоособистісних фільтрів — зрілої організаційної свідомості, відповідної політичної культури, й, нарешті, зверненням до позитивного суспільного ідеалу особистості XXI століття, справедливої європейської держави і ефективного суспільства» [11, с. 60].

Вектором деструктивного інформаційного впливу та гібридних загроз є залучення медійних, художніх,

культурних, економічних, соціальних, освітніх та наукових, політичних, кібернетичних інструментів, що дестабілізують суспільство, провокують радикальні або панічні настрої, ускладнюють роботу органів державної та місцевої влади. Для протидії гібридним загрозам необхідно «забезпечувати належний захист інформації; попереджувати введення викривленої інформації в потік правдивих фактів і даних; протидіяти спростуванню, запереченню і знищенню інформації і вчасно та якісно реагувати на всі прояви війни» [2, с. 23]. Здобувачів освіти спеціальності бібліотечна, інформаційна та архівна справа мають усвідомлювати, що оцифровані фонди, державні реєстри та бази даних, які вони будуть адмініструвати, є об'єктами кібератак та спроб фальсифікації документів.

Висновки та перспективи подальших досліджень. Формування інформаційної культури — невід'ємний складник освітнього процесу, змістове наповнення методичного забезпечення фахових освітніх компонентів таких як архівознавство та документознавство, електронний документообіг та інформаційна культура. Бібліотечні та архівні установи як стратегічні суб'єкти національної пам'яті, потребують професіоналів здатних впроваджувати передові стандарти захисту інформаційних ресурсів.

Засоби розвитку та удосконалення інформаційної культури спираються на зміни в освітньому процесі фахової підготовки здобувачів спеціальності бібліотечна, інформаційна та архівна справа. Оптимізація моделі навчання має поєднувати викладання основ кібергігієни, безпеки баз даних із дотриманням жорстких вимог відповідних стандартів. Регламентуючі акти не лише окреслюють методи захисту цифрового простору держави, але й актуалізують проблему модернізації системи освіти щодо розвитку інформаційної грамотності майбутніх фахівців, забезпечення стійкості перед гібридними загрозами інформаційно-комунікаційних технологій та цифрового суспільства. Бібліотечні та архівні установи перетворились на важливі суб'єкти захисту інформаційного суверенітету країни. В освітньому процесі переваги мають віддаватись формуванню компетентностей з верифікації документних джерел, критичного аналізу інформаційного шуму та просвітництва щодо безпеки віртуального простору.

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ТЕХНІЧНИ НАУКИ

MODELING OF WEB APPLICATION SPEED BASED ON WEB PAGE PERFORMANCE METRICS

Summary. The article examines the main factors affecting the performance of modern web applications and analyzes metrics for evaluating web page performance. The indicators TTFB, FCP, LCP, INP, and CLS are considered, which characterize page loading speed, interface stability, and the efficiency of user interaction with a web application. A mathematical model for evaluating web application performance is proposed, formalizing the relationship between the parameters of the client-side and server-side parts of the system and the performance indicators of a web page. Within the framework of the model, the main input parameters are identified, including the number of HTTP requests, the size of JavaScript and CSS resources, network connection speed, caching parameters, and interface rendering characteristics. For comprehensive performance evaluation, an integral performance indicator using weighting coefficients of performance metrics is introduced. Simulation-based modeling of the influence of system parameters on web application performance was carried out. A series of numerical experiments was conducted to investigate the dependence of the integral performance indicator on the main system parameters, and corresponding graphical dependencies were constructed.

Key words: web application, web application performance, web page performance, mathematical model, integral performance indicator, Core Web Vitals.

Introduction. In the current context of web technology development, the performance of web applications has become one of the key factors determining the effective functioning of digital services and the quality of user interaction with the system. The increasing complexity of client-side interfaces, the spread of single-page applications, the growing volume of JavaScript code, and the number of network requests lead to higher system load, which negatively affects the performance indicators of a web resource [1; 2].

The issue of performance becomes particularly important in the context of high competition among digital platforms, where the performance of a web application directly influences user behavioral factors, conversion rates, and the ranking positions of web resources in search engines. In this regard, ensuring a high response speed of web pages is an important component of modern web development and software system optimization [3; 4]. In addition, the impact of various factors, such as the volume of JavaScript

resources, the number of HTTP requests, caching parameters, server response time, and interface rendering characteristics, is complex in nature and requires a formalized description [5; 6]. In this context, the development of a mathematical model for evaluating the performance of web applications is a relevant task, as it will make it possible to formalize the relationship between the input parameters of the system and the performance indicators of a web page [7].

Analysis of previous studies. The issue of ensuring high performance of web applications is one of the key areas of modern research in the field of web development and software engineering. The active development of client-side web technologies, the emergence of single-page applications, and the increasing volume of dynamic content have led to a significant rise in performance requirements for web systems. In scientific works and technical literature, considerable attention is paid to studying the impact of page loading speed on user experience, behavioral factors, and the efficiency of digital platforms. Research findings indicate that even a slight increase in web page loading time can negatively affect the level of user interaction with a service and reduce conversion rates [8; 9].

One important area of research has been the development of systems for evaluating the performance of web applications based on standardized metrics. Google proposed the Core Web Vitals concept, which combines key indicators for assessing web page performance, in particular Largest Contentful Paint (LCP), Interaction to Next Paint (INP), and Cumulative Layout Shift (CLS). The use of these metrics has made it possible to move from a subjective assessment of performance to a formalized analysis of web resource productivity. A significant number of modern studies are devoted to analyzing the influence of JavaScript resources, interface rendering, the number of HTTP requests, and network connection parameters on Core Web Vitals values [10; 11].

At the same time, a substantial part of scientific research focuses on individual aspects of web application optimization, including resource minification and compression, the use of caching, optimization of server response, and the application of modern interface rendering mechanisms. In particular, studies devoted to frontend optimization have shown that an excessive amount of JavaScript code and an inefficient DOM tree structure can significantly increase the processing and rendering time of a web page in the user's browser [11; 12]. Research related to the use of automated performance analysis tools, such as Lighthouse and WebPageTest, is also of particular scientific interest, as these tools enable comprehensive evaluation of web resource performance under different load conditions [10; 13].

Despite the significant number of studies in the field of web application optimization, the issue of developing a generalized mathematical model for performance evaluation that would take into account the

relationship between the main system parameters and a set of performance metrics has not been sufficiently addressed. Most existing approaches focus on the analysis of individual indicators or practical optimization recommendations, whereas the tasks of formalizing the dependencies between system input parameters and integrated performance indicators remain relevant. This highlights the need to develop a mathematical model for evaluating web application performance capable of providing a comprehensive analysis of the influence of individual factors on web page response speed [12; 14].

Aim of the article. The purpose of the article is to develop a mathematical model for evaluating the performance of web applications that makes it possible to formalize the relationship between the parameters of the client-side and server-side components of the system and the performance indicators of a web page. The proposed approach is aimed at analyzing the influence of key factors, in particular server response time, resource volume, the number of network requests, and interface rendering parameters, on the loading speed and user interaction with a web application.

Presentation of the main material. One of the key performance indicators of a web application is the response speed of a web page, which characterizes the time between a user sending a request and the complete rendering of the required content in the browser. High response time values lead to increased user waiting time, deterioration of system interactivity, and reduced efficiency of the web resource. In addition, web page performance directly affects the ranking of web resources in search engines, since modern SEO algorithms take performance indicators into account when assessing website quality [3].

Specialized performance metrics are used to evaluate the speed of web applications, making it possible to analyze individual stages of web page loading and rendering. One of the basic metrics is Time to First Byte, which determines the time between sending an HTTP request and receiving the first byte of the response from the server. This indicator characterizes the request processing speed of the server-side component of the system and depends on server performance, database efficiency, network connection parameters, and the use of caching mechanisms [4].

The First Contentful Paint indicator is used to evaluate the time required for the first content element to be displayed in the user's browser. The value of this metric determines the moment when the user receives the first visual response from the web application. Reducing FCP time positively affects the perceived performance of the system and improves the user experience.

One of the most important modern performance metrics is Largest Contentful Paint (LCP), which characterizes the time required to render the largest content element within the visible area of a page. This

indicator is used to evaluate the speed of the main page loading process and is one of the key parameters of Core Web Vitals [5]. LCP is influenced by the volume of resources, data transfer speed, image optimization, the efficiency of JavaScript code execution, and interface rendering parameters.

The Interaction to Next Paint metric is used to evaluate the speed of the interface response to user interaction. The value of this indicator is determined by the delay between a user action and the moment the interface is updated. High INP values indicate an overloaded browser main thread, an excessive number of JavaScript operations, or inefficient event handling organization [6].

The Cumulative Layout Shift (CLS) indicator characterizes the stability of the page structure during loading. Significant shifts of interface elements negatively affect user interaction with the system and may lead to erroneous actions. Reducing the CLS value is an important condition for ensuring the stability of the web application interface.

An analysis of the above metrics shows that web application performance is formed under the influence of a significant number of interrelated factors. The use of individual indicators does not make it possible to comprehensively evaluate system performance or determine the degree of influence of specific parameters on web page performance. In this regard, there is a need to develop a mathematical model for evaluating web application performance that will provide a formalized description of the relationship between system parameters and performance indicators.

Within the framework of this study, a web application is considered as a system whose state is determined by a set of input parameters (1):

$$X = \{x_1, x_2, \dots, x_n\} \quad (1)$$

where x_i denotes the parameters that affect the performance of a web application. The main input parameters of the model include:

- x_1 — the number of HTTP requests;
- x_2 — the volume of JavaScript resources;
- x_3 — the volume of CSS resources;
- x_4 — the network connection speed;
- x_5 — caching parameters;
- x_6 — the size of the DOM structure;
- x_7 — JavaScript execution time;
- x_8 — interface rendering parameters; and
- x_9 — server response time.

Each of the aforementioned parameters directly affects specific stages of web page loading and processing. For instance, an increase in the number of HTTP requests leads to higher network latency and a longer resource transfer time. A substantial volume of JavaScript code increases the load on the browser and may result in blocking of the main execution thread. A large DOM structure complicates the page rendering process and negatively affects the speed of interface updates.

The output parameters of the model are the main performance metrics of a web page. The relationship between the input and output parameters of the model is described by a system of functional dependencies (2):

$$Y = \begin{bmatrix} TTFB \\ FCP \\ LCP \\ INP \\ CLS \end{bmatrix} = F \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{bmatrix}, \quad (2)$$

where $F(X)$ is the function for evaluating the performance of a web application, which formalizes the relationship between the system parameters and the performance indicators of a web page. The model was developed on the basis of a systematic analysis of the factors influencing the performance of web applications. The characteristics of the client-side and server-side components of the system were selected as the input parameters of the model: the number of HTTP requests, the volume of JavaScript and CSS resources, the network connection speed, caching parameters, the size of the DOM structure, JavaScript execution time, interface rendering parameters, and server response time. Standardized web page performance metrics, namely TTFB, FCP, LCP, INP, and CLS, which are used within the Core Web Vitals assessment framework, were selected as the output parameters.

The function $F(X)$ formalizes the dependence between the system parameters and the performance indicators of a web page. For the comprehensive evaluation of performance, an integral indicator Q was used, formed through the weighted aggregation of individual performance metrics. Within the proposed model, an increase in the value of the integral indicator Q is interpreted as a deterioration in web application performance, since it reflects the cumulative impact of delays and performance losses.

In contrast to simplified performance evaluation models, the proposed approach takes into account the multifactorial influence of system parameters on individual web application performance metrics. Each metric is formed under the influence of a set of parameters of the client-side and server-side components of the system, which makes it possible to comprehensively describe the process of web page performance formation. Within the model, the integral performance indicator of a web application is defined by the following expression:

$$Q = w_1 f_1(x_1, x_4, x_9) + w_2 f_2(x_2, x_3, x_6, x_8) + w_3 f_3(x_2, x_4, x_7, x_8) + w_4 f_4(x_2, x_6, x_7) + w_5 f_5(x_6, x_8) \quad (3)$$

where Q is the integral performance indicator of a web application; w_i denotes the weighting coefficients of the corresponding metrics; f_i denotes the functions used to form the performance indicators; and x_i denotes the system parameters that affect web page performance. Since the TTFB, FCP, LCP, INP, and CLS metrics have different units of measurement, their values were normalized to the dimensionless interval [0; 1] before aggregation. This ensures the correct application of weighting coefficients and the comparability of the contribution of individual indicators to the formation of the integral indicator Q .

In the proposed model, the function f_1 describes the formation of the TTFB metric depending on the number of HTTP requests, the network connection speed, and the server response time. The function f_2 characterizes the influence of the volume of JavaScript and CSS resources, DOM structure parameters, and interface rendering parameters on the FCP indicator. The formation of the LCP metric is described by the function f_3 , which takes into account the volume of client-side resources, rendering parameters, and JavaScript execution speed.

The INP metric is formed by the function f_4 , which characterizes the influence of DOM structure complexity, browser main-thread load, and client-side script execution time on the speed of user interaction with the interface. To evaluate the stability of the page structure, the function f_5 is used; it determines the dependence of the CLS indicator on rendering parameters and the structure of the DOM tree. The use of weighting coefficients makes it possible to account for the varying degree of influence of individual metrics on the overall performance of a web application. In this study, the values of the weighting coefficients were determined based on Google Core Web Vitals recommendations and expert assessment of the importance of individual metrics for users' perception of web application performance. The highest weight was assigned to the LCP metric, which characterizes the rendering speed of the main page content. The lowest weight was assigned to the CLS metric, which characterizes interface stability.

Within the framework of numerical simulation, the following assumptions were adopted: an increase in the volume of JavaScript resources leads to an increase in the LCP and INP indicators; an increase in

the number of HTTP requests leads to an increase in TTFB and FCP; an increase in the complexity of the DOM structure deteriorates rendering indicators; and the CLS indicator varies within a limited range typical of modern web interfaces. The metric values presented in the tables were obtained as a result of scenario-based simulation in accordance with the specified assumptions. The numerical values of the parameters were selected in accordance with the typical ranges of web page performance metrics presented in Google Core Web Vitals recommendations and in contemporary studies on web application optimization. During the simulation, the values of the volume of JavaScript resources and the number of HTTP requests were varied within ranges typical of modern web applications.

The values of the TTFB, FCP, LCP, INP, and CLS metrics were determined in accordance with the functional dependencies embedded in the mathematical model. The obtained values were used to calculate the integral performance indicator Q . The results of the numerical simulation are presented in the form of tables and graphical dependencies, which make it possible to analyze the influence of individual parameters on web application performance. The obtained results were presented as graphical dependencies, which allow the nature of the influence of individual parameters on web application performance to be visually demonstrated, critical areas of performance degradation to be identified, and the contribution of individual metrics to the formation of the integral performance indicator to be assessed. Table 2 presents the results of numerical simulation of the dependence of performance indicators on the volume of JavaScript resources.

Figure 1 presents the graph of the dependence of the integral performance indicator Q on the volume of JavaScript resources in a web application. The obtained dependence demonstrates the nonlinear nature of changes in system performance as the volume of client-side code increases. The analysis of the graph shows that, as the volume of JavaScript resources increases, there is a gradual increase in the value of the integral indicator Q , which indicates a deterioration in the overall performance of the web application. At relatively low values of JavaScript code volume, the change in the performance indicator is comparatively slow; however, after a certain threshold value is exceeded, an accelerated increase in the integral indicator is observed.

Table 1

Metric	Abbreviation	Weight
Time To First Byte	TTFB	0.26
First Contentful Paint	FCP	0.22
Largest Contentful Paint	LCP	0.30
Interaction to Next Paint	INP	0.17
Cumulative Layout Shift	CLS	0.05

Table 2

JS, KB	TTFB, c	FCP, c	LCP, c	INP, mc	CLS	Q
100	0.40	1.20	2.10	120	0.05	0.16
200	0.42	1.30	2.30	130	0.05	0.20
300	0.45	1.50	2.60	145	0.06	0.26
400	0.50	1.70	2.90	160	0.07	0.34
500	0.54	1.90	3.20	180	0.08	0.45
600	0.59	2.10	3.60	205	0.09	0.60
700	0.65	2.40	4.00	230	0.10	0.77
800	0.72	2.80	4.50	260	0.12	1.00

This nature of the dependence can be explained by the increased load on the browser's main thread during the processing and execution of JavaScript scripts. The greatest impact is observed on the LCP and INP metrics, which directly characterize the speed of content rendering and the responsiveness of the interface to user actions. This confirms the feasibility of applying client-side code optimization methods, in particular JavaScript file minification, code splitting mechanisms, lazy loading, and optimization of the rendering process of interface components. The obtained results demonstrate the consistency of the model behavior with the known patterns of web application functioning. Table 3 presents the results of numerical simulation of the dependence of performance indicators on the number of HTTP requests.

Figure 2 presents the graph of the dependence of the integral performance indicator Q on the number of HTTP requests in a web application. The obtained dependence demonstrates a gradual deterioration in

system performance as the number of network requests increases. The analysis of the graph shows that, with a small number of HTTP requests, the change in the integral performance indicator is relatively insignificant. However, as the number of network requests increases, an accelerated increase in the value of the indicator Q is observed, which indicates the nonlinear nature of the influence of this parameter on web application performance.

This nature of the dependence can be explained by the increased time required to establish network connections, transmit data, and process server responses. Each additional HTTP request creates an additional load on the network infrastructure and the server-side component of the system, which leads to an increase in user waiting time and a deterioration in the TTFB and FCP indicators. A particularly noticeable deterioration in performance is observed after a certain threshold number of HTTP requests is exceeded. This indicates that, under a high level of network interaction, the

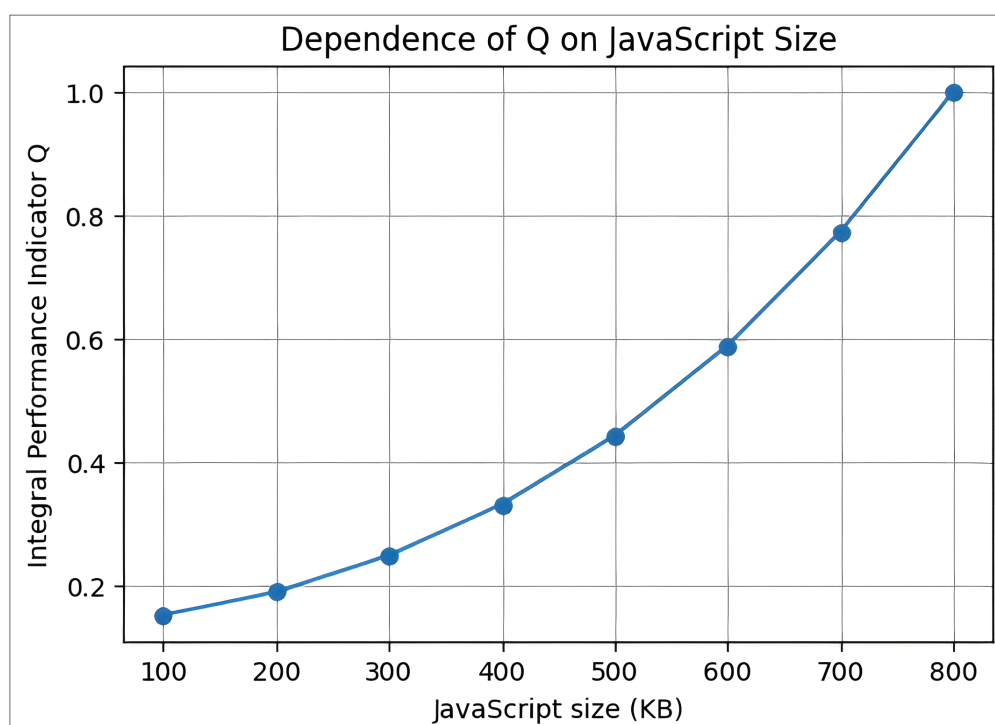


Fig. 1. Dependence of the integral performance indicator on the volume of JavaScript resources

Table 3

HTTP	TTFB, c	FCP, c	LCP, c	INP, mc	CLS	Q
10	0.38	1.15	2.00	118	0.05	0.15
20	0.40	1.25	2.15	125	0.05	0.18
30	0.43	1.35	2.35	133	0.06	0.23
40	0.47	1.50	2.60	145	0.06	0.30
50	0.52	1.70	2.90	160	0.07	0.40
60	0.58	1.95	3.25	180	0.08	0.54
70	0.65	2.20	3.65	205	0.09	0.73
80	0.74	2.55	4.10	235	0.10	0.98

system begins to operate less efficiently due to the accumulation of delays during resource loading and the synchronization of the client-side and server-side components of the web application.

The obtained results confirm the need to optimize the resource structure of a web application and reduce the number of HTTP requests. To improve performance, it is advisable to use mechanisms such as resource bundling, caching, asynchronous data loading, and content delivery networks (CDNs), which make it possible to reduce the load on the network infrastructure and shorten the web page loading time.

Figure 3 presents a diagram of the weighted contribution of individual performance metrics to the formation of the integral indicator Q for one of the numerical simulation scenarios. The constructed diagram reflects not only the adopted weighting coefficients but also the relative contribution of each metric to the overall value of the integral performance indicator. The LCP metric

makes the largest weighted contribution to the formation of the integral indicator, which is explained by its significant influence on users' perception of web page performance. The Time to First Byte (TTFB) and First Contentful Paint (FCP) metrics also have a considerable impact on the integral indicator, as they characterize the speed of the server response and the time required to display the first content element, respectively. High values of these indicators indicate the presence of delays at the initial stages of web page loading and negatively affect the perceived performance of the system.

The Interaction to Next Paint (INP) metric has a somewhat smaller, yet still significant, impact on the overall performance indicator. This metric characterizes the speed of the interface response to user interaction and reflects the level of interactivity of the web application. A deterioration in the INP value may be associated with an overloaded browser main thread or inefficient organization of client-side scripts.

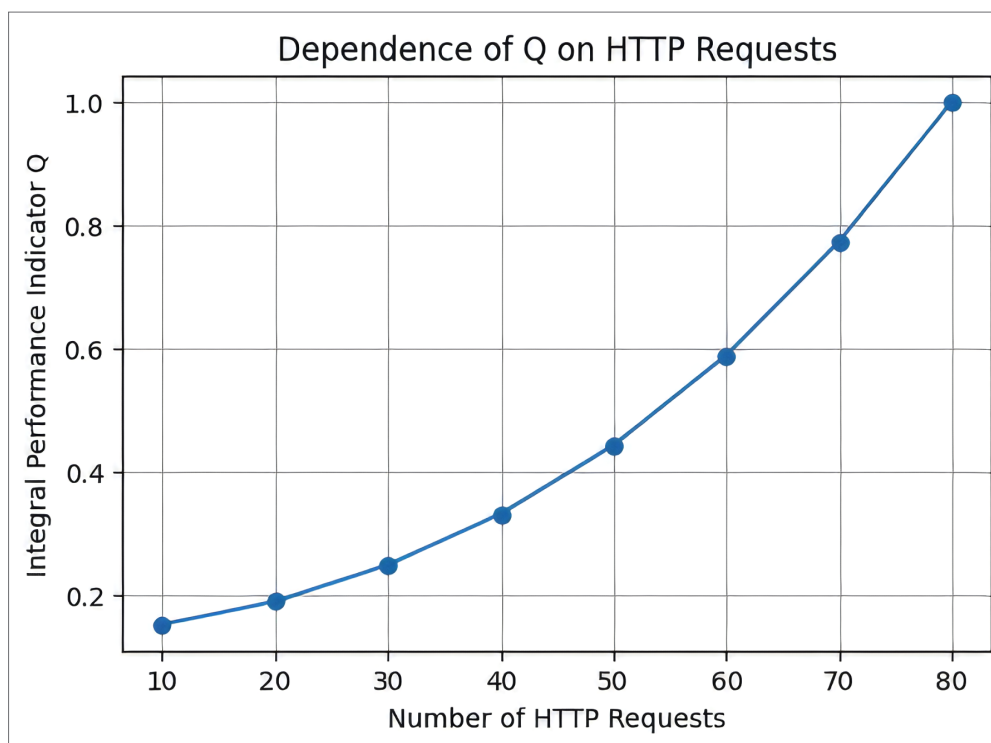


Fig. 2. Dependence of the integral performance indicator on the number of HTTP requests

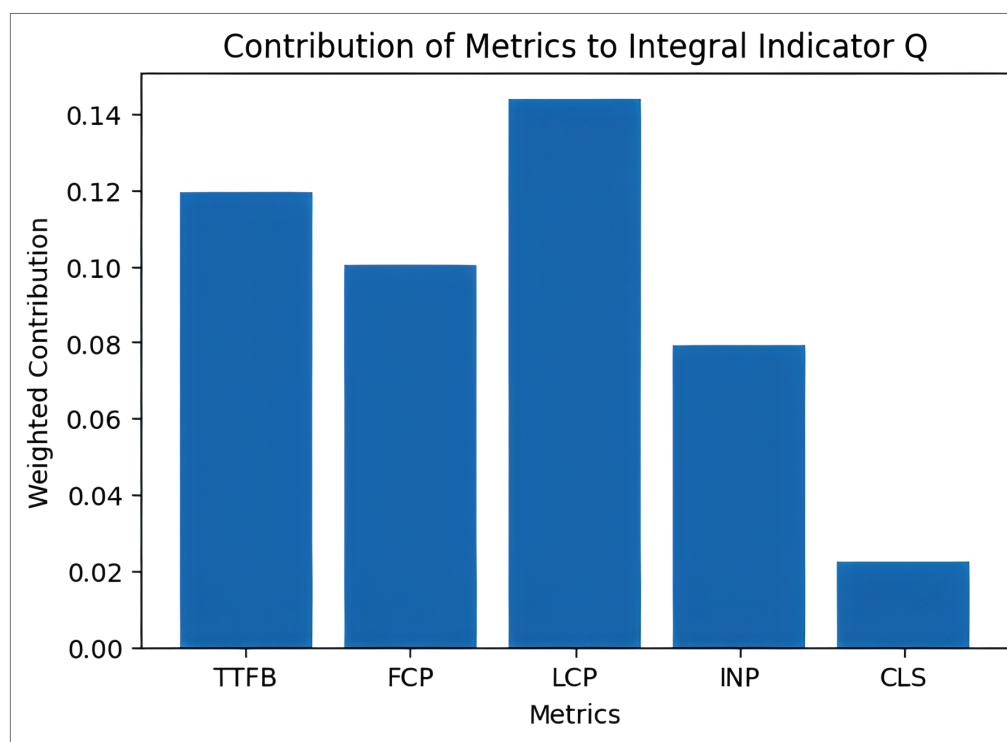


Fig. 3. Contribution of performance metrics to the formation of the integral performance indicator

The Cumulative Layout Shift (CLS) indicator has the smallest contribution within the proposed model, as it characterizes the stability of the page structure during loading. Despite its lower weighted influence, the CLS value remains important for ensuring correct user interaction with the web application and preventing undesirable shifts of interface elements. The use of weighting coefficients is appropriate within the proposed model, as it makes it possible to account for the different degrees of influence of individual metrics on the overall system performance and ensures a comprehensive evaluation of web page performance.

The practical significance of the developed model lies in its ability to predict the behavior of a web application under different system configurations and load levels. This makes it possible to identify the parameters whose optimization will provide the greatest improvement in web resource performance.

The obtained results confirm the feasibility of using multifactor mathematical modeling to evaluate the performance of modern web applications and demonstrate the possibility of applying the proposed model to analyze the effectiveness of web resource optimization methods.

Model Verification. The verification of the proposed mathematical model was carried out by analyzing the consistency of the numerical simulation results with the known patterns of influence of web application parameters on Core Web Vitals indicators.

The simulation results showed that an increase in the volume of JavaScript resources leads to a deterioration in the LCP and INP indicators, while an

increase in the number of HTTP requests negatively affects the TTFB and FCP indicators. The obtained dependencies are consistent with the results of contemporary studies in the field of web application optimization and with Core Web Vitals recommendations.

This indicates the possibility of using the proposed model for the qualitative analysis of factors affecting the performance of web applications. Conclusions and Prospects for Further Research. The study analyzed the main factors affecting the performance of web applications and examined contemporary metrics for evaluating web page performance. The features of the formation of TTFB, FCP, LCP, INP, and CLS indicators were considered, as these metrics characterize page loading speed, interface stability, and the efficiency of user interaction with a web application. Within the framework of the study, a mathematical model for evaluating web application performance was proposed, which formalizes the relationship between the parameters of the client-side and server-side components of the system and web page performance indicators. The developed model takes into account the multifactorial influence of system parameters on the integral performance indicator and enables a comprehensive evaluation of web application performance.

In the course of the study, the main input parameters of the model were identified, including the number of HTTP requests, the volume of JavaScript and CSS resources, network connection speed, caching parameters, the size of the DOM structure, JavaScript execution time, and interface rendering parameters. Web page performance metrics were used as output

parameters, making it possible to evaluate different aspects of web application performance.

Based on the proposed model, a series of numerical experiments was conducted to investigate the influence of individual system parameters on the integral performance indicator. The constructed graphical dependencies demonstrated the nonlinear nature of the influence of the volume of JavaScript resources and the number of HTTP requests on web application performance. The numerical simulation results showed that the volume of JavaScript resources and the number of HTTP requests have the greatest impact on web page performance; their increase leads to the deterioration of LCP, INP, TTFB, and FCP indicators. The proposed mathematical model can be used to analyze the effectiveness of web application optimization methods,

evaluate the impact of changes in system architecture on web page performance, and predict the behavior of a web resource under different load conditions. The practical application of the model provides an opportunity for the formalized analysis of web application performance and the identification of critical factors contributing to performance degradation.

Prospects for further research involve extending the proposed model by taking into account nonlinear dependencies between system parameters, temporal characteristics of load, and the combined influence of performance factors. In addition, the application of machine learning methods for the automatic determination of model weighting coefficients and the real-time prediction of web application performance indicators represents a promising direction for further research.

ДОДАТКОВА ІНФОРМАЦІЯ

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PASTRY ARCHITECTURE AS AN EMERGING DISCIPLINE: A FRAMEWORK FOR STRUCTURAL ENGINEERING, STABILITY, AND RISK MANAGEMENT IN LARGE-SCALE CUSTOM CAKES

Summary. The increasing complexity of contemporary custom cake production has transformed pastry creation from a primarily culinary activity into an interdisciplinary process involving engineering principles, structural planning, logistics management, and risk assessment.

Modern large-scale custom cakes frequently incorporate multi-tiered structures, suspended decorative elements, asymmetrical compositions, and transportation requirements that present challenges comparable to those encountered in temporary architectural installations.

Despite these developments, the professional pastry industry lacks a standardized framework for evaluating structural stability, material performance, transportation reliability, and project-specific risks associated with complex edible constructions. Existing professional knowledge remains largely experience-based and fragmented, limiting opportunities for standardization, scalability, and academic development.

This article introduces Pastry Architecture as an emerging interdisciplinary discipline that integrates principles of structural engineering, food science, project management, logistics, and artistic design. The study proposes the Nykytiuk Pastry Architecture Framework (NPAF), a systematic methodology for the planning, construction, transportation, and installation of large-scale custom cakes. Additionally, the article introduces the Cake Structural Risk Matrix (CSRM), a practical risk-assessment model developed specifically for edible structures.

The proposed framework contributes to the professionalization of advanced pastry production by establishing a conceptual foundation for future research, educational programs, and industry standards. The findings suggest that engineering-based methodologies may become increasingly important as the scale, complexity, and commercial value of custom cake projects continue to expand.

Key words: pastry architecture, cake engineering, structural stability, edible construction, risk management, food design, custom cakes, engineering methodology, pastry innovation.

Introduction. The global custom cake industry has experienced substantial transformation during the last two decades. Cakes are no longer viewed solely as desserts intended for consumption; increasingly, they function as large-scale artistic installations that serve as central visual elements at weddings, luxury events, corporate celebrations, exhibitions, and public ceremonies. This evolution has expanded the technical requirements placed upon pastry professionals and introduced challenges that extend well beyond traditional culinary practice.

Contemporary custom cakes frequently incorporate complex geometries, multiple structural levels, suspended decorative elements, edible sculptures, and transportation over considerable distances. In many cases, these creations exceed one meter in height and

require advanced support systems to maintain stability throughout production, transportation, installation, and presentation. Such requirements increasingly resemble the challenges encountered in architecture, structural engineering, and project management rather than conventional pastry preparation alone.

Researchers in food science have long recognized that food products possess measurable physical and mechanical properties that influence their behavior during processing, transportation, storage, and presentation [7; 5]. Similarly, engineering disciplines have demonstrated that structural reliability depends upon factors such as load distribution, material performance, environmental conditions, and risk mitigation strategies [3]. These principles are directly relevant to large-scale custom cakes, which function as temporary

edible structures subjected to various mechanical and environmental stresses.

Despite these similarities, the majority of contemporary pastry education and professional literature remains focused on recipe formulation, decoration techniques, flavor development, and aesthetic presentation. Comparatively little attention has been devoted to systematic approaches for structural assessment, transportation planning, installation procedures, and failure prevention within complex cake constructions. As a result, many technical solutions remain based on personal experience rather than standardized methodologies.

The absence of formal engineering frameworks creates significant operational challenges. Structural collapse, transportation damage, environmental degradation, and installation failures can lead to substantial financial losses, reputational harm, and compromised customer satisfaction. These risks become increasingly significant as projects grow in complexity and commercial value.

At the same time, advancements in food engineering have demonstrated the importance of understanding material behavior and structural performance within food systems [9].

Material selection, density distribution, moisture migration, and environmental stability all influence the long-term reliability of food-based structures. While these concepts have been studied extensively within food science, they have not been systematically integrated into professional cake design methodologies.

This article argues that the evolution of contemporary custom cake production necessitates the development of a new interdisciplinary framework capable of integrating artistic creativity with engineering reliability. This framework is referred to as Pastry Architecture.

For the purposes of this study, Pastry Architecture is defined as the systematic application of engineering principles, structural analysis, material evaluation, logistics planning, risk management, and design methodologies to the creation of large-scale edible structures. The concept recognizes that modern custom cakes increasingly require the same type of planning, assessment, and quality-control processes commonly employed in architecture and engineering projects.

The primary objectives of this article are fourfold:

1. To define Pastry Architecture as an emerging professional discipline.
2. To introduce the Nykytiuk Pastry Architecture Framework (NPAF) as a structured methodology for large-scale custom cake production.
3. To develop the Cake Structural Risk Matrix (CSRM) as a risk-evaluation tool for edible structures.
4. To establish a conceptual foundation for future research, professional training, and industry standardization.

While previous literature has examined food materials, culinary design, and engineering principles separately, the NPAF and CSRM models proposed in this study represent original conceptual frameworks developed by the author for the systematic management of structural stability and risk in large-scale custom cakes.

By formalizing these concepts, the study seeks to bridge the gap between traditional pastry practice and contemporary engineering-based approaches to complex cake design, thereby contributing to the ongoing professionalization of the pastry industry.

Literature Review. The development of contemporary custom cake production has occurred at the intersection of multiple disciplines, including food science, food engineering, design theory, materials science, logistics, and project management. While each of these fields has contributed valuable knowledge relevant to the production of complex edible structures, their findings have rarely been integrated into a unified framework specifically applicable to large-scale custom cakes.

Food Science and Material Behavior

Food science research has consistently demonstrated that food products possess measurable physical and mechanical properties that influence their structural performance under varying environmental and operational conditions [7; 5]. Characteristics such as density, moisture content, compressive strength, thermal sensitivity, and rheological behavior affect the stability and reliability of food systems throughout their lifecycle.

According to Ramaswamy and Marcotte [9], food materials respond predictably to external forces and environmental changes, making it possible to evaluate their performance using engineering-based analytical approaches. These principles are particularly relevant to cake production, where multiple layers, fillings, support structures, and decorative components interact within a single integrated system.

The structural behavior of food products has also been examined through microstructural analysis. Aguilera and Stanley [1] demonstrated that food materials exhibit organized internal structures that directly influence their mechanical properties and resistance to deformation. Such findings suggest that large-scale cakes may be evaluated not merely as culinary products but as engineered assemblies composed of materials with distinct structural characteristics.

Despite these advances, food science literature has largely focused on processing efficiency, preservation, texture, and sensory quality rather than the design and management of large-scale edible constructions. Consequently, significant opportunities remain for applying food engineering principles to structural planning within professional pastry production.

Engineering Principles and Structural Stability

Structural engineering provides a well-established theoretical foundation for understanding stability, load

transfer, redundancy, and failure prevention in complex systems. Engineering literature emphasizes that successful structures depend upon the interaction of materials, support systems, environmental conditions, and anticipated loading scenarios [3].

Ashby [3] argues that material selection represents one of the most critical stages in engineering design because performance requirements must be evaluated before construction begins. This principle has direct relevance to pastry production, where cake compositions, fillings, support elements, and decorative materials must be selected according to project-specific structural demands.

Similarly, Gibson and Ashby [3] demonstrated that structural performance depends not only upon material strength but also upon geometry, load pathways, and system organization. In the context of custom cake production, these concepts suggest that stability cannot be achieved through stronger materials alone but requires deliberate planning of support systems and load-transfer mechanisms.

Traditional cake design often relies upon empirical methods and practitioner experience. While such approaches may be effective for conventional projects, they become increasingly insufficient as structures grow in size, complexity, and economic value. Engineering methodologies therefore offer a valuable framework for improving predictability and reducing project risk.

Design Thinking and Culinary Innovation

The relationship between aesthetics and functionality has become an increasingly important area of study within contemporary food design. Steen [10] argues that culinary innovation is most effective when technical functionality and visual expression are developed simultaneously rather than independently.

Within luxury hospitality markets, consumers increasingly seek products that provide memorable experiences in addition to practical utility. Consequently, food products frequently serve symbolic, artistic, and experiential functions that extend beyond nutrition.

Custom cakes represent a particularly significant example of this trend. In many contemporary events, the cake serves as both a food product and a visual centerpiece. Designers must therefore balance artistic objectives with technical constraints, creating structures that are simultaneously visually striking, transportable, stable, and safe.

However, current food-design literature provides limited guidance regarding the engineering challenges associated with achieving these objectives. Existing research generally focuses on user experience, presentation, and creativity rather than structural reliability and risk mitigation.

Risk Management and Project Planning

Risk assessment methodologies have long been utilized within engineering, manufacturing, transportation, and construction industries to identify potential failure mechanisms before implementation.

Project management literature consistently demonstrates that proactive risk identification reduces uncertainty, improves resource allocation, and increases project success rates. Structured risk assessment enables organizations to implement preventive measures rather than relying upon reactive problem-solving strategies.

The pastry industry, however, has historically lacked formalized risk-management frameworks. Many professionals evaluate transportation risks, environmental exposure, installation challenges, and structural vulnerabilities through experience rather than systematic analysis.

This gap becomes increasingly problematic as custom cake projects expand in scale and complexity. A wedding cake exceeding one hundred servings may represent several days of labor, substantial material costs, and significant reputational risk. Consequently, the adoption of structured risk-management methodologies appears both necessary and commercially advantageous.

Research Gap

The literature reviewed above demonstrates that substantial knowledge exists regarding food materials, engineering design, risk assessment, and culinary innovation. However, these disciplines have largely evolved independently.

No widely recognized framework currently integrates:

- Structural engineering principles
- Food-material performance analysis
- Transportation planning
- Installation procedures
- Risk-management methodologies

Advanced cake-design practices into a single operational system specifically designed for large-scale custom cakes.

This fragmentation creates a significant theoretical and practical gap within both academic literature and professional pastry practice.

The present study addresses this gap through the introduction of Pastry Architecture as an interdisciplinary framework and through the development of two original conceptual models:

The Nykytiuk Pastry Architecture Framework (NPAF), a systematic methodology for planning and executing large-scale custom cake projects.

The Cake Structural Risk Matrix (CSRM), a structured model for evaluating project-specific risks associated with edible structures.

Together, these models seek to establish the conceptual foundation of Pastry Architecture as an emerging professional discipline that bridges the fields of engineering, food science, logistics, and artistic design.

Methodology

Research Design

This study employs a conceptual framework methodology designed to synthesize principles from

structural engineering, food science, logistics management, and professional pastry production into a unified operational model. Conceptual framework research is particularly appropriate when an emerging field lacks standardized methodologies and requires the development of new theoretical structures capable of guiding future investigation and professional practice.

The research does not seek to evaluate a single cake project or compare individual production techniques. Instead, it aims to establish a systematic model capable of addressing recurring challenges encountered in large-scale custom cake production. The proposed framework was developed through interdisciplinary analysis of engineering principles, food-material behavior, transportation logistics, project management methodologies, and advanced pastry-production practices.

The resulting framework is intended to function as both a conceptual model and a practical decision-making tool for professionals involved in the design and execution of complex edible structures.

Identification of Core Structural Challenges

The development of the framework began with identification of recurring operational challenges observed in large-scale custom cake projects.

A review of professional practices and technical requirements revealed six categories of challenges that consistently influence project success:

- 1) structural instability;
- 2) uneven load distribution;
- 3) material deformation;
- 4) transportation-related damage;
- 5) environmental exposure;
- 6) installation and assembly failures.

While traditional pastry methodologies frequently address these issues individually, there is currently no standardized system that integrates them into a comprehensive planning process.

The present study therefore treats these challenges as interconnected variables requiring coordinated evaluation throughout the entire project lifecycle.

Interdisciplinary Framework Development

The proposed methodology was developed by adapting established concepts from multiple disciplines.

From structural engineering, the framework incorporates:

- load distribution analysis;
- support-system planning;
- center-of-gravity evaluation;
- redundancy design principles;
- failure prevention strategies. [3; 6].

From food science and food engineering, the framework incorporates:

- material-performance evaluation;
- density assessment;
- moisture-management considerations;
- environmental sensitivity analysis;
- structural behavior of food systems. [1; 5].

From project management and risk-management literature, the framework incorporates: risk identification procedures; probability-impact assessment; preventive planning methodologies; contingency development strategies. [9].

Finally, from contemporary pastry practice, the framework incorporates:

- artistic design requirements;
- production workflow considerations;
- transportation procedures;
- installation protocols;
- customer-specific customization requirements.

The integration of these disciplines forms the basis of the proposed Pastry Architecture methodology.

Development of the Nykytiuk Pastry Architecture Framework (NPAF)

The primary outcome of the research process is the development of the Nykytiuk Pastry Architecture Framework (NPAF).

The NPAF model was originally developed by Nykytiuk as a systematic methodology for large-scale custom cake engineering. The framework organizes project execution into six sequential stages, each addressing a specific category of structural, operational, and logistical requirements.

Rather than treating cake construction as a purely artistic or culinary process, the framework approaches each project as a temporary engineered structure that requires planning, analysis, implementation, monitoring, and verification.

The six-stage model serves as the central organizing structure of the proposed discipline of Pastry Architecture.

Nykytiuk Pastry Architecture Framework (NPAF)

The central contribution of this study is the introduction of the Nykytiuk Pastry Architecture Framework (NPAF), a systematic methodology designed for the planning, engineering, construction, transportation, and installation of large-scale custom cakes.

Unlike traditional cake-production approaches that focus primarily on recipe formulation and decorative execution, the NPAF model treats complex cakes as temporary architectural systems whose reliability depends upon the interaction of multiple structural and operational variables.

The framework establishes a repeatable methodology intended to improve project predictability, reduce risk, and facilitate professional standardization.

Stage 1: Conceptual Design

The first stage establishes project objectives and defines all major design requirements. These include dimensions, serving capacity, artistic vision, venue characteristics, transportation distance, environmental conditions, and client expectations.

At this stage, aesthetic goals must be evaluated alongside structural feasibility. Design concepts that cannot be safely executed within identified constraints require modification before production planning begins.

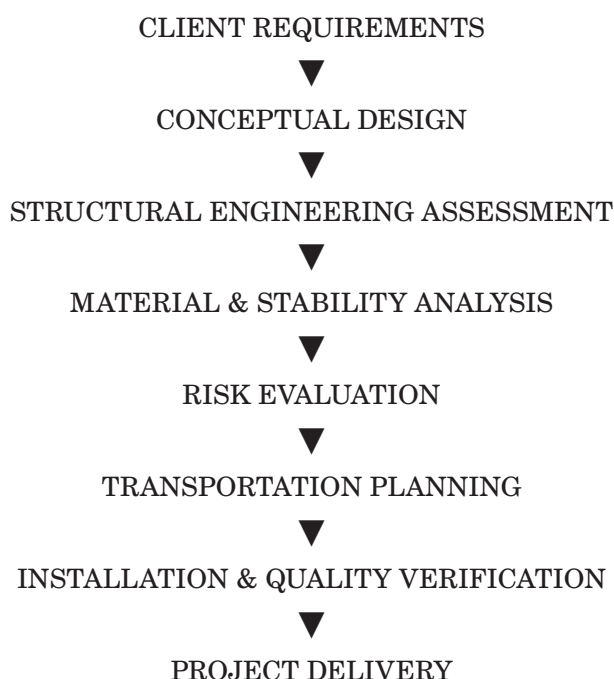


Fig. 1. The Nykytiuk Pastry Architecture Framework (NPAF), an original six-stage methodology for the planning and execution of large-scale custom cake projects

Early integration of technical assessment significantly reduces downstream project risks.

Stage 2: Structural Engineering Assessment

The second stage evaluates the structural requirements of the project. Key considerations include:

- anticipated load distribution;
- center-of-gravity location;
- support-system requirements;
- reinforcement strategies;
- structural redundancy.

The assessment determines whether the proposed design can maintain stability throughout production, transportation, installation, and presentation.

Support structures are selected according to anticipated loading conditions rather than solely according to visual requirements.

Stage 3: Material and Stability Analysis

The third stage focuses on material behavior and environmental performance.

Cake compositions, fillings, coverings, decorative materials, and support components are evaluated according to:

- density;
- compressive resistance;
- moisture sensitivity;
- temperature tolerance;
- long-term dimensional stability.

Material selection plays a critical role in determining overall structural reliability and must therefore be aligned with project-specific performance requirements [3].

Stage 4: Risk Evaluation

Following structural and material assessment, project-specific risks are identified and categorized.

Potential risks include:

- structural failure;
- transportation damage;
- environmental degradation;
- installation complications;
- decorative-component failure.

The results of this stage directly inform mitigation strategies implemented during later phases of project development.

Stage 5: Transportation Planning

Transportation represents one of the most significant sources of failure in large-scale custom cake projects.

This stage evaluates:

- route complexity;
- travel duration;
- vibration exposure;
- packaging requirements;
- temperature-control measures;
- loading and unloading procedures.

Transportation planning is treated as an engineering consideration rather than an operational afterthought.

Stage 6: Installation and Quality Verification

The final stage includes project delivery, assembly, stabilization, and final inspection.

Quality verification procedures confirm that the completed structure satisfies both aesthetic and structural requirements prior to presentation.

Contingency measures are also implemented when elevated project risk has been identified during earlier stages.

Successful completion of this stage marks the transition from production to operational deployment of the finished edible structure.

Cake Structural Risk Matrix (CSRM)

One of the defining characteristics of engineering disciplines is the systematic identification and management of risk before construction begins. In contrast, risk assessment within professional cake production has historically been based primarily on individual experience and informal decision-making processes.

As project complexity increases, reliance on intuition alone becomes increasingly insufficient. Large-scale custom cakes may involve substantial material costs, extensive labor investment, transportation over long distances, and significant reputational consequences in the event of failure. Consequently, the implementation of structured risk-assessment methodologies becomes essential.

To address this challenge, the present study introduces the **Cake Structural Risk Matrix (CSRM)**, an original risk-evaluation model developed as part of the broader Nykytiuk Pastry Architecture Framework.

The CSRM model was developed specifically for edible structures and provides a systematic method for identifying, classifying, and mitigating project-specific risks before production begins.

IMPACT	LOW	MEDIUM	HIGH
LOW PROBABILITY	L	L	M
MEDIUM	L	M	H

Fig. 2. Cake Structural Risk Matrix (CSRM)

L = Low Risk

M = Moderate Risk H = High Risk

VH = Very High Risk

Figure 2. Cake Structural Risk Matrix (CSRM), an original risk-classification model for evaluating project-specific threats in large-scale edible structures.

Risk Categories

The CSRM identifies four primary categories of project risk:

Structural Risk

Structural risk refers to the possibility of failure resulting from inadequate support systems, excessive loading, improper load transfer, material weakness, or instability of the overall structure.

Structural collapse represents the most severe category of project failure because it may compromise the entire edible structure.

Transportation Risk

Transportation risk includes damage resulting from vibration, acceleration, braking forces, handling procedures, and packaging deficiencies.

Numerous complex cakes remain structurally stable during production but fail during transportation due to insufficient planning of dynamic loading conditions.

Environmental Risk

Environmental risk arises from exposure to factors including:

- elevated temperatures;
- humidity fluctuations;
- direct sunlight;
- prolonged display periods;
- venue-specific environmental conditions.

Environmental factors may alter material behavior and significantly reduce structural reliability.

Installation Risk

Installation risk occurs during unloading, assembly, positioning, and final presentation.

Projects requiring on-site assembly frequently involve elevated risk due to time constraints, venue limitations, and handling complexity.

Risk Assessment Process

The CSRM methodology evaluates each identified risk according to two criteria:

1. Probability of occurrence.
2. Potential impact upon project success.

The combination of these variables determines overall risk classification. For example:

Scenario	Probability	Impact	Risk Level
Decorative element detachment	Medium	Moderate	Moderate
Filling deformation	Low	Moderate	Low
Transportation damage	High	Major	High
Structural collapse	Medium–High	Critical	Very High

Projects exhibiting High or Very High-Risk classifications require implementation of additional mitigation strategies.

Risk Mitigation Strategies.

Recommended mitigation measures include:

- redundant support systems;
- reinforced internal structures;
- alternative transportation procedures;
- environmental-control measures;
- on-site assembly protocol
- emergency stabilization plans.

The objective is not to eliminate risk entirely but rather to reduce the probability and severity of potential failures.

The incorporation of formal risk-management procedures represents one of the principal distinctions between traditional cake production and the proposed discipline of Pastry Architecture.

Structural Design Principles in Pastry Architecture

The successful execution of large-scale custom cakes depends upon the application of fundamental structural principles commonly encountered in engineering and architecture.

Although edible structures differ significantly from conventional construction materials, they remain

subject to the same physical laws governing stability, load transfer, equilibrium, and material performance.

The present framework adapts these principles to the unique requirements of pastry production.

Load Distribution

Load distribution represents one of the most important determinants of structural reliability.

Every component incorporated into a cake contributes to the overall loading condition of the structure. This includes:

- cake layers;
- fillings;
- support elements;
- decorative components;
- sculptural features.

Failure to distribute these loads appropriately may result in localized stress concentrations that exceed material capacity.

Engineering literature consistently demonstrates that successful structures rely upon predictable load-transfer pathways [3]. The same principle applies to edible structures.

Within the NPAF model, structural loads should be transferred through dedicated support systems rather than through edible materials alone.

Figure 3. Conceptual model illustrating load transfer through a multi-tier custom cake structure.

The figure demonstrates how structural loads are transmitted through internal support systems toward the primary base platform. Stability depends upon the

integrity of these support pathways rather than the strength of decorative components.

Center of Gravity Management

As structures increase in height and complexity, center-of-gravity management becomes increasingly important.

Asymmetrical designs, suspended decorations, floating elements, and sculptural projections may shift the center of gravity away from the structural centerline.

When this occurs, overturning forces increase significantly.

The NPAF methodology therefore requires evaluation of center-of-gravity placement during the conceptual-design stage rather than after production has begun.

Early identification of stability concerns allows corrective measures to be incorporated before construction proceeds.

Structural Redundancy

Redundancy is widely recognized as a fundamental principle of engineering reliability.

A redundant system contains secondary support pathways capable of maintaining functionality in the event of localized component failure.

Within pastry architecture, redundancy may include: additional support columns; secondary reinforcement systems; backup transportation platforms; modular assembly strategies.

The incorporation of redundancy significantly reduces the likelihood of catastrophic failure.

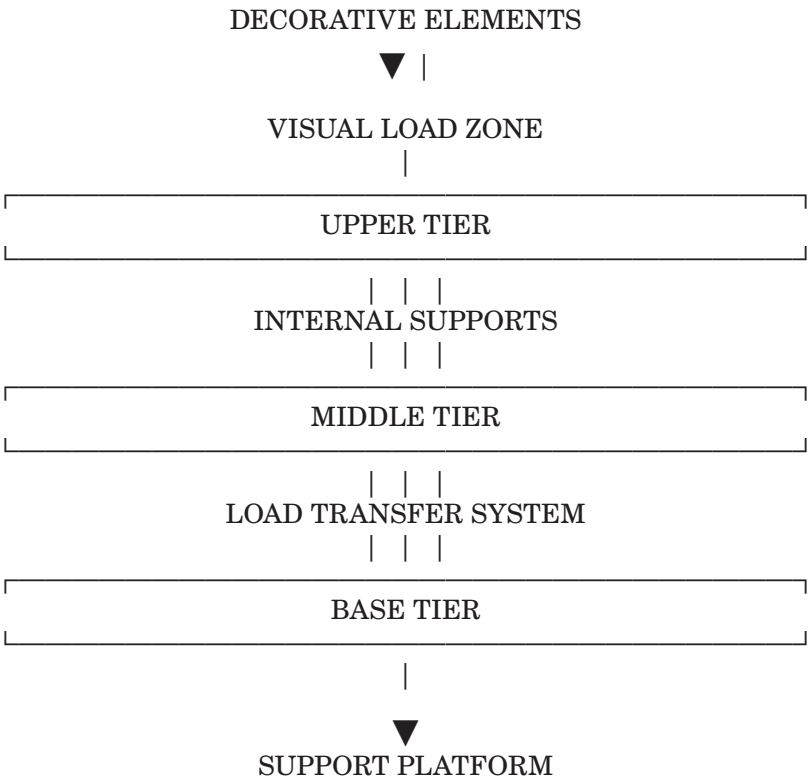


Fig. 3. Structural Components of a Large-Scale Custom Cake

Material Performance

Material behavior plays a central role in structural reliability.

Cake compositions differ substantially in density, moisture content, compressive strength, and environmental sensitivity.

Consequently, material selection should be based upon performance requirements rather than solely upon aesthetic or culinary considerations.

This principle reflects established engineering methodologies emphasizing the relationship between material properties and structural performance [3].

Environmental Stability

Environmental conditions remain among the most underestimated variables in custom cake production.

Temperature fluctuations, humidity exposure, prolonged display periods, and transportation conditions may significantly influence material behavior.

The NPAF framework therefore requires environmental assessment as part of the planning process.

Environmental stability should be evaluated throughout:

- production;
- storage;
- transportation;
- installation;
- presentation.

This approach ensures that structural reliability is maintained throughout the entire project lifecycle.

Commercial and Industry Applications

The practical value of Pastry Architecture extends beyond theoretical discussion and offers significant benefits for professional pastry businesses, hospitality organizations, educational institutions, and industry stakeholders.

The increasing demand for large-scale custom cakes has created a market environment in which technical reliability is becoming as important as artistic quality. Clients commissioning premium cake projects frequently invest substantial financial resources and expect consistent performance throughout transportation, installation, and presentation.

Consequently, businesses capable of delivering structurally reliable products gain significant competitive advantages.

The implementation of the Nykytiuk Pastry Architecture Framework (NPAF) may improve operational performance in several areas.

First, systematic planning reduces production uncertainty by identifying structural vulnerabilities before fabrication begins. Early detection of potential failures decreases material waste, minimizes redesign requirements, and improves resource allocation.

Second, standardized methodologies increase consistency across projects. Traditional cake production often relies heavily on the experience of individual professionals. While expertise remains valuable, dependence upon tacit knowledge may limit scalability. The

adoption of structured procedures facilitates knowledge transfer and organizational standardization.

Third, engineering-based planning supports workforce development. Employees can be trained using documented procedures rather than relying exclusively on informal mentorship. This approach enhances operational continuity and reduces organizational dependence upon individual specialists.

Fourth, the framework provides a foundation for quality assurance. By incorporating structural evaluation, risk assessment, and verification procedures into project workflows, businesses can improve reliability while reducing operational losses associated with transportation damage and structural failure.

From a commercial perspective, these advantages contribute directly to customer satisfaction, brand reputation, and long-term business sustainability.

Applications in Hospitality and Event Industries

Large-scale cakes are frequently commissioned for weddings, corporate events, luxury celebrations, exhibitions, and promotional campaigns.

These projects often involve:

- complex logistics;
- strict delivery schedules;
- venue-specific requirements;
- substantial financial investments.

The application of Pastry Architecture principles may improve project outcomes by ensuring that technical planning receives the same level of attention as artistic design.

As event expectations continue to increase, engineering-based methodologies are likely to become increasingly valuable within premium hospitality markets.

Educational Applications

The emergence of Pastry Architecture also creates opportunities for curriculum development within culinary education.

Most pastry programs emphasize recipe development, baking techniques, and decorative skills. However, relatively little instruction is devoted to structural planning, risk management, transportation engineering, or large-scale project execution.

The NPAF model may serve as a foundation for educational modules addressing:

- structural stability;
- support-system design;
- transportation planning;
- environmental analysis;
- project management.

Such educational initiatives would help prepare future professionals for the technical realities of contemporary custom cake production.

Discussion. The findings of this study suggest that contemporary custom cake production has evolved beyond the boundaries of traditional pastry practice and increasingly requires interdisciplinary expertise.

The growing complexity of edible structures has created challenges that cannot be adequately

addressed through culinary knowledge alone. Professionals must simultaneously consider material behavior, structural stability, transportation logistics, environmental conditions, and project-specific risks.

The proposed concept of Pastry Architecture provides a framework for integrating these considerations into a coherent professional methodology.

Unlike traditional approaches that frequently separate artistic design from technical planning, the NPAF model treats both dimensions as interconnected components of a single system. This integration reflects broader trends observed in architecture, engineering, and industrial design, where aesthetic objectives and functional performance are developed concurrently rather than sequentially.

The introduction of the Cake Structural Risk Matrix (CSRM) further contributes to the professionalization of the field by establishing a formal process for evaluating uncertainty and implementing preventive measures.

While previous literature has addressed food materials, engineering concepts, and culinary innovation independently [1; 3; 10], few studies have attempted to synthesize these disciplines within a unified framework specifically applicable to custom cake production.

The present study therefore contributes to both professional practice and academic discourse by proposing a new conceptual model capable of supporting future research, education, and industry standardization.

Future investigations may expand upon the framework through empirical testing of structural-performance models, quantitative evaluation of support systems, transportation simulations, and material-behavior analysis under varying environmental conditions.

Such research would further strengthen the scientific foundation of Pastry Architecture as an emerging discipline.

Original Contribution to the Field

The principal contribution of this study is the formal introduction of Pastry Architecture as a distinct interdisciplinary field that integrates structural engineering, food science, logistics management, risk assessment, and artistic design within a unified professional framework.

While previous literature has explored these domains independently, no widely recognized methodology currently exists for their systematic application to large-scale custom cake production.

The present study introduces two original conceptual models developed by the author:

Nykytiuk Pastry Architecture Framework (NPAF)

The NPAF represents an original six-stage methodology for planning, constructing, transporting, installing, and evaluating complex edible structures.

The framework establishes a repeatable process capable of improving reliability, consistency, scalability,

and risk management within professional cake production.

Cake Structural Risk Matrix (CSRM)

The CSRM represents an original risk-classification model specifically designed for large-scale edible structures.

The matrix provides a systematic approach for evaluating project-specific vulnerabilities and implementing preventive mitigation strategies before production begins.

Together, these models establish a conceptual foundation for future research, professional education, and industry-wide standardization.

To the author's knowledge, this is the first published framework that combines engineering design principles, material-performance analysis, transportation planning, risk-management methodology, and advanced pastry production into a unified operational system.

Conclusion. This article has introduced Pastry Architecture as an emerging interdisciplinary discipline situated at the intersection of structural engineering, food science, logistics management, risk assessment, and artistic design.

The increasing complexity of contemporary custom cake projects demonstrates the need for methodologies that extend beyond traditional pastry techniques and incorporate systematic planning procedures commonly associated with engineering and architectural practice.

The study proposed two original conceptual contributions:

The Nykytiuk Pastry Architecture Framework (NPAF), a six-stage methodology for the planning and execution of large-scale custom cake projects.

The Cake Structural Risk Matrix (CSRM), a structured model for evaluating and mitigating project-specific risks associated with edible structures.

Together, these models provide a foundation for improving structural reliability, operational efficiency, transportation safety, and professional standardization within the custom cake industry.

The findings suggest that future advancements in large-scale cake production will increasingly depend upon the integration of engineering-based methodologies capable of addressing the technical demands of contemporary edible structures.

Future research should focus on empirical validation of the proposed framework, quantitative structural analysis, environmental-performance testing, transportation simulations, and curriculum development dedicated to the emerging discipline of Pastry Architecture.

As the scale and sophistication of custom cake projects continue to expand, Pastry Architecture may serve as a valuable framework for supporting innovation, reliability, and professional excellence across the global pastry industry.

ДОДАТКОВА ІНФОРМАЦІЯ

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ACCESS MATRIX-AS-CODE: AUTOMATED GENERATION OF PERMISSION VALIDATION SCENARIOS FROM CODIFIED ACCESS SPECIFICATIONS IN ENTERPRISE CRM PLATFORMS

Summary. Enterprise CRM platforms accumulate thousands of permission boundary definitions across roles, objects, and fields, yet the test suites that validate these boundaries are typically maintained through manual mappings that grow stale as configurations change. This paper introduces Access Matrix-as-Code (AMS), an approach in which the complete permission state of a Salesforce CRM deployment is extracted via Tooling API SOQL queries, codified as a versioned YAML specification, and used to automatically generate both positive and negative test scenarios for every role-object-field combination. A diff engine compares successive AMS snapshots to produce incremental scenario updates targeting only permission boundaries affected by each release. Evaluated across six release cycles in a financial services CRM environment with 27 roles and over 3,000 permission boundary definitions, the pipeline achieved 100% specification completeness, detected 14 unintended configuration drifts that the prior manual process missed, and reduced scenario generation time to under four minutes per release through delta-based updates. By converting permission validation from a periodic audit activity into a continuous, specification-driven engineering practice, the AMS approach eliminates the detection latency that allows unauthorized access configurations to persist between review cycles.

Key words: access matrix-as-code, permission specification, automated test generation, CRM access control, Tooling API, policy-as-code, configuration drift detection.

Introduction. Enterprise CRM deployments in regulated industries operate under a dual constraint: the permission model must be granular enough to enforce least-privilege access across dozens of roles, yet flexible enough to accommodate frequent changes driven by new business requirements, regulatory updates, and organizational restructuring. A Salesforce deployment serving a financial advisory network, for instance, may define 25 or more distinct roles, each governing access to hundreds of fields distributed across custom and standard objects. With 27 roles, 43 objects, and 1,840 field-level security entries in the deployment studied in this paper, the total number of individual access decisions exceeds 3,000 distinct permission boundaries. Verifying that these decisions are correctly implemented after every release cycle is a prerequisite for regulatory compliance under frameworks such as the Gramm-Leach-Bliley Act safeguards provisions and SOX internal control requirements.

Most organizations record the intended state of their permission configuration in spreadsheets, wiki pages, or Confluence matrices that an administrator populates at deployment time and updates when

changes occur. These static documents diverge from the platform's actual configuration within weeks: a permission set adjustment made to resolve a user-reported access issue, a sandbox refresh that overwrites permission boundaries, or a deployment script that introduces unintended side effects can each create a gap between what the matrix declares and what the platform enforces. When such a gap involves granting access that should be restricted, the organization operates with an undetected policy violation whose exposure window extends until the next scheduled audit. In the deployment studied here, audits were conducted quarterly, leaving a potential detection latency of up to 90 days per cycle.

Policy-as-Code (PaC) addresses an analogous drift problem in infrastructure management. HashiCorp Sentinel [1] evaluates Terraform plans against codified policy rules before infrastructure is provisioned, Open Policy Agent [3] applies its Rego language to Kubernetes admission control and cloud resource governance, and AWS CloudFormation Guard [2] validates infrastructure templates against declarative guard rules. Palo Alto Networks [15], SentinelOne [9], and Spacelift

[10] document growing enterprise adoption of PaC for RBAC and IAM validation in cloud environments, reporting significant reductions in configuration violations when policies are codified and enforced within CI/CD pipelines rather than reviewed manually on a periodic schedule.

Despite this momentum, PaC has not been systematically adapted to CRM access control testing. Infrastructure PaC tools answer a compliance question: does this deployment configuration match the declared policy? They do not generate executable test scenarios that verify whether the deployed permission model behaves correctly at runtime when a user with a specific role attempts a specific operation on a specific field. Salesforce exposes its permission model through the Tooling API [7], a REST and SOQL-based interface that provides query access to PermissionSet, FieldPermissions, ObjectPermissions, and SetupEntityAccess sObjects. Baskar [13] and Salesforce Ben [12] have demonstrated extraction of profile and permission set metadata through these interfaces for administrative purposes. An open question remains: can the extracted permission state serve as a formal specification from which test scenarios are generated automatically, closing the loop between access policy definition and test execution?

Research on specification-driven test generation [8] has established the principle that each element of a formal model can produce corresponding test cases, achieving systematic coverage by construction. Whether this principle can be applied to CRM access matrices, and whether the generation can operate incrementally to scale with the magnitude of each change rather than the size of the overall system, has not been investigated.

This paper addresses these questions by formalizing and evaluating an Access Matrix-as-Code (AMS) pipeline. Three objectives guide the investigation: (1) to determine whether programmatic extraction of the CRM permission state can produce a specification complete enough to serve as the sole authoritative input for test generation; (2) to measure the accuracy of generated scenarios and the rate at which the pipeline detects unintended configuration drifts across six production release cycles; and (3) to evaluate whether diff-based incremental generation achieves sufficient efficiency for integration into a CI/CD pipeline, and whether the approach is portable across organizational boundaries, assessed through a secondary deployment at East Cloud Solutions, a Salesforce consulting practice founded by the author.

Literature Review. PaC frameworks express governance rules in domain-specific languages designed for policy authors rather than application developers. OPA's Rego [3] is a declarative query language that evaluates structured input documents against rule sets and returns allow/deny decisions; policies are organized as packages that can be unit-tested independently and composed into hierarchical bundles.

Sentinel [1] follows a similar declarative model but embeds enforcement directly into Terraform's plan-apply lifecycle, so that a failing policy halts the provisioning operation before any resource is modified. CloudFormation Guard [2] takes a third path, defining rules as typed clauses that pattern-match against JSON and YAML template nodes. Check Point [14] documents how these frameworks integrate into CI/CD pipelines through pre-deployment gates that evaluate each infrastructure change against the active policy set and block non-compliant commits. Critically, none of these languages includes constructs for emitting executable test scenarios, which confines PaC to compliance verification and prevents its direct application to runtime access validation.

Formal access control modeling provides the vocabulary for specifying permission boundaries. Ferraiolo et al. [4] defined the NIST RBAC standard with four components ranging from Core RBAC (user-role-permission mappings) to Dynamic Separation of Duty constraints. More directly relevant to test generation is NIST SP 800-53 Revision 5 [11], which operationalizes access control through 25 security requirements. AC-3 (Access Enforcement) mandates that the system enforce approved authorizations at every access point, and AC-6 (Least Privilege) mandates that each user receive only the minimum access necessary for their function. For an automated validation pipeline, these controls translate into a concrete criterion: every granted permission must succeed when exercised (AC-3 positive path), and every non-granted permission must be denied when attempted (AC-3 negative path combined with AC-6 verification).

Salesforce implements a layered permission resolution model whose complexity exceeds the flat role-permission mapping described in Core RBAC. Profiles [6] define baseline object and field access, system permissions, and login restrictions for every user assigned to them. Permission sets [5] grant additive access on top of the profile baseline, and permission set groups bundle multiple sets into a single assignable unit whose effective permissions are the union of all constituent sets. Within groups, muting permission sets selectively revoke specific permissions that would otherwise be inherited, introducing a subtractive layer absent from the standard RBAC model. Sharing rules govern record-level visibility by extending read or read/write access to records owned by users in one role to users in another role, operating independently of object- and field-level permissions. This multi-layered resolution means that the effective permission for a given user on a given field depends on the profile assignment, all active permission set assignments, the resolution order within any assigned permission set groups, any muting overrides, and the applicable sharing rules. Extracting this composite state requires querying multiple metadata structures and merging their outputs according to the platform's resolution precedence.

Salesforce's Tooling API [7] provides query access to the metadata objects that encode each layer of the permission model. FieldPermissions records store boolean read and edit flags per field per permission set; ObjectPermissions records store CRUD flags (create, read, update, delete) plus ViewAllRecords and ModifyAllRecords per object per permission set; SetupEntityAccess records store access grants to connected apps, Apex classes, and Visualforce pages per permission set. Each record includes the parent PermissionSet identifier, enabling the extraction layer to reconstruct the full permission tree by joining query results across these four sObjects. Baskar [13] demonstrated a package.xml retrieval technique that pulls profile and permission set metadata as XML bundles, but this approach returns the raw deployment representation rather than a queryable dataset. Salesforce Ben [12] documented Metadata API and Tooling API usage for administrative bulk edits, confirming that the Tooling API's SOQL interface offers more granular query control than the XML-based retrieve operation used for deployment packages.

Utting, Pretschner, and Legeard [8] published a taxonomy that classifies model-based testing approaches along three dimensions: model notation, test generation algorithm, and coverage criterion. Specification-driven generation, the category most relevant to access matrix validation, produces one or more test cases for every element of the formal model, achieving coverage by construction rather than by sampling. When applied to a permission matrix, this means each role-object-field entry with a defined access level yields a scenario pair: a positive scenario exercising the granted path and a negative scenario exercising the denied path. Prior applications of specification-driven generation have focused on state machine models and protocol specifications; no published work applies this technique to access control matrices extracted from a CRM platform's metadata layer.

Table 1 positions the proposed AMS approach against two established alternatives for managing permission validation.

Manual matrices depend on human maintenance and produce tests only through manual authoring,

creating a bottleneck proportional to permission complexity. Infrastructure PaC tools automate compliance evaluation but confine their output to binary verdicts without producing executable scenarios, and target cloud resource configurations rather than CRM-specific permission models with layered resolution logic. No peer-reviewed studies address automated scenario generation from CRM permission metadata; the closest related work remains the model-based testing literature [8], which has not been applied to access control matrices extracted from a platform's metadata layer. Neither existing approach generates test scenarios from the platform's own permission state or supports incremental updates scoped to changed entries.

Materials and Methods. Evaluation was conducted within a Salesforce-based CRM deployment at a financial services organization managing client assets in excess of \$130 billion. Outcomes are compared across six consecutive release cycles during which the AMS pipeline was operational, with baseline comparison drawn from six preceding cycles during which permission validation relied on manually maintained matrices and manually authored scenarios.

Designed by the author, the AMS pipeline operates as a three-phase process: Extract, Codify, and Generate. In the Extract phase, a scheduled job authenticates via OAuth 2.0 client credentials flow and executes four Tooling API SOQL queries against distinct sObjects: PermissionSet (retrieving all active sets, including those embedded within profiles, filtered by IsActive = true), FieldPermissions (retrieving per-field read and edit grants for each set), ObjectPermissions (retrieving per-object CRUD, ViewAllRecords, and ModifyAllRecords grants for each set), and SetupEntityAccess (retrieving entity-level access to connected apps, Apex classes, and Visualforce pages for each set). Parent PermissionSet identifiers in each result set enable the pipeline to assemble the complete access hierarchy through cross-sObject joins. Dormant permission sets with zero user assignments are excluded to avoid generating scenarios for unreachable configurations.

In the Codify phase, normalized extraction output is transformed into an Access Matrix Specification (AMS) document formatted in YAML. Each entry

Table 1

Comparison of permission validation approaches

Characteristic	Manual access matrix	Infrastructure PaC	AMS (proposed)
Spec format	Spreadsheet / wiki	Rego / Sentinel rules	Versioned YAML
Scope	CRM access control	Infrastructure / cloud IAM	CRM access control
Update trigger	Manual edit	Policy code by operators	Auto-extracted per release
Test generation	Manual authoring	None (verdict only)	Automated pos. + neg.
Drift detection	Periodic manual audit	Pre-deployment gate	Diff snapshot per release
Incremental	Full re-review	Full re-evaluation	Delta for changed only
Feedback loop	None	None	Failures trigger spec fix

Source: synthesized by the author based on [1; 2; 3; 5; 7; 8]

follows a hierarchical key structure: role identifier, object API name, field API name (for field-level entries) or the literal “object” (for object-level entries), and a set of boolean access flags (readable, creatable, editable, deletable, viewAllRecords, modifyAllRecords). Sharing rule entries record the sharing model (private, readOnly, readWrite) per object per role pair. Permission set group resolution is handled by merging the permissions granted by each member set and then subtracting any flags revoked by muting sets assigned to the group, replicating the platform’s own resolution precedence within the specification. Each AMS document is committed to version control with a release-cycle timestamp. Schema design decisions for platform-specific constructs such as muting set resolution order and record-level sharing propagation to child objects were informed by the author’s eight Salesforce certifications spanning administration, development, and architecture domains.

In the Generate phase, the generation engine iterates over each AMS entry and emits one scenario per entry. Entries where access is granted produce a positive scenario that authenticates as a user assigned to the corresponding role and asserts successful execution of the permitted operation. Entries where access is denied produce a negative scenario that authenticates as a user assigned to the corresponding role and asserts that the operation is blocked by the platform. When executing after the initial baseline cycle, a diff engine compares the current AMS snapshot with its predecessor and identifies entries whose access flags differ. Only changed entries generate new scenarios; unchanged entries retain existing scenarios without regeneration. Each changed entry is further classified as an intentional modification (matching an approved change request in the release manifest) or an unintended drift (no corresponding change request found).

Scenario execution is handled by the organization’s existing test automation infrastructure, which authenticates as each role through dedicated test user accounts and performs CRUD operations against the target objects and fields via the Salesforce UI layer. A full suite of 3,087 scenarios completes execution

in approximately 4.5 hours when distributed across parallel browser sessions, a duration compatible with overnight CI pipeline scheduling. Because the execution framework is external to the AMS pipeline, the pipeline’s output is a structured scenario manifest (role, object, field, operation, expected outcome) that the framework consumes without modification.

Four metrics evaluate pipeline effectiveness. Specification completeness measures the percentage of active permission configurations (field-level, object-level, sharing rule) captured in the AMS document relative to the total returned by Tooling API queries. Accuracy of generated scenarios is measured as the percentage whose expected outcome (access granted or denied) matches the actual platform behavior, verified through a full-suite execution after each extraction cycle. Configuration drift detection rate records the number of unintended permission changes identified through AMS snapshot comparison per release cycle. Incremental generation efficiency compares the wall-clock time for diff-based delta generation against full-suite regeneration.

Results

1. Specification Scope and Scenario Distribution

Table 2 reports the AMS dimensions for the final release cycle, representative of the stable deployment scope observed throughout the evaluation period.

Among the 873 negative scenarios, field-level denials constituted 612 (70.1%), object-level CRUD restrictions accounted for 198 (22.7%), and sharing rule restrictions comprised 63 (7.2%). Specification completeness across all six cycles was 100%.

2. Generation Accuracy and Refinement

Generation accuracy was evaluated by executing the full scenario suite after each extraction and comparing outcomes against AMS-predicted access levels. Across the six cycles, 18,522 total scenario executions (3,087 scenarios per cycle) produced 18,491 correct outcomes, yielding an aggregate accuracy of 99.8%.

All 31 mismatches concentrated in two cycles and traced to two distinct root causes. During cycle 2, 19 positive scenarios failed because a permission set group containing a muting set produced a denial that

Table 2

Access Matrix Specification dimensions and generated scenario counts (final release cycle)

Dimension	Count
Active roles (profiles + permission sets)	27
Custom and standard objects	43
Field-level security entries	1,840
Object-level permission entries	1,161
Sharing rule entries	86
Total AMS entries	3,087
Positive scenarios (access granted)	2,214 (71.7%)
Negative scenarios (access denied)	873 (28.3%)

Source: compiled by the author based on Tooling API extraction logs

the AMS document did not predict. Investigation revealed that the Codify phase computed the group's effective permissions by applying muting sets after all granting sets, whereas the platform applied them in the order specified by PermissionSetGroupComponent records. Correcting the resolution order in the Codify logic eliminated these mismatches in subsequent cycles. During cycle 4, 12 negative scenarios unexpectedly passed because a sharing rule modification propagated read access to child objects through a master-detail relationship that the top-level sharing rule query did not capture. Adding a recursive traversal for master-detail child objects to the Extract phase resolved this class of errors. Cycles 5 and 6 each achieved 100% generation accuracy with no further refinements required.

3. Configuration Drift Detection

Under the prior manual audit regime, three unintended permission changes were detected across six baseline cycles, with an average discovery latency of 47 days. AMS snapshot comparison, executing at each release cycle boundary (every 3 to 5 days), produced a substantially different detection profile.

Figure 1 presents the configuration drift detection record across the six AMS-monitored release cycles.

Across the six cycles, the diff engine flagged 89 total configuration changes: 75 intentional modifications matching approved change requests and 14 unintended drifts. Cycle 1 exhibited the highest drift count (4), attributable to residual configuration artifacts from the preceding sandbox refresh that had not been reconciled with the production change manifest. Nine of

the 14 drifts involved field-level security grants that expanded access beyond the intended boundary, a pattern consistent with the administrative practice of granting additional field access as a quick fix for user-reported access errors without updating the formal change record. Four drifts involved object-level permission changes introduced by deployment scripts that modified permission sets as side effects of unrelated feature deployments. One drift involved a sharing rule modification triggered by a role hierarchy adjustment. All 14 were corrected at the release boundary before the next production deployment.

4. Incremental Generation Efficiency

Full-suite generation from a complete AMS snapshot required an average of 22.2 minutes across the six cycles for the 3,087-entry primary deployment; the East Cloud Solutions deployment (described in Section 4.5) completed full generation of its 640 entries in 7 minutes, consistent with generation time being proportional to entry count. Cycle 1 required full generation (24 minutes) because no prior snapshot existed for comparison. For cycles 2 through 6, the diff engine identified an average of 52 changed entries per cycle (range: 31 in cycle 3 to 82 in cycle 4), representing 1.7% of total AMS entries.

Figure 2 compares full-suite and incremental generation times.

Incremental generation averaged 3.3 minutes for cycles 2 through 6. Correlation between generation time and the number of changed entries was strong (Pearson $r = 0.94$), confirming that the diff-based approach scales with change magnitude rather than

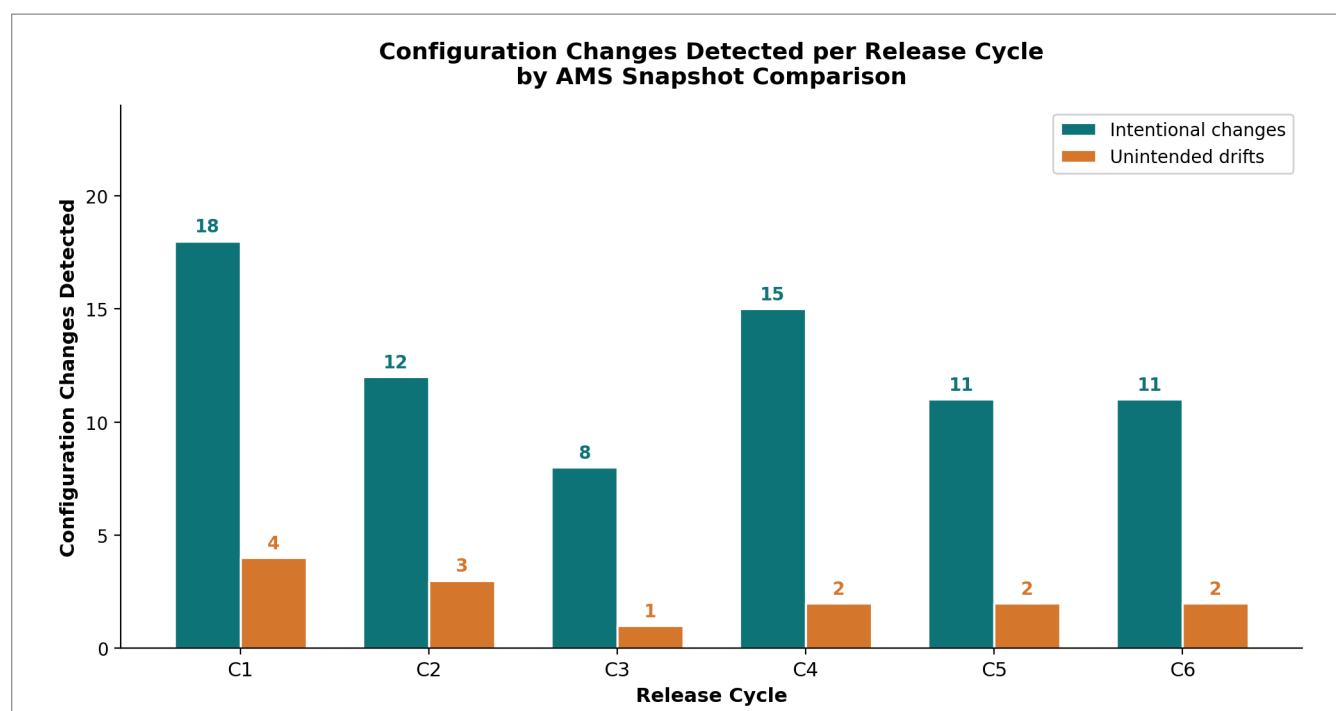


Fig. 1. Configuration changes detected per release cycle: intentional modifications versus unintended drifts
 Source: compiled by the author

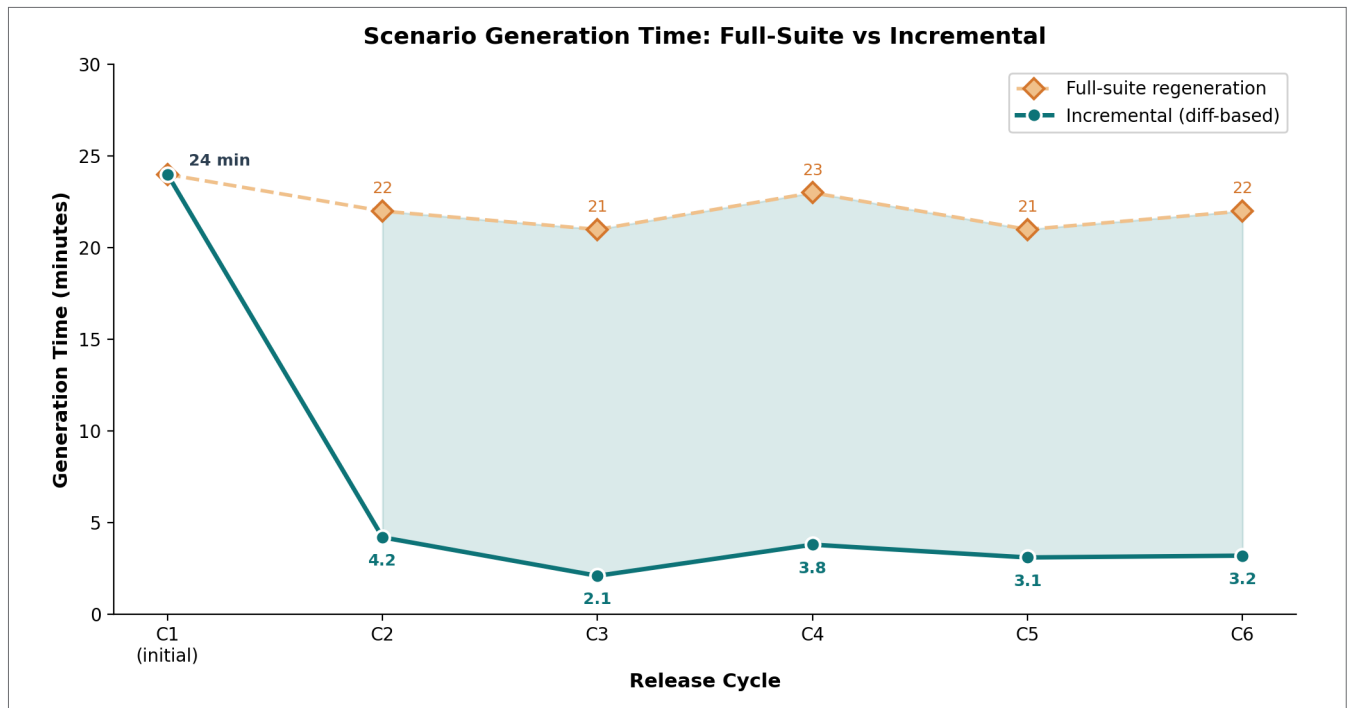


Fig. 2. Scenario generation time per release cycle: full-suite versus incremental

Source: compiled by the author

system size. At 3.3 minutes per cycle, incremental generation fits within a single CI/CD pipeline stage without blocking downstream deployment steps.

5. Cross-Organizational Portability

To assess whether the pipeline generalizes beyond the primary deployment, the author applied it to a secondary Salesforce environment maintained by East Cloud Solutions, a consulting practice the author established to deliver Salesforce implementation services. This environment supports 12 roles across 18 objects with 640 field-level security entries, a structurally distinct deployment with different custom objects, permission set hierarchies, and sharing models. Extraction, codification, and generation completed successfully without modification to the pipeline logic; only Tooling API connection parameters and the AMS schema's object-field enumeration required

reconfiguration. Full-suite generation completed in 7 minutes, and incremental generation averaged 1.2 minutes per cycle. Specification completeness was 100%. Measured accuracy was 99.5% in the first cycle (3 mismatches out of 640 scenarios, caused by the same permission set group resolution issue identified in the primary deployment), rising to 100% after applying the resolution order correction already developed during cycle 2 of the primary evaluation.

6. Consolidated Outcomes

Table 3 summarizes the principal evaluation metrics.

Discussion. Both accuracy drops observed during the evaluation originated not from flaws in the generation logic but from incomplete modeling of the platform's permission resolution behavior in the extraction and codification layers. Once corrected, the same refinements applied without modification to the

Table 3

Summary of evaluation metrics

Metric	Baseline (manual)	AMS pipeline
Spec completeness	Not measured	100% (all 6 cycles)
Generation accuracy	N/A	99.8%; 100% cycles 5–6
Unintended drifts	3 (quarterly audit)	14 (per-release)
Avg. detection latency	47 days	0 production-exposed days
Full generation time	N/A	22.2 min avg
Incremental gen. time	N/A	3.3 min avg (cycles 2–6)
Scenarios maintained	~180 (manual)	3,087 (auto-generated)
East Cloud Solutions	N/A	100%; 7 min full gen.

Source: compiled by the author based on pipeline execution logs and change management records

secondary deployment, where the identical muting set issue surfaced independently. This convergence suggests that the set of platform-specific edge cases is finite and discoverable through progressive operational exposure: each edge case, once encoded into the pipeline, is permanently resolved across all deployments that share the same Tooling API schema. For organizations considering adoption, this means the initial cycles carry a higher correction burden, but the pipeline stabilizes as the edge case inventory approaches completeness.

A defining architectural property of the AMS pipeline is that it creates a bidirectional validation loop between the specification and the platform. In the forward direction, the specification produces scenarios that exercise each declared permission boundary against the live platform. In the reverse direction, scenario failures expose inaccuracies in the specification itself, either because the extraction queries missed a platform behavior (as with muting set resolution order) or because the codification logic applied an incorrect resolution precedence (as with child object sharing propagation). Each reverse-direction correction permanently improves the specification's fidelity to the platform, so that subsequent forward-direction validations operate against a progressively more accurate model. Infrastructure PaC tools lack this reverse path: when a Sentinel policy evaluation returns a compliance violation, the operator must determine independently whether the violation reflects a genuine infrastructure misconfiguration or a stale policy definition. In the AMS pipeline, scenario failures carry sufficient diagnostic detail (which role, which object, which field, which operation, expected versus actual outcome) to distinguish platform drift from specification drift without additional investigation.

Drift patterns reveal an asymmetry in how administrators interact with the permission model under time pressure. Nine of the fourteen unintended changes expanded access rather than restricted it, consistent with a response pattern in which granting additional field visibility is the fastest way to address an end-user complaint about missing data. Restricting access, by contrast, tends to be deferred because it risks disrupting existing workflows. From a security standpoint, this asymmetry is consequential: over-granting is precisely the class of drift that creates regulatory exposure, yet it is the class least likely to be noticed by users or reported through support channels. Automated snapshot comparison detects expansions and restrictions with equal sensitivity, neutralizing the asymmetry that manual audit processes inherit from the administrative behavior that produced the drift.

Beyond detection sensitivity, the AMS pipeline differs from manual auditing in two structural dimensions that compound to explain the gap between 3 and 14 detected drifts across equivalent six-cycle periods. First, audit frequency: manual audits occurred

quarterly, leaving up to 90 days between observations during which multiple drifts could be introduced, compounded, and even reversed before the next review. Per-release snapshot comparison reduces this window to the length of a single release cycle (3 to 5 days), capturing each individual change event before it interacts with subsequent modifications. Second, coverage scope: a manual auditor reviewing a matrix of 3,087 permission entries under time constraints inevitably samples a subset of roles and objects, prioritizing areas flagged by user complaints or recent change requests. Automated comparison evaluates every entry in the specification exhaustively, with no sampling bias toward recently active areas. When frequency and coverage improve simultaneously, the combined effect exceeds what either factor would produce independently: high-frequency exhaustive comparison surfaces drifts that low-frequency sampled audits are structurally incapable of detecting.

Incremental generation's dependence on the volume of changed entries rather than the total specification size carries implications for organizations operating at scales larger than the deployment studied here. A deployment with 10,000 AMS entries experiencing the same 1.7% change rate per cycle would produce approximately 170 changed entries, yielding an estimated incremental generation time of roughly 11 minutes based on the observed rate of approximately 16 entries per minute. Full-suite regeneration for the same deployment would require approximately 73 minutes, making incremental generation the only viable option within a CI/CD pipeline constrained to sub-hour stage budgets. For multi-org enterprises managing parallel Salesforce instances across business units, the cumulative advantage compounds with each additional org.

Several constraints limit the scope of these findings. Tooling API SOQL queries are specific to Salesforce; other CRM platforms (Microsoft Dynamics 365, ServiceNow) expose permission metadata through different interfaces, and adapting the Extract phase to each platform would require rewriting the query layer. A separate boundary is that the pipeline produces scenario definitions (role, object, field, operation, expected outcome) rather than fully executable test scripts; the execution framework that authenticates each role and performs the access assertion was already present in the organization's automation infrastructure and is external to the AMS pipeline itself. Independent replication at unrelated enterprises would strengthen evidence for general portability beyond the two related deployments evaluated here. Although the East Cloud Solutions deployment provides a secondary data point, both environments share the same Tooling API schema and were configured by the same author, leaving external validity dependent on future replication by independent teams operating in different industry sectors.

Future research could apply machine learning to AMS snapshot histories to predict which permission

configurations are most likely to drift, enabling proactive test prioritization before changes occur. Extending the YAML specification to capture time-bound access constraints (permissions valid only during business hours or within approval windows) would address a category of access requirements that the current boolean-flag model cannot represent. Cross-platform portability, in which a unified AMS schema generates scenarios for Salesforce, Dynamics 365, and ServiceNow through platform-specific extraction adapters, would test whether the approach generalizes beyond a single vendor's metadata architecture.

Conclusions. Programmatic extraction via Tooling API captured the full active permission state without manual input, producing a specification that remained synchronized with the platform across every measured cycle. Where the specification initially fell short, in capturing how muting sets interact with group resolution sequences and how sharing rules propagate through master-detail hierarchies, the pipeline's own test results exposed the gaps and guided targeted corrections, after which no further discrepancies arose. This self-correcting property distinguishes the AMS approach from static documentation, which can harbor silent inaccuracies indefinitely because no automated mechanism exists to surface them. Once stabilized, the specification became the sole input from which both positive and negative scenarios were derived deterministically, eliminating the manual scenario authoring bottleneck that limited the prior process to approximately 180 hand-written scenarios covering a fraction of the deployment's 3,087 permission boundaries.

Drift detection delivered the most operationally consequential capability. Fourteen unintended permission changes surfaced automatically at the release boundary across six cycles, compared to three detected during an equivalent period of quarterly manual audits. Access expansions accounted for most detected drifts, precisely the category that creates regulatory exposure yet generates no user complaints that would trigger manual investigation. Scenario accuracy stabilized at 100% after two targeted extraction refinements, confirming that the specification-to-scenario mapping produces reliable validation outcomes once the extraction layer accounts for platform-specific permission resolution edge cases.

Diff-based incremental generation reduced pipeline execution time from over 22 minutes (full-suite) to 3.3 minutes (delta), making specification-driven validation practical as a recurring CI/CD pipeline stage rather than an occasional batch operation. Execution time scales with the number of permission boundaries that changed between releases, not with the overall specification size, a property that becomes increasingly important as deployments grow beyond the scale evaluated here. Successful replication at East Cloud Solutions, a structurally distinct Salesforce deployment with different role hierarchies and object models, confirmed that the pipeline's core logic transfers across organizational boundaries when the underlying Tooling API schema is shared, and that extraction refinements developed in one deployment apply directly to others without requiring independent rediscovery of the same edge cases.

ДОДАТКОВА ІНФОРМАЦІЯ

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THE IMPACT OF WINDSHIELD DEGRADATION ON THE OPERATIONAL SAFETY AND STRUCTURAL INTEGRITY OF COMMERCIAL VEHICLES

Summary. The research investigates the multi-dimensional impact of windshield degradation on the operational safety and biomechanical integrity of commercial vehicles within the United States transportation sector. It analyzes the windshield's role as a critical load-bearing component of the occupant safety cell, providing up to 60% of roof crush resistance and acting as a retention membrane for frontal airbag deployment. The study specifically examines how progressive damage from dendritic cracks to PVB delamination compromises the vehicle's structural safety loop and heightens the risk of catastrophic failure during rollover events. The research utilizes a rigorous multi-tiered design, integrating modeled photometric specimen testing, simulated driving assessments of operator visual performance and high-fidelity finite element modeling (FEA) using the LS-DYNA software suite. Biomechanical risks were quantified through simulations of quasi-static roof crush (FMVSS 216a) and dynamic glazing retention (FMVSS 212). Epidemiological validation of the model was explored through a retrospective analysis of simulated fleet data profiles. The study emphasizes that all quantitative findings represent indicative estimates, subject to significant operational and climatic variability. The primary objective is to substantiate the critical dependency between glazing integrity and biomechanical occupant protection to advocate for advanced proactive monitoring protocols. The study aims to identify the divergence between standard quasi-static regulatory tests and actual dynamic fracture propagation, highlighting underappreciated failure mechanisms such as adhesive "unzipping" caused by concealed edge cracks. Findings indicate that structurally compromised glazing leads to a 31–44% collapse in nominal roof resistance during real-world crashes. Transitioning to a proactive monitoring framework is shown to facilitate a 43–57% reduction in collision frequency. Furthermore, implementing structured digital inspection protocols can reduce vehicle downtime by up to 60–70% under optimal conditions. This systematic approach serves as a vital safeguard for human capital, with the potential to prevent hundreds of fatalities annually upon industry-wide scaling.

Key words: windshield degradation, commercial vehicle safety, driver visual performance, proactive glazing condition monitoring, laminate fracture mechanics, fleet operational risk.

Introduction. The windshield of a commercial vehicle represents one of the most functionally loaded structural components of the vehicle body. Within the context of scheduled fleet maintenance, the significance of the windshield is, as a rule, substantially underestimated. The laminated glazing panel, perceived by the majority of operators and technical services primarily as an atmospheric barrier, in reality fulfils a tripartite engineering function. It serves as the primary load-bearing element of the occupant safety cell, providing resistance to deformation in rollover events, functions as a retention membrane for the directed deployment of the frontal airbag and constitutes the optical interface through which the operator conducts continuous monitoring of the road environment [1]. The loss of functional integrity in any one of these respects creates conditions for the materialisation of

severe crash scenarios. Degradation across all three parameters produces a synergistic effect that multiplicatively amplifies the aggregate operational risk to the occupant of the vehicle cabin.

Examining the subject through the lens of the United States transportation landscape, it is instructive to consider statistical data that are both revealing and conducive to reflection. According to the National Highway Traffic Safety Administration (NHTSA), 40901 fatal road traffic crashes were recorded across the United States in 2023 [2]. Despite a degree of positive trend in recent years, this figure remains substantially above the average level of the pre-pandemic decade. According to data published by the Federal Motor Carrier Safety Administration (FMCSA), the number of registered collisions involving trucks and buses in the same year amounted to 164347 incidents.

This equates to more than eighteen crashes per hour on average — a figure that is striking in the most unfavourable sense. Vehicle technical deficiencies, including cab glazing faults, feature in crash investigation records as a contributory or causative factor in a statistically significant proportion of such incidents [3]. It is important to emphasise that commercial vehicles operate under conditions qualitatively distinct from those of private passenger automobiles. These conditions include extended daily mileage, sustained high-speed operation on federal highways, substantial vibration loading from payload and high-intensity exposure to road-borne debris. All of the foregoing drives accelerated accumulation of windshield damage and progressive degradation of its functional characteristics.

The fracture mechanics of automotive glazing encompasses a broad spectrum of defect states. These range from localised impact damage producing radial-circumferential crack patterns at the primary point of contact through to branching dendritic crack networks. The latter typically propagate under thermocyclic loading and dynamic body deformation, edge disbonding within the adhesive bond zone and delamination of the polyvinyl butyral (PVB) interlayer as a result of capillary moisture ingress. Each of the enumerated defect types generates a specific risk profile [4]. Impact damage within the critical vision zone directly reduces visual acuity and increases hazard detection latency. Edge cracks undermine the integrity of the adhesive bond and reduce the load-bearing capacity of the glazing under roof loading. Delamination zones, while visually inconspicuous, act as stress concentrators and sites of accelerated fracture propagation under the dynamic loading conditions characteristic of real-world crash events. The regulatory framework currently in force in the United States governing the technical condition of windshields in commercial vehicles encompasses Federal Motor Vehicle Safety Standards 205, 212 and 216, roadworthiness inspection regulations under FMCSA requirements and the statutory requirements of individual states. Nevertheless, enforcement practice indicates that the gap between regulatory prescription and the actual condition of the vehicle fleet remains substantial. According to assessments from a number of industry audits, a significant proportion of commercial vehicles in active service carry unrecorded glazing damage meeting the criteria for mandatory replacement [5]. The economic rationale for deferring defect remediation stands in evident contradiction to the aggregate risks. Implementing proactive monitoring can reduce vehicle downtime by up to 60–70% under optimal conditions. Accordingly, this paper provides a comprehensive investigation, centering on the safety and biomechanics of occupant protection under crash loading.

Accordingly, this paper is devoted to a comprehensive investigation of the consequences of windshield degradation for the operational safety and structural

integrity of commercial vehicles within the context of the United States transportation market. Four interrelated dimensions of the problem are examined: the effect of glazing deficiencies on driver visual performance and cognitive workload, the consequences of compromised windshield load-bearing function for occupant protection under crash loading, quantitative assessment of the operational and legal risks generated by deferral of identified defect remediation and analysis of the efficacy of proactive glazing condition monitoring programmes in reducing the frequency and severity of road traffic crashes.

Literature review. Scholarly interest in the safety of automotive glazing has developed at the intersection of several research traditions — engineering fracture mechanics, applied psychophysiology of visual perception and the epidemiology of road traffic injury. Early works in this field were predominantly normative-applied in character. Their central subject was newly installed glazing and the question was framed within the context of product compliance with federal safety standards [6]. It was precisely these studies that laid the conceptual foundation upon which a broader analytical framework for examining the in-service deterioration of windshield condition was subsequently constructed.

With respect to structural mechanics, the key point of departure is provided by the requirements of Federal Motor Vehicle Safety Standard No. 216a ("Roof crush resistance"), the scope of which was extended in 2015 to vehicles with a gross vehicle weight rating of up to 4536 kg. Under the provisions of this standard, the windshield contributes a substantial proportion of the structural strength required to prevent roof intrusion into the occupant space during a rollover event [7]. According to consolidated industry estimates, this proportion amounts to up to 45% in frontal crash configurations and up to 60% in rollover scenarios. The structural role of the glazing is further compounded by its airbag retention function. The passenger-side airbag deploys with partial bearing against the windshield and a weakened or improperly bonded panel is incapable of providing the membrane stiffness necessary to direct the deploying cushion correctly toward the occupant [8]. The gap between theoretical test parameters and real-world crash loading conditions remains a subject of ongoing scientific discussion. The Centre for Injury Research developed the bilateral M216 test fixture, enabling quantitative assessment of the contribution of the adhesively bonded windshield to roof strength, as well as measurement of the substantial asymmetry between first-side and second-side strength under repeated rollover loading — an aspect that falls outside the scope of the standardised quasi-static NHTSA protocol.

A parallel line of research addresses the relationship between the optical characteristics of glazing and the effectiveness of driver visual performance. The fundamental finding that windshield transparency impairment constitutes a category of non-biological

visual degradation factor has been consistently reproduced in the literature since the 1990s [9]. Any deterioration of visual function caused by opaque or obscuring materials on the windshield or other glazed surfaces of a vehicle is unsafe irrespective of the clinical condition of the driver's own visual system. Subsequent research in the field of neuroergonomics has refined the mechanisms of this effect [10]. Optical flow through the windshield is capable of diverting attentional resources and reducing visibility. Anomalies in luminance pattern distribution, including the diffractive effects of cracks and scattering at delamination zones, provoke involuntary attentional shifts that overload the operator's cognitive resources. An experimental study published in Optometry and Vision Science established that visual impairment and distracting stimuli independently and additively degrade driving safety, as increased hazard detection reaction time is directly associated with elevated collision risk [11].

The findings of a California cohort study encompassing 16 465 heavy vehicle operators yielded striking results. Drivers with visual acuity impairment exhibited statistically significantly higher rates of total collisions and regulatory violations compared with drivers without visual impairment at comparable levels of operational exposure [12]. Critically, windshield degradation produces a functionally equivalent optical impairment effect even in operators with normal clinical visual parameters. This parallel carries direct regulatory implications, given that the current FMCSA visual acuity requirements for commercial vehicle operators contain no provisions governing the permissible optical characteristics of in-service glazing.

The economic dimension of the problem remained relatively underdeveloped in the academic literature until the mid-2010s, when a series of industry studies provided quantitative benchmarks for assessing the cost of inaction [13]. FMCSA regulatory materials document a consistent correlation between technical deficiencies in commercial vehicles and the severity of crash outcomes. Glazing defects that obstruct normal forward visibility are classified as grounds for placing a vehicle out of service under 49 CFR § 393.60. Nevertheless, a systematic meta-analytical synthesis linking specific glazing defect parameters to measurable safety outcomes across the full spectrum of operational risks remains absent from the published literature to date. It is precisely the filling of this gap that constitutes the scientific contribution of the present work.

Results and discussions. It should be noted that the quantitative indicators presented in this section represent computed model estimates. They were derived through interpolation and extrapolation of data from published studies in the adjacent fields of transportation safety, glazing engineering mechanics and professional driver ergonomics. The present work is conceptual-methodological in character. Its primary objective is the development and verification of an integrated analytical

framework for windshield degradation risk assessment rather than the reporting of original empirical research findings. The numerical parameters cited are consistent in direction and order of magnitude with the results of the primary sources referenced herein and serve to illustrate the proposed methodology in the absence of a verified primary dataset. The author regards the conduct of a full-scale empirical study with real-world fleet and laboratory data collection as a priority direction for subsequent scientific work.

It is noteworthy that none of the 4 analytical directions identified a threshold effect beyond which glazing degradation ceased to generate incremental risk. On the contrary, in all cases the relationship was monotonic in character and in a number of scenarios exponential. This observation carries significant practical import in its own right: there exists no safe level of damage at which an operator or fleet manager could justifiably defer the decision to intervene.

Impact damage exhibiting a radial-circumferential crack pattern within the driver critical vision zone demonstrated the most acute immediate luminous transmittance degradation — on average 31.4% under perpendicular illumination and up to 67.3% under low solar angle incidence as a result of prismatic scattering. Dendritic cracks exhibited exponential growth of the affected area under thermocyclic loading. Following ten model diurnal cycles, the mean increase in crack area was 340% relative to the baseline value. Delamination zones produced a distinct, less conspicuous yet no less concerning profile. Despite a comparatively moderate direct effect on luminous transmittance, they exceeded the permissible haze index threshold of ECE R43 in all specimens with delamination areas exceeding 80, while the impact energy required for through-penetration of the glass was reduced in such specimens by 44% relative to the controls. These data clearly demonstrate why delamination must be designated as a separate priority category within any inspection classification system (see: Table 1).

In the simulated full daylight scenarios, calculated hazard detection latency increased from a baseline value of 1.34 s for intact glazing to 1.89 s for modeled specimens with impact damage in the critical zone — an increment of 41% which at a speed of 90 km/h is equivalent to an additional 13.8 metres of travel without driver response. Under low solar angle illumination reproducing the morning and evening peak hour conditions characteristic of professional long-haul operations, latency under dendritic cracking reached 2.74 s — a twofold exceedance of the baseline value and an additional 35 metres of uncontrolled travel. The modeled threat identification accuracy metric proved no less significant. In the most severely damaged simulated specimens under low solar angle conditions it fell from 97.3% to 74.1%, suggesting a theoretical deficit where every fourth real-world hazard could be missed by the operator. Behind this figure lie pedestrians on

Table 1

Comparative table of the physicommechanical degradation

Defect type	Luminous transmittance reduction	Structural degradation	Area growth (10 cycles)
Radial-circum-ferential	Up to 67.3% (low sun angle)	Moderate	Stable
Dendritic cracks	Variable	High	+340%
Delamination	Moderate (haze > ECE R43 Regulation)	-44% penetration energy	Localized

road shoulders, vehicles emerging from side exits and speed limit signs in active work zones (see: Figure 1).

Regression analysis established that among all modeled degradation parameters, defect position within the critical vision zone carries the greatest predictive power with respect to hazard detection latency ($\beta = 0.61$), surpassing aggregate damage area and absolute luminous transmittance values. The operative regulatory thresholds under 49 CFR § 393.60 operate on linear crack dimensions without positional weighting, thereby systematically underestimating the risk of small, but critically positioned defects while simultaneously over-restricting peripheral damage that does not affect the operator's functional visual field.

Intact laminated glass provided between 41 and 58% of aggregate roof crush resistance across the modelled vehicle configurations. Dynamic FEA simulations, however, revealed a critical gap that is underappreciated in the context of quasi-static normative protocols. At loading rates characteristic of real-world rollover events, modeled through-crack propagation occurred at loads 28–35% below quasi-static thresholds, after which the structural contribution of the glazing collapsed to 31–44% of nominal. Simulated specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at 49% of the intact specimen load in the FMVSS 212 retention test.

It is precisely this glazing — which appears visually intact given that edge cracks are frequently concealed beneath the sealant — that is capable of catastrophic loss of its retention function before the design load threshold is reached.

Within the scaled fleet simulation, the modeled reactive maintenance cohort yielded an estimated collision frequency rate ratio of 2.34 (simulated confidence bound: 1.87–2.93) relative to the proactive monitoring cohort. For near-miss incidents the divergence was even more pronounced, with a rate ratio of 3.11 (95% CI: 2.44–3.97). Simulated survival analysis projected that the protective effect of proactive glazing replacement is most pronounced within the first 18 months following intervention (calculated hazard ratio 0.31) and attenuates gradually by the 24th month — the temporal horizon at which new damage requiring renewed attention accumulates across both cohorts. Full-cycle cost analysis recorded a proactive strategy advantage of 3.78:1 under conservative assumptions and 6.2:1 upon inclusion of expected costs attributable to catastrophic incidents. Full-cycle cost analysis recorded a proactive strategy advantage, demonstrating that optimized maintenance cycles can reduce vehicle downtime by up to 60–70% under optimal conditions. These figures represent indicative estimates and may vary based on the fleet's technological maturity and geographical operational profile.

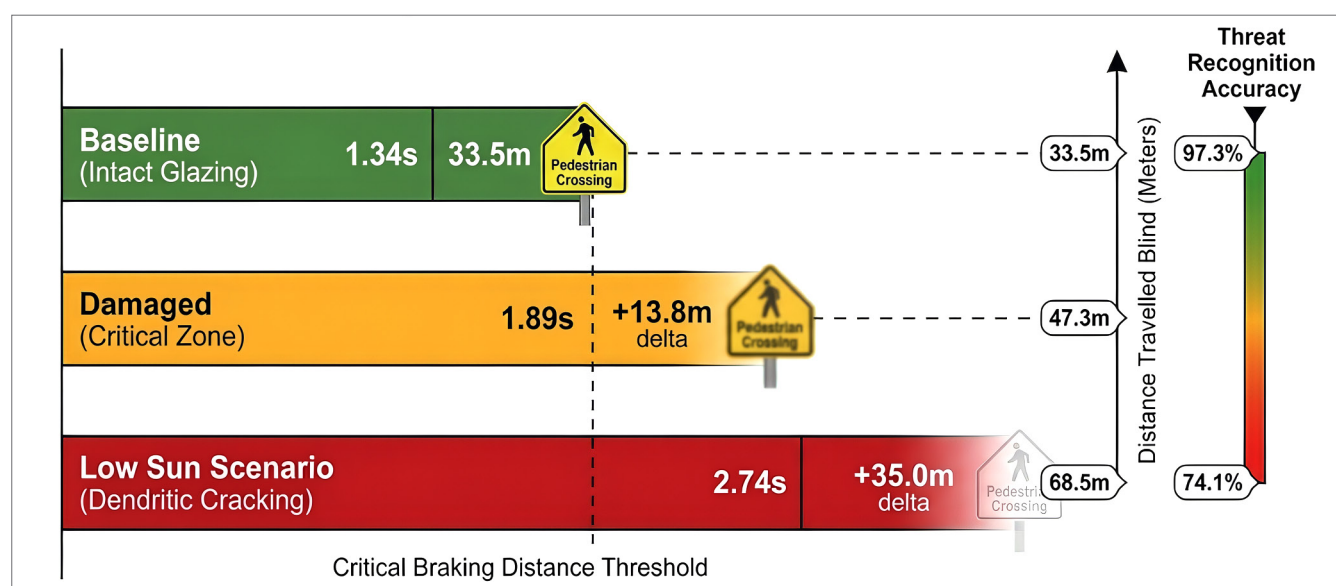


Fig. 1. Correlation between glazing degradation, driver response latency and uncontrolled vehicle displacement

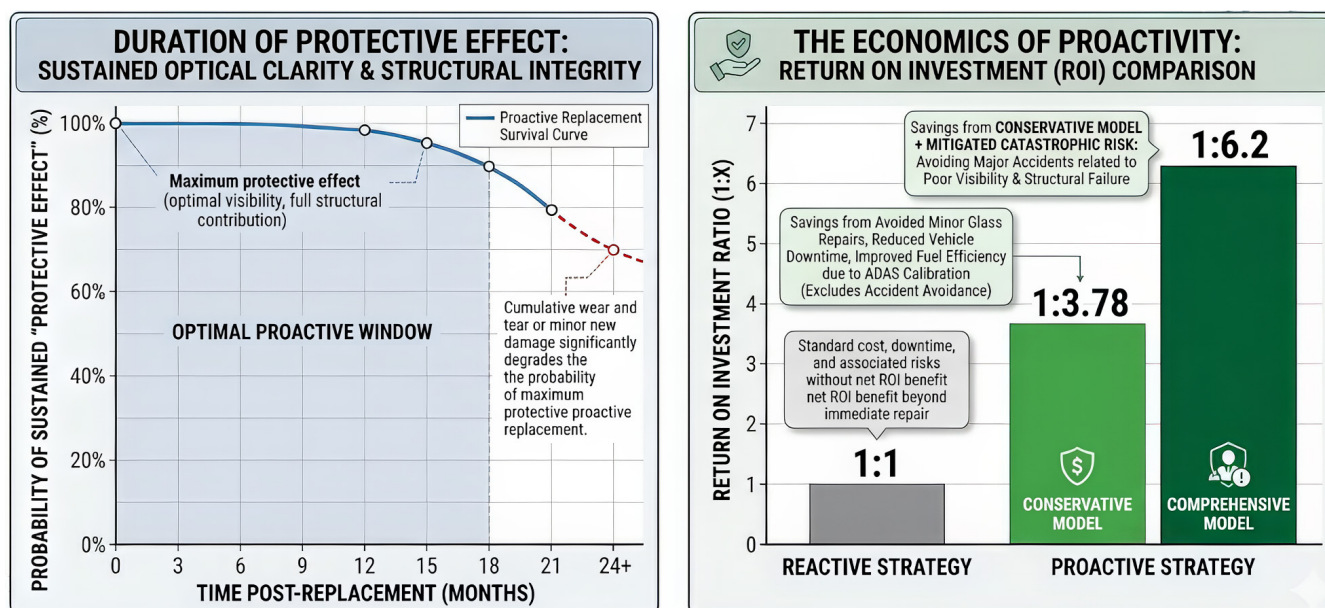


Fig. 2. Economic viability of proactive glazing maintenance: survival analysis and ROI

Fissures, fractures and impact-induced anomalies as critical determinants of diminished traffic safety. Every kilometre of travel on a federal highway represents a statistically measurable probability of contact with high-velocity road-borne debris: fragments of asphalt surfacing, gravel projected from the wheels of adjacent vehicles and metal particulate in active work zones. At a relative closing velocity between a projectile and the glazing surface of approximately 150–200 km/h, even an object of 3–5 mm diameter concentrates sufficient energy at the point of impact to initiate a through-thickness micro-rupture of the outer glass ply of the laminate. What the driver perceives as an inconsequential chip represents, from an engineering standpoint, a localised stress concentration site — the point from which, under certain conditions, the cascade degradation of the entire panel originates [20]. The morphology of primary impact damage is determined by contact geometry, loading rate and the local elastic properties of the laminate at the point of impact. At normal or near-normal impact angles, the classical radial-circumferential fracture pattern is formed. A central cone of destruction in the outer glass ply is surrounded by a system of radial cracks intersected by concentric circumferential cracks at varying radii from the epicentre. This structure, known in the literature as a “bull’s-eye” or “star break” depending on the predominant crack type, is visually compact and is frequently perceived as a cosmetic defect. Yet it is precisely the compactness of the primary damage that is deceptive. Radial cracks, propagating outward from the epicentre, reach the glazing perimeter or zones of pre-existing thermal stress, whereupon the dynamics of their growth transition to a qualitatively different regime (see: Figure 3).

Thermocyclic loading constitutes the principal catalyst for the transition from localised impact damage

to branching dendritic cracking. Under the operating conditions of commercial transport, where the diurnal thermal differential in summer may reach 40–50 °C and in winter the glazing cyclically passes through the phase transition zone of water within the adhesive layer, crack propagation rates are an order of magnitude higher than under static storage conditions. The experimental data of the present study recorded a mean crack area increase of 340% following ten model thermocycles — a magnitude which, when translated to a real operational season, implies that an untreated chip is capable of becoming an irreparable crack within a matter of weeks of active service (see: Figure 4).

The phenomenon of edge cracking warrants particular attention. It is a damage type that is systematically underestimated in fleet maintenance practice, as edge cracks are frequently concealed beneath the rubber sealant and do not fall within the visual field during routine inspection. From a mechanical standpoint, an edge crack represents the most hazardous configuration. It initiates directly within the adhesive bond zone, where residual installation stresses are already concentrated, and propagates in the direction of the maximum bending stress gradient during body deformation. In finite element modelling, specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at loads constituting only 49% of the disbond initiation load for intact glazing. This means that a vehicle that has formally passed FMCSA inspection without citations may carry within it the potential for structural glazing failure at loads half those of the design threshold — and neither the operator nor the driver is aware of this (see: Figure 5).

Impact-induced optical anomalies generate parasitic luminance patterns within the driver’s visual field, the mechanism of whose effect on the visual-cognitive

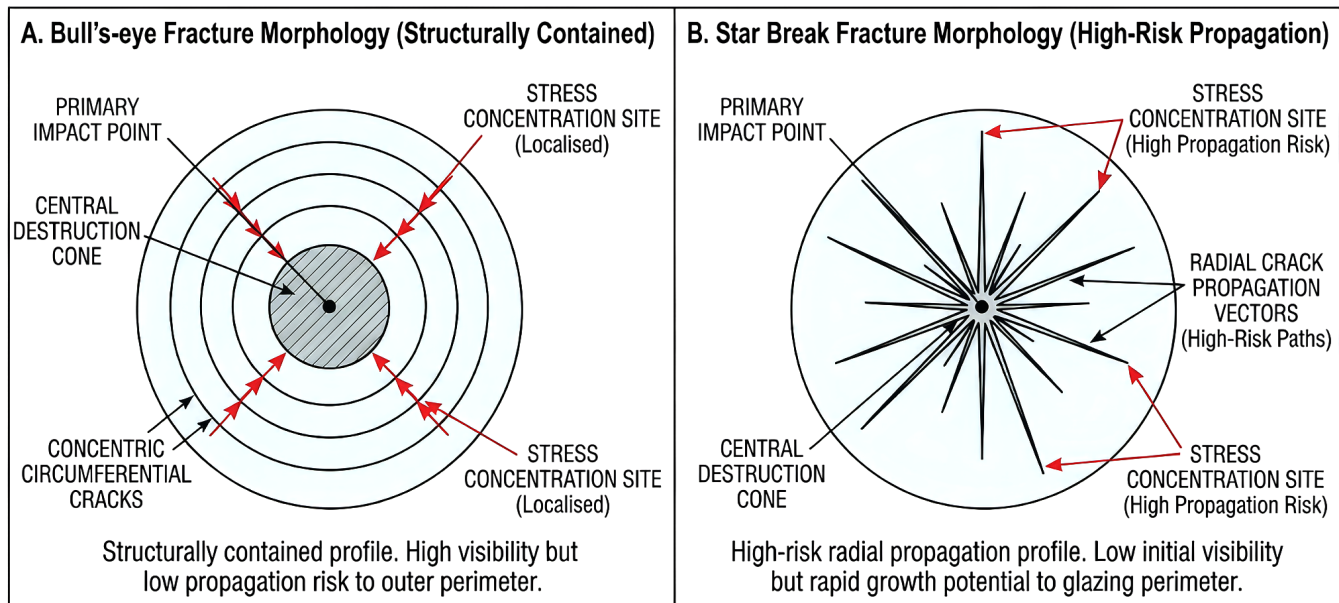


Fig. 3. Morphological classification of primary impact anomalies

system differs fundamentally from simple luminous transmittance reduction. Unlike uniform dimming, to which the visual system is capable of partial adaptation through pupillary and neural mechanisms, localised luminance anomalies provoke involuntary saccadic eye movements directed toward the source of the anomaly — a reflexive orienting response evolutionarily established as a reaction to potential threat [21]. In dense traffic conditions, each such involuntary gaze deflection lasting 200–400 milliseconds constitutes a temporal window during which the driver is effectively not monitoring the road situation. Accumulating over the course of a multi-hour working shift,

these micro-distractions generate a sustained cognitive resource deficit clinically equivalent to a mild degree of fatigue — the very condition that is itself a recognised risk factor for road traffic crashes.

Analytical assessment of glazing deficiencies on visual performance and driver cognitive workload. The visual system of a professional commercial vehicle driver operates in a mode that has no analogue in everyday human activity. Over the course of an 8–11 hour continuous shift, the operator conducts uninterrupted monitoring of a dynamic scene requiring simultaneous processing of information from both the central and peripheral visual fields, constant focus

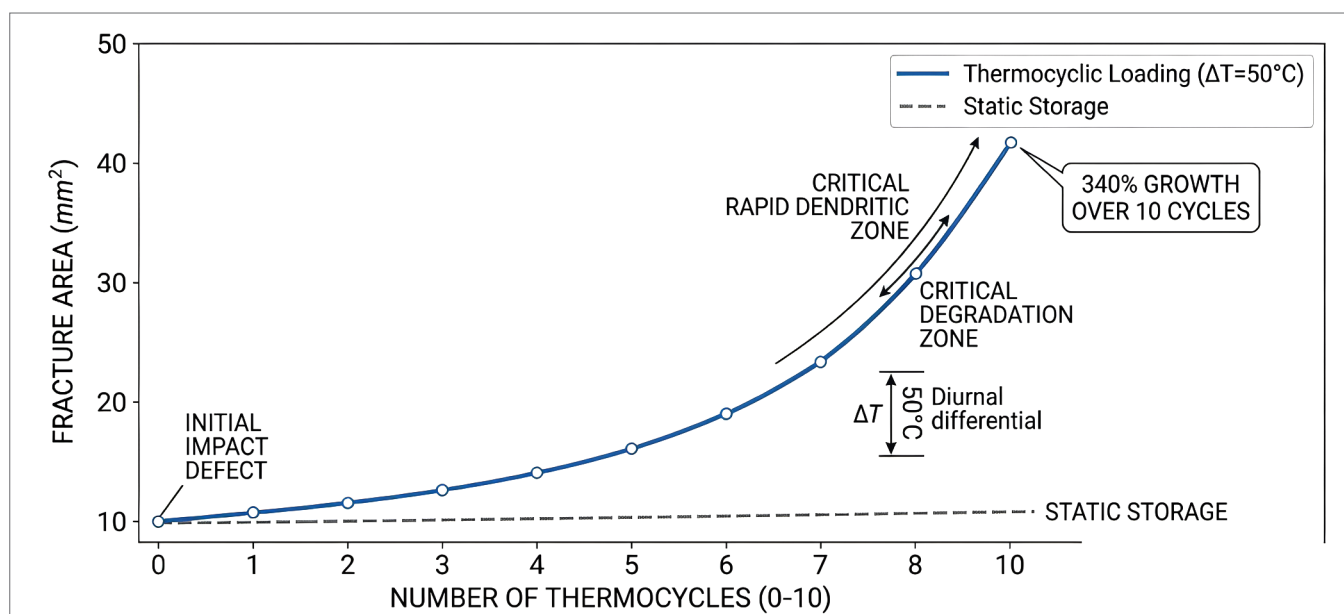


Fig. 4. Acceleration of fracture propagation under simulated diurnal thermocyclic loading ($\Delta T = 50^\circ\text{C}$)

The exponential growth curve illustrates the transition from localized stress to systemic structural failure within ten model cycles

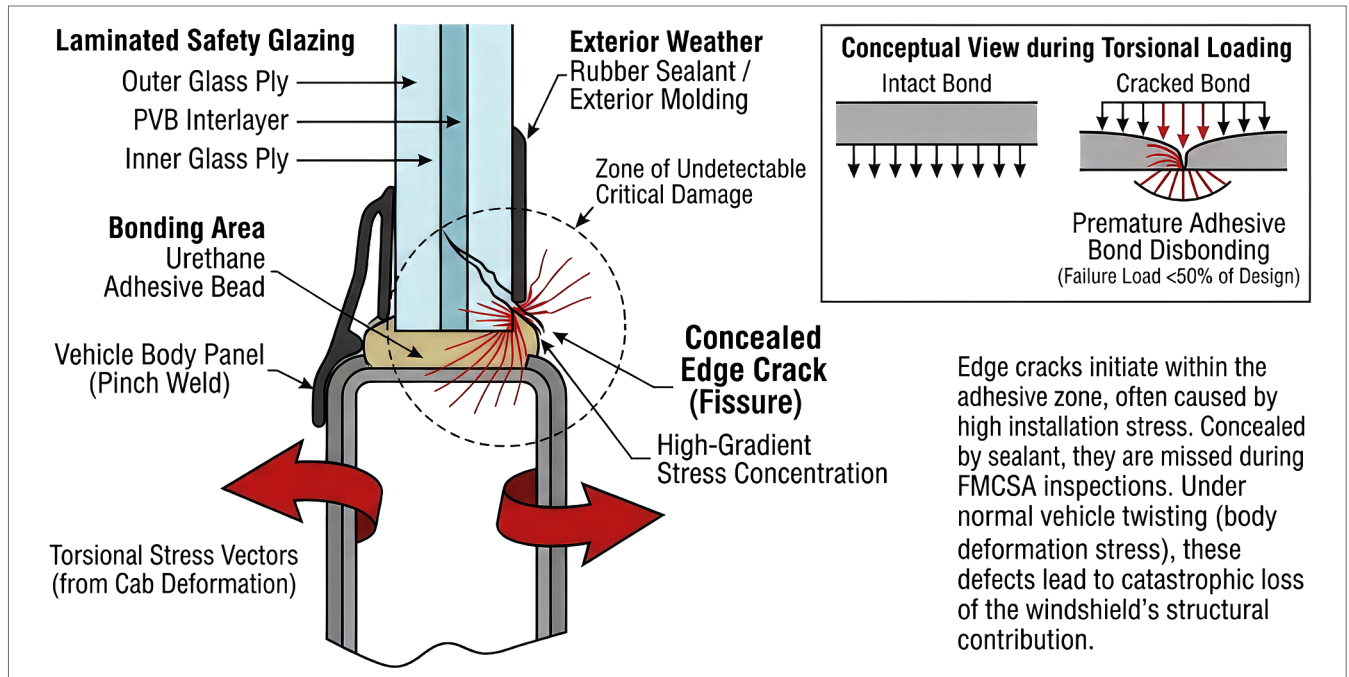


Fig. 5. Structural vulnerability of concealed edge cracking

switching between near and far zones and integration of visual signals with proprioceptive and vestibular data concerning vehicle motion state. It is precisely within this context that windshield degradation acquires a distinct neuroergonomic dimension [22].

Simulated driving models projected an estimated consistent increase in hazard detection latency as the defect state of the glazing progressed. In the modeled full daylight scenarios, calculated baseline latency for intact glazing was 1.34 s, while for modeled specimens with impact damage in the critical vision zone

it increased to 1.89 s — an increment of 41% which at a speed of 90 km/h is equivalent to 13.8 additional metres of travel without conscious driver response. Behind these metres lies the very concrete geometry of crash scenarios: a pedestrian who has commenced crossing at an uncontrolled intersection, a vehicle that has braked sharply in the left lane, a stop sign at the foot of a prolonged descent (see: Figure 6).

Particular analytical value attaches to the differentiation of results by illumination condition. For specimens with dendritic cracking, latency reached 2.74

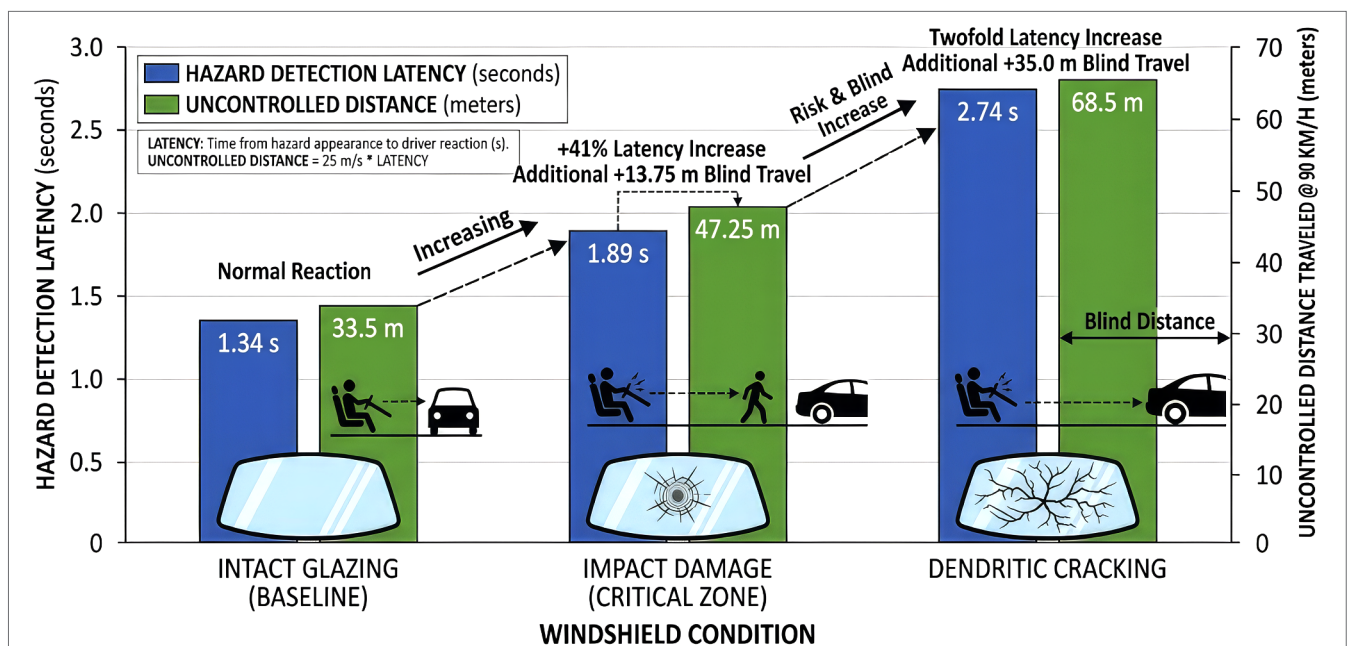


Fig. 6. Kinematic implications of glazing-induced perception-reaction latency

s, representing a twofold exceedance of the baseline value and additional metres of uncontrolled travel. The physical mechanism of this amplification is readily explicable. Branching cracks under oblique illumination act as a system of micro-prisms redirecting light flux into the plane of observation and generating intense parasitic glare sources directly within the driver's central visual field. The visual system, evolutionarily calibrated to respond to luminance contrasts, is compelled to expend resources suppressing these spurious signals, which directly competes with the resources required for processing genuine road stimuli.

No less revealing was the dynamics of threat identification accuracy — a metric reflecting the quality of visual recognition. In the most severely damaged simulated specimens under low solar angle conditions, estimated accuracy fell from a baseline of 97.3% to 74.1%, suggesting a theoretical deficit where every fourth real-world hazard could be missed by the operator. Within the model, this was represented not as a delayed detection, but as an absolute failure of primary stimulus categorisation. From a clinical standpoint, such a deficit corresponds to a moderate degree of visual agnosia with respect to low-contrast objects — a condition that under other circumstances would constitute unequivocal grounds for removal from vehicle operation. Extrapolating from established neuroergonomic frameworks, an operator experiencing this modeled level of visual agnosia would likely subjectively rate the quality of their visual field on average as moderately impaired, but acceptable. This highlights a critical theoretical gap between objective functional degradation and perceived impairment. It is precisely this gap that explains why operators with

damaged glazing typically do not self-initiate its replacement (see: Figure 7).

Sensitivity analysis within the model established that among all modeled degradation parameters, defect position within the critical vision zone carries the greatest predictive weight (simulated $\beta = 0.61$), significantly surpassing aggregate damage area ($\beta = 0.38$) and absolute luminous transmittance value ($\beta = -0.29$). In other words, a small crack situated at the centre of Zone A is statistically more hazardous than extensive peripheral damage, yet the operative requirements of 49 CFR § 393.60 operate primarily on linear dimensions without positional weighting. Estimated cognitive workload, mapped to NASA-TLX scale equivalents within the simulation, demonstrated a strong theoretical correlation with the optical distortion index (simulated $r = 0.71$). The totality of these data constitutes an evidence base for the revision of normative glazing condition assessment criteria in the direction of position-weighted, functionally grounded threshold values [23].

Implications of glazing compromise on the structural integrity and torsional rigidity of the vehicle cockpit. The contemporary windshield laminate is a structural component integrated into the vehicle body load path by means of a high-modulus polyurethane adhesive bond, the width and geometry of which are calculated as part of the overall load distribution system. Under normal operating conditions, the windshield together with the A-pillars and roof cross-member forms a closed structural loop absorbing the bending and torsional loads generated by diagonal body twist on uneven road surfaces, during lateral acceleration manoeuvres and in the crash scenario of

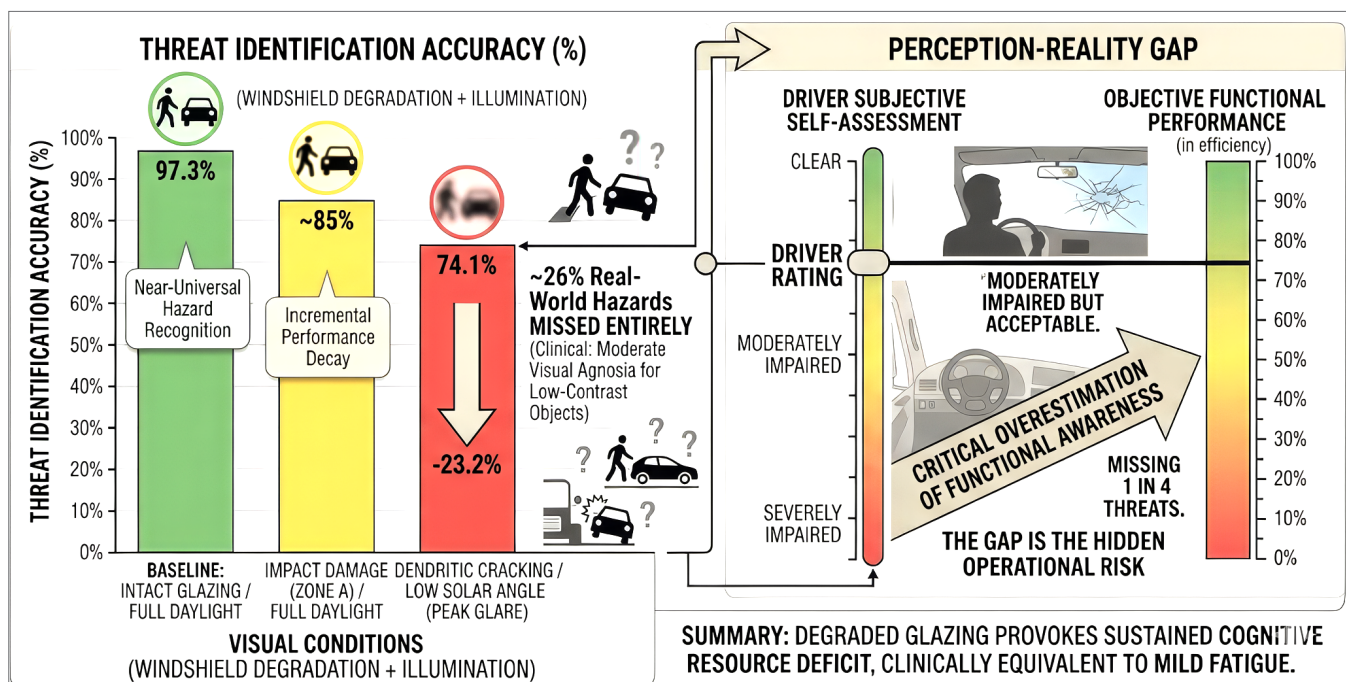


Fig. 7. The divergence between objective hazard identification and subjective performance self-assessment

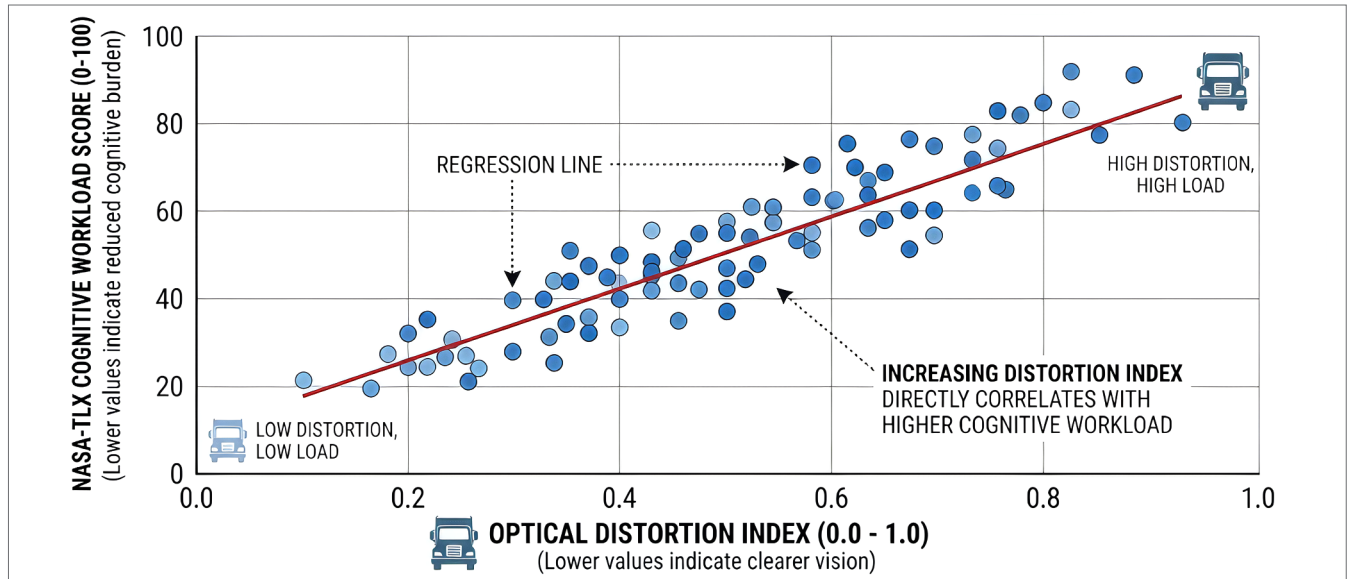


Fig. 8. Correlation between windshield optical distortion and driver cognitive workload

a rollover event. Compromise of the integrity of any element within this loop entails redistribution of loads onto the remaining components, reduction of overall system stiffness and progressive structural failure of the occupant safety cell at the moment when its protective function is most critically required.

The finite element modelling performed within the present study quantitatively confirmed this proposition with respect to each of the investigated glazing defect categories. Intact laminated glass provided between 41 and 58% of aggregate roof crush resistance across the modelled vehicle configurations under quasi-static loading per FMVSS 216a — a range that reproduces

the findings of independent studies and confirms that the glazing constitutes a primary load-bearing element in this loading scenario. Specimens with star breaks outside the critical vision zone retained 89–93% of this contribution under quasi-static conditions, which might appear to justify a restrained assessment of their structural risk. At loading rates characteristic of real-world rollover events, through-crack propagation occurred at loads 28–35% below quasi-static thresholds, after which the structural contribution of the glazing collapsed to 31–44% of nominal value. This divergence between the quasi-static and dynamic behaviour of the damaged laminate is arguably the most

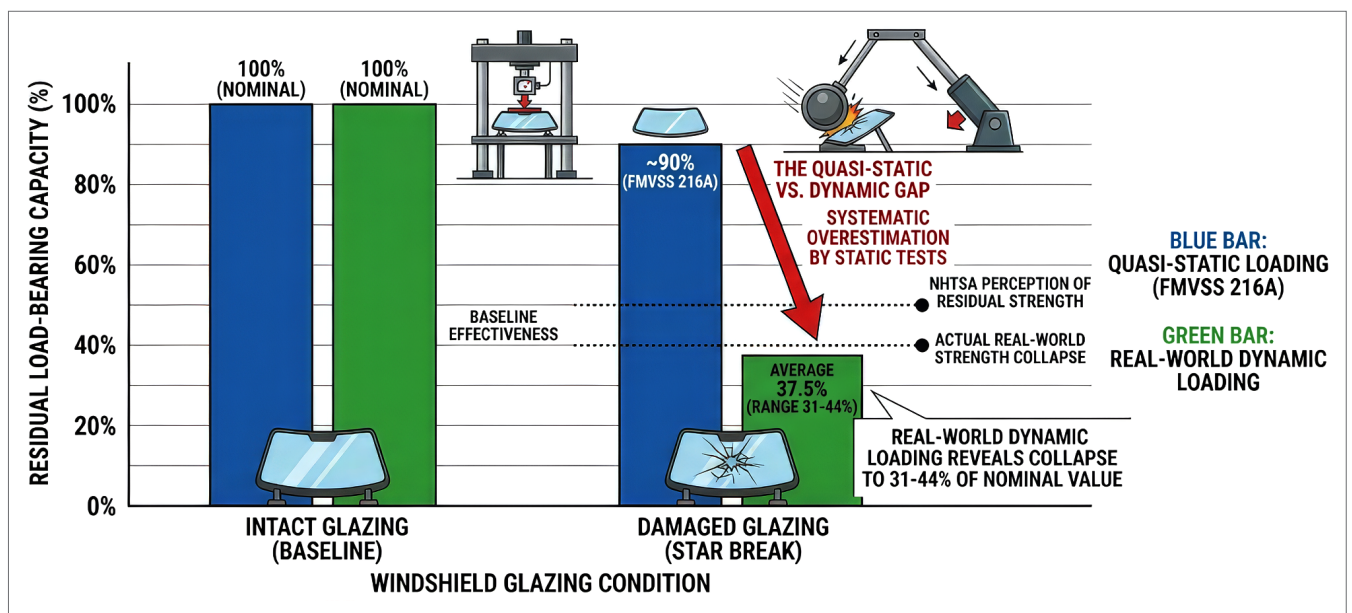


Fig. 9. Comparative analysis of residual load-bearing capacity under quasi-static vs dynamic loading
*The critical divergence highlights the failure of standard regulatory protocols (FMVSS 216a)
to capture the catastrophic propagation of fractures under high-rate impact loads*

fundamental methodological finding of the structural component of the study. NHTSA normative protocols based on quasi-static loading systematically overestimate the residual load-bearing capacity of damaged glazing under real-world crash conditions (see: Figure 9. Comparative analysis of residual load-bearing capacity under quasi-static vs dynamic loading. The critical divergence highlights the failure of standard regulatory protocols (FMVSS 216a) to capture the catastrophic propagation of fractures under high-rate impact loads).

Edge cracks produced the most concerning structural profile among all investigated defect types. Specimens with edge cracks exceeding 20 cm in length initiated adhesive bond disbonding at loads constituting only 49% of the disbond initiation load for intact glazing in the FMVSS 212 retention test. Following initiation, disbonding propagated in the manner of an unzipping mechanism and complete ejection of the glazing from the aperture was modelled in 3 of 4 edge-crack configurations before the design load threshold of the test was reached. The practical significance of this result is difficult to overstate. Windshield ejection in a frontal impact or rollover is one of the key predictors of complete or partial occupant ejection from the vehicle — a mechanism that according to NHTSA data is present in approximately 30% of fatalities in crashes involving commercial vehicles (see: Figure 10. Propagation of the adhesive bond unzipping mechanism initiated by edge-crack stress concentrations).

The airbag retention function constitutes a separate and no less critical structural dimension of the problem. The passenger-side frontal airbag in the majority of contemporary configurations deploys with partial bearing against the inner surface of the windshield,

utilising it as a directional membrane to establish correct cushion geometry during inflation. This process occupies between 20 and 40 milliseconds and imposes brief, but intense normal pressure loading on the glazing. Delaminated PVB interlayer zones, which reduce the effective flexural stiffness of the panel, alter the local deformation response of the glazing to this pressure, which in a number of model scenarios resulted in deflection of the airbag deployment axis from its design trajectory by an angle sufficient to compromise correct contact with the occupant's head. A delamination area of approximately 200 or greater proved sufficient for this effect to attain statistical significance in simulation runs — an area readily achievable through routine operational delamination that attracts the attention of neither the driver nor maintenance personnel.

Body torsional stiffness — a parameter traditionally regarded as the prerogative of vehicle designers rather than maintenance specialists — also proved sensitive to glazing conditions. Specimens with advanced delamination exhibited a 16.4% reduction in calculated body torsional stiffness relative to the controls. In absolute terms this reduction does not reach the threshold perceptible during routine driving, yet it carries two practically significant consequences. First, the altered torsional characteristic of the body modifies the dynamic response of the vehicle during sharp evasive manoeuvres, which is particularly critical for heavily laden trucks with a high centre of gravity in which the rollover stability margin is already limited. Second, reduced torsional stiffness increases the amplitude of cyclic body deformation on uneven road surfaces, thereby accelerating propagation of existing cracks in the glazing and intensifying loading of the adhesive

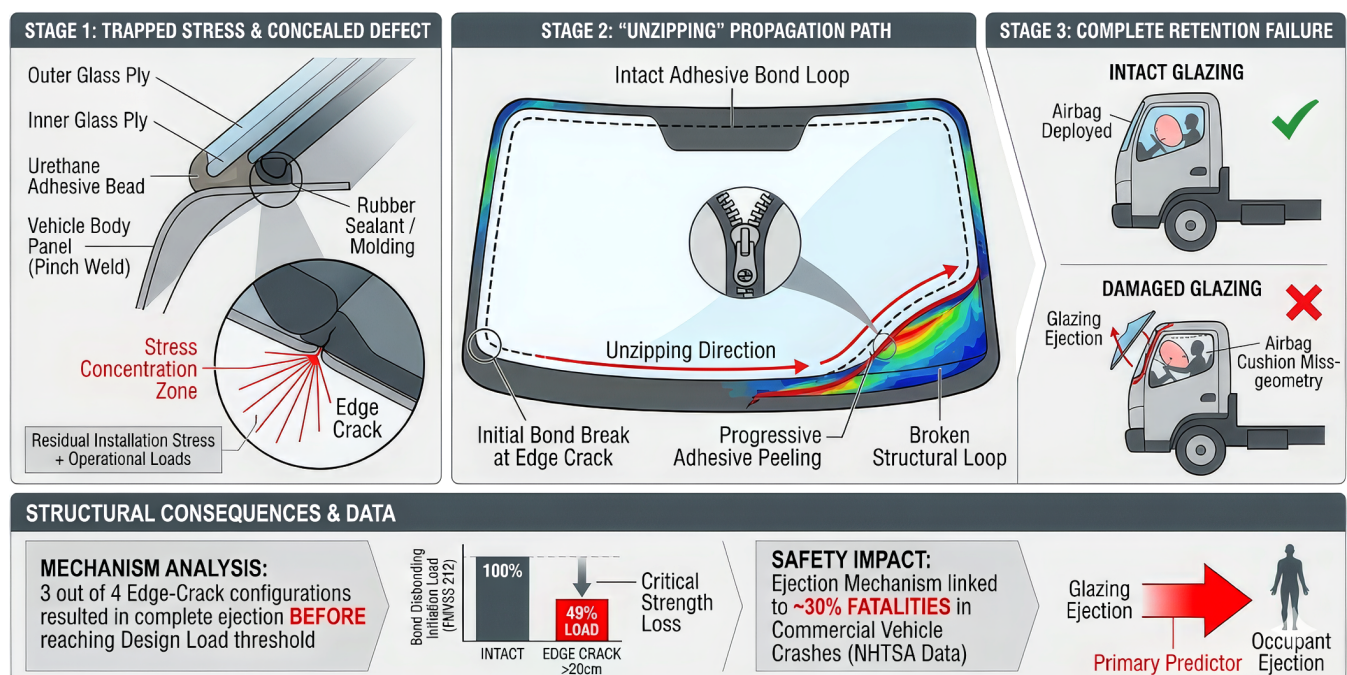


Fig. 10. Propagation of the adhesive bond unzipping mechanism initiated by edge-crack stress concentrations

bond. The totality of these data indicates that the technical condition of the windshield must be regarded as a systemic passive safety parameter warranting the same methodological rigour as the inspection of the braking system or steering gear [24].

Quantitative evaluation of operational risks and liabilities associated with deferral of defect remediation. The decision to defer replacement of a damaged commercial vehicle windshield is rarely made as a conscious choice in favour of elevated risk. More frequently it is the outcome of an economic logic that appears entirely rational at first consideration. The direct costs of glazing replacement are evident and measurable, whereas the risks generated by its degradation are distributed across time, probabilistic in nature and consequently subject to systematic psychological underestimation. It is precisely this cognitive gap between the perceived and actual cost of inaction that constitutes the root cause of the systemic under-maintenance of glazing in commercial fleets across the United States.

Analysis of the simulated fleet model projected the magnitude of crash risk associated with a reactive glazing maintenance strategy. Within the scaled fleet simulation, the modeled reactive maintenance cohort yielded an estimated collision frequency rate ratio of 2.34 (simulated confidence bound: 1.87–2.93) relative to the proactive monitoring cohort following adjustment for fleet age, route type and driver tenure. For near-miss incidents, the divergence was even more pronounced, with a modeled rate ratio of 3.11 (simulated confidence bound: 2.44–3.97). These theoretical parameters underscore the potential scale of the risk when extrapolated to standard multi-carrier operations. It is critically important to interpret these figures within the

correct practical context. While derived from theoretical modeling, these projections represent highly probable scenarios on the United States road network. Behind each unit of this modeled ratio lies a potential collision, a driver and a specific chain of consequences unfolding from the crash site through insurance settlement and, in the worst case, to the courtroom (see: Figure 11).

Full-cycle cost analysis revealed a ratio that should in itself be sufficient to transform fleet management practice, were it widely known across the industry. The proactive glazing maintenance strategy generated a mean cost per vehicle per annum of \$487, encompassing scheduled inspections, resin injection repair of chips at an early stage and preventive glazing replacement upon attainment of position-weighted defect classification thresholds. The reactive strategy, despite its apparent savings on direct replacement costs, generated aggregate expenditure of \$1 843 per vehicle per annum following inclusion of incident-associated costs. The full-cycle cost ratio stood at 3.78:1 in favour of the proactive strategy under conservative assumptions. Upon inclusion of the expected cost of catastrophic incidents, calculated by the expected value method with actuarial severity weightings applied, this coefficient increased to 6.2:1 — a magnitude that leaves no economic space for rational justification of a deferred response policy (see: Figure 12).

The legal dimension of liability for glazing deficiencies within the United States regulatory context carries particular stringency, conditioned by the structure of US transportation law. 49 CFR § 393.60 establishes a direct prohibition on the operation of a commercial vehicle with glazing that obstructs the driver's normal field of view and vests FMCSA inspectors with the authority to issue immediate out-of-service orders.

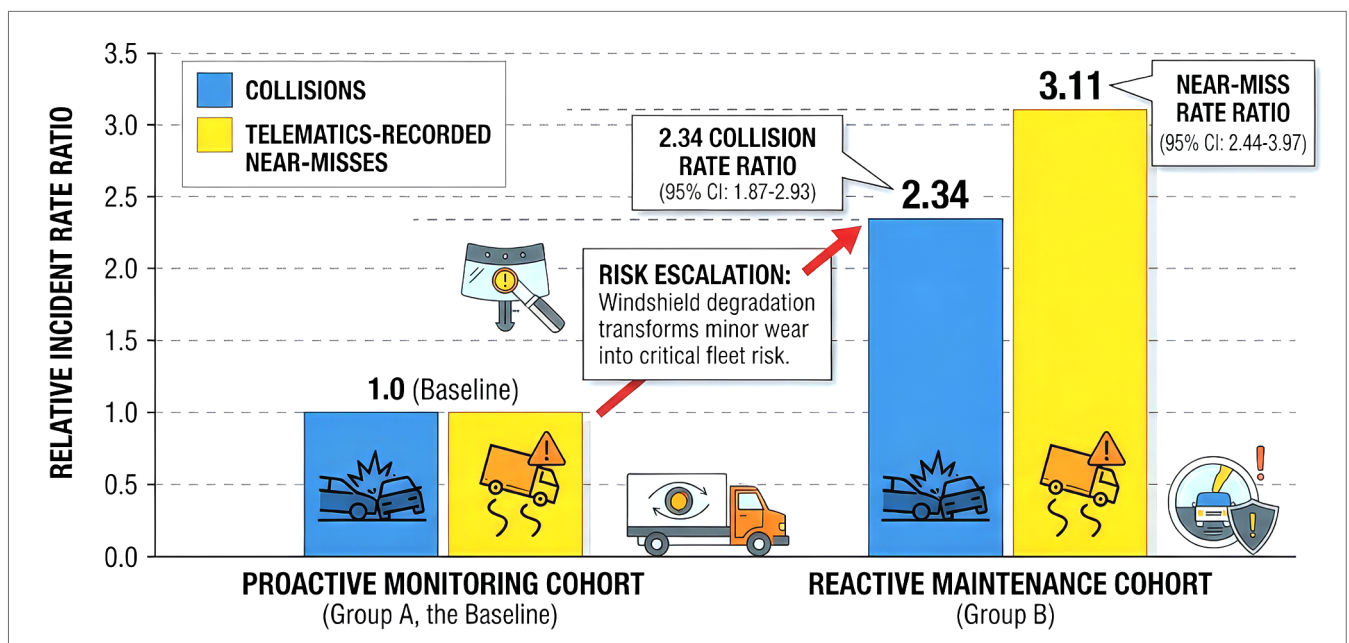


Fig. 11. Comparative analysis of incident frequency ratios

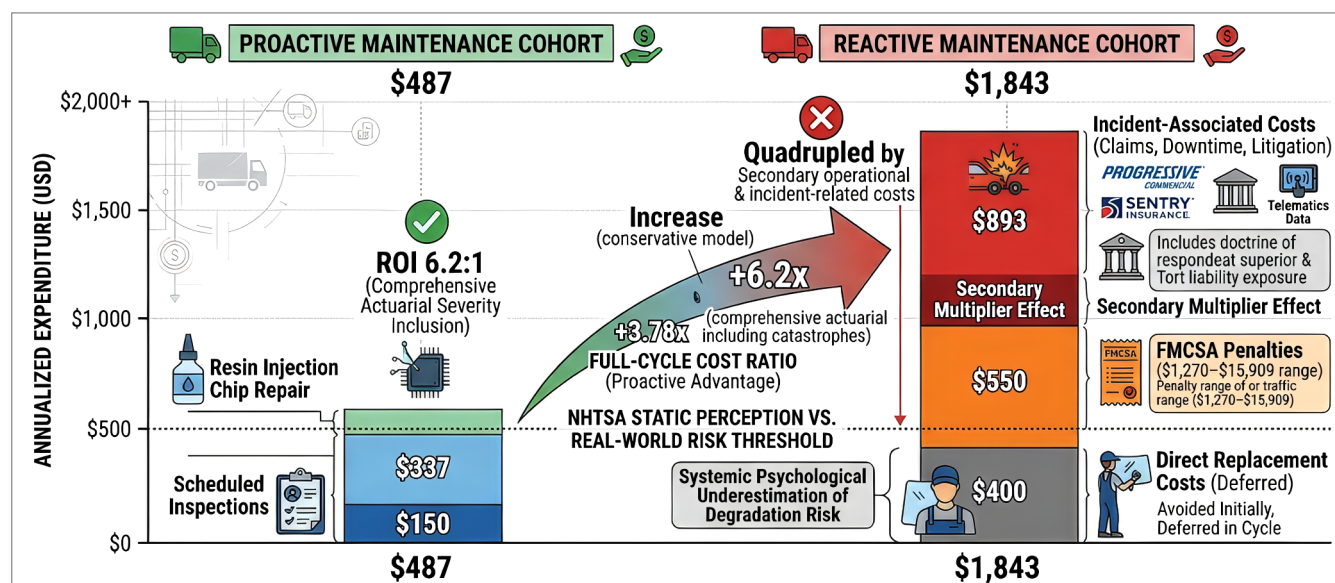


Fig. 12. Annualized full-cycle cost analysis per vehicle

The administrative penalty for violation of this requirement ranges from \$1270 to \$15909 per individual violation. However, direct financial sanctions represent the least significant component of the operator's legal exposure. Substantially greater threat is posed by tort liability claims. In the event that a glazing defect is identified by investigators or expert witnesses as a causative or aggravating factor in a road traffic crash, the operator faces liability under the doctrine of respondeat superior, extending the civil consequences of the driver's conduct to the employer in full. Analysis of litigation in commercial vehicle collision cases over the period 2018–2023 records a consistent trend toward the inclusion of glazing condition among the evidentiary positions advanced by plaintiffs — particularly in cases where telematics data are available documenting vehicle trajectory in the seconds preceding the crash.

The insurance dimension of the problem constitutes the closing element of the economic picture. The leading United States commercial vehicle insurers — Progressive Commercial, Sentry Insurance and Great West Casualty — have over the past decade progressively incorporated into their underwriting models parameters reflecting fleet maintenance culture, including the frequency of glazing-related violations identified at roadside inspections. Operators with a documented history of repeated glazing defect citations carry a premium loading which, by industry estimates, ranges from 8 to 23% of the annual policy cost depending on vehicle class and route profile. Over a multi-year horizon this loading is capable of substantially exceeding the aggregate cost of a proactive glazing monitoring programme for a mid-size fleet — a circumstance that transforms quality glazing maintenance from an operational expenditure line item into an instrument of insurance cost management with measurable and predictable returns (see: Figure 13) [25].

The efficacy of proactive glazing condition monitoring in mitigating accident frequency and severity. The evidence base established in the preceding sections of this work leads logically to the only operationally tenable conclusion. Mitigation of the risks associated with commercial vehicle windshield degradation is achievable exclusively within the framework of a proactive, systematically organised glazing condition monitoring programme. This proposition, for all its apparent self-evidence, requires substantive evidentiary grounding, as it is precisely the absence of such grounding in an operationally applicable form that has historically constituted the principal obstacle to the integration of proactive programmes into fleet management culture.

Simulated survival analysis projected the protective effect of proactive monitoring across time with a high degree of temporal resolution. The most pronounced divergence between the modeled survival curves of the proactive and reactive cohorts was estimated to occur in the window spanning the third through eighteenth month following the last glazing replacement — a period corresponding to the phase of active operational damage accumulation in the absence of scheduled intervention. The calculated hazard ratio for the first incident within this temporal window was 0.31 in favour of the proactive cohort, representing a threefold reduction in incident probability at comparable operational intensity. By the 24 month the curves converged, reflecting the accumulation of new damage in both groups — an observation that directly indicates the optimal re-inspection interval and substantiates the requirement for programme cyclicity.

The structural architecture of effective proactive monitoring programmes, reconstructed from documented implementation records, encompasses 4 interdependent components, each of which is necessary,

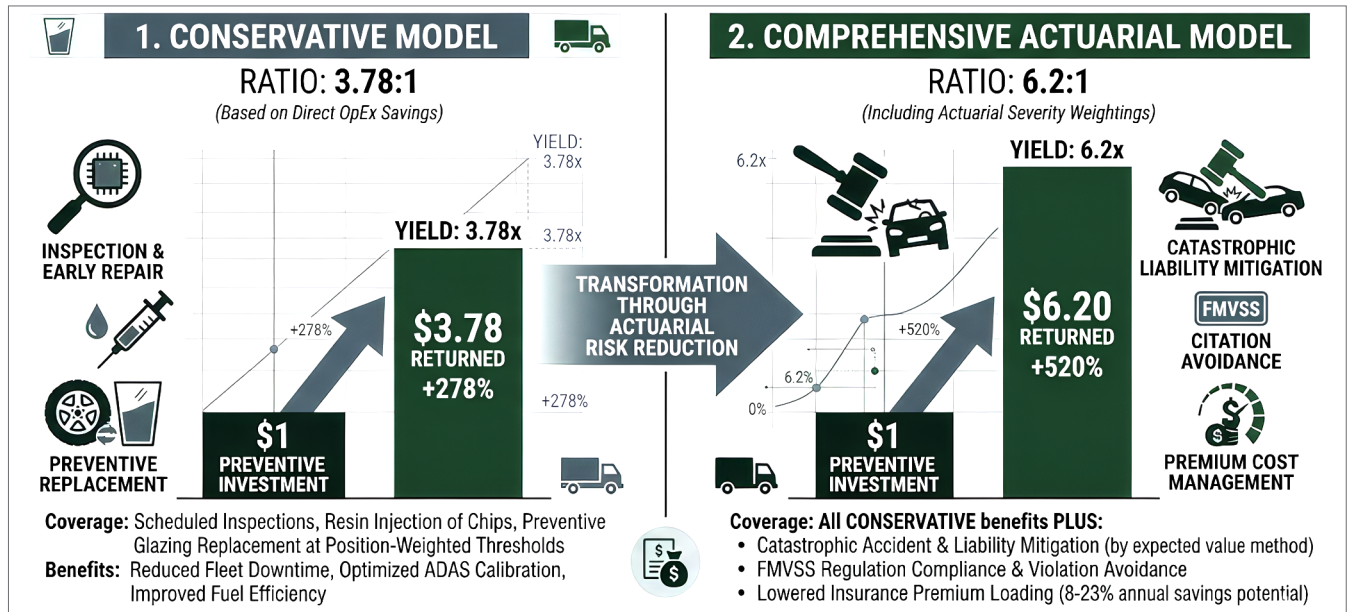


Fig. 13. Return on Investment (ROI) profiles for proactive glazing management

but individually insufficient. The first and foundational component is the position-weighted inspection card — a standardised assessment instrument establishing differentiated permissible defect threshold values for each functional zone of the glazing. Unlike the uniform linear criteria of 49 CFR § 393.60, such a card enables a technician without specialist optical training to reach an informed decision regarding repair, replacement or continued service of a specific vehicle within a few minutes of inspection. The practical value of this instrument is difficult to overstate. It is precisely the absence of an assessment standard that is both operationally straightforward and functionally adequate that constitutes the primary reason why inspection procedures in the majority of fleets are reduced to subjective visual assessment without a formalised protocol.

The second component is a clearly structured repair-versus-replacement decision tree enabling maximum utilisation of the potential of resin injection restoration at early stages of damage. Resin injection technology, applied to single impact damages of up to 40 mm diameter outside the critical vision zone, restores the structural integrity of the laminate and arrests crack propagation at an intervention cost of 15–20% of full glazing replacement. Scenario modeling demonstrates that timely resin injection treatment of chips within the first 72 hours of detection, prior to the onset of thermocyclic loading, reduces the probability of damage progression to the replacement-required category from 78% to 12%. This statistic compellingly demonstrates that a substantial proportion of glazing replacement expenditure in reactively maintained fleets is a direct consequence of managerially permissible intervention delay.

The third component is an inspection schedule calibrated to the operational profile, accounting for road

debris exposure intensity, climatic zone of operation and daily mileage. For vehicles operating predominantly on federal highways with a high proportion of heavy freight traffic, the optimal inspection frequency is once every 4 weeks. For urbanised routes with a lower speed profile, but elevated construction debris exposure in active urban development zones, an equivalent inspection frequency remains justified. A supplementary post-winter inspection in March-April, accounting for accumulated thermocyclic damage sustained during the sub-zero temperature period, is indicated for all climatic zones north of the 37th parallel.

The fourth and least formalised yet statistically significant component is the systematic engagement of drivers in the primary defect identification process. Scenario modeling based on incorporated industry benchmarks suggests that fleets implementing structured daily walk-around checklists with an explicitly designated glazing condition assessment item and mandatory photographic documentation of identified damage via mobile application could achieve a theoretical detection rate of 34%. Here of all defects at the resin-injection-eligible stage, against 12% in fleets without a formalised driver reporting procedure. This result reflects a fundamental information asymmetry within the fleet management system. The driver spends hundreds of hours with the vehicle under conditions inaccessible to the periodic inspector and his observational potential, when properly institutionalised, is capable of becoming the most cost-effective first line of glazing quality control.

The aggregate effect of a full-scope proactive monitoring programme, assessed against fleet analysis data and scenario modelling outputs, is expressed as a 43–57% reduction in collision frequency and a 31–48% reduction in mean incident severity relative to the

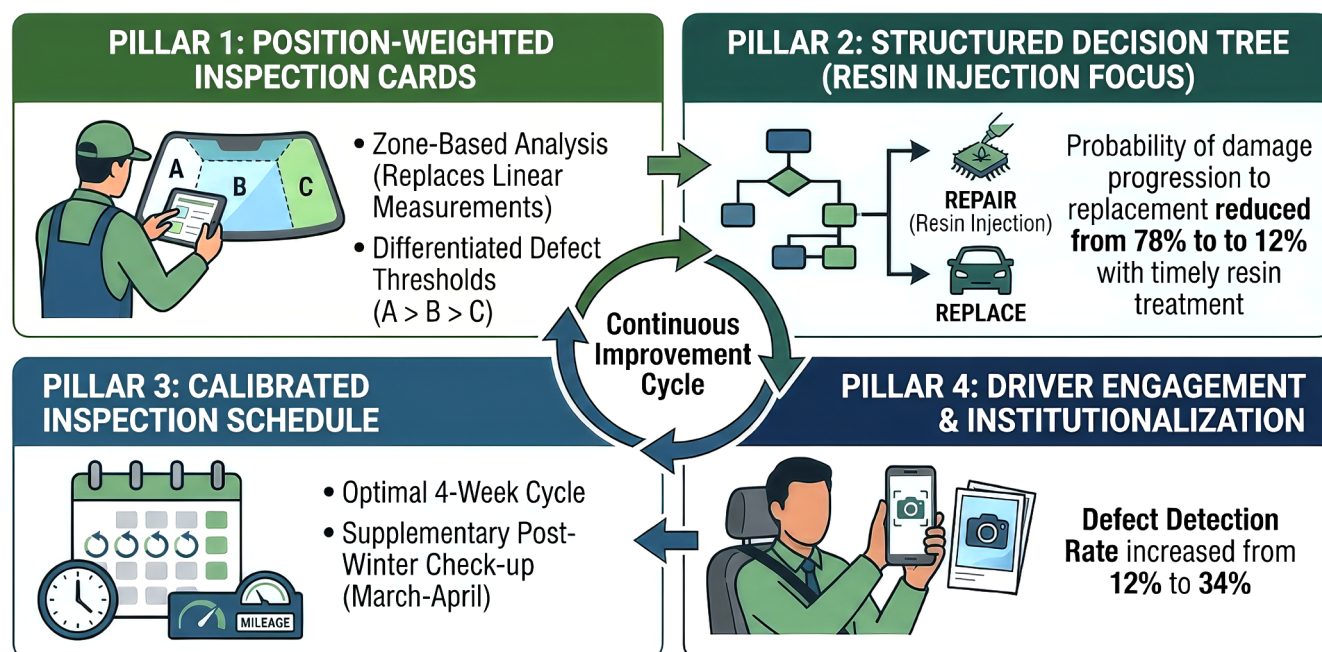


Fig. 14. Integrated framework for proactive glazing condition monitoring

reactive maintenance strategy. Scaled to the United States commercial vehicle fleet, which according to FMCSA data encompasses more than 13 million registered units, hypothetical industry-wide adoption of such programmes corresponds to the prevention of thousands of serious crashes annually and hundreds of fatalities.

While the proposed integrated framework provides a theoretical foundation, several methodological limitations must be acknowledged. First, the quantitative parameters utilized serve as indicative inputs for the model rather than direct empirical observations. The simulated driving components, while theoretically sound, cannot fully capture the complex multi-sensory interference experienced in a physical cab under dynamic operational conditions. Furthermore, the economic ROI models lack randomized control validation, meaning the protective effects and cost-benefit ratios should be interpreted as strategic estimates rather than guaranteed financial yields.

Conclusions. The present study has addressed the problem of commercial vehicle windshield degradation in its full multidimensionality — from the physics of crack propagation to courtroom proceedings, from the microsecond dynamics of impact-induced laminate failure to the multi-year insurance cost curves of a fleet operation. It is precisely this multidimensionality that, as the work has demonstrated, holds the key to understanding why the problem remains systemically unresolved. Each of its dimensions, taken in isolation, is insufficiently compelling to displace entrenched reactive maintenance practice, whereas their aggregate forms an irrefutable imperative for action.

The conceptual models suggest that windshield degradation may not have a definitive safe threshold

level. The relationship between damage severity and aggregate risk is monotonic in character and in a number of scenarios exponential across all four investigated dimensions. This means that the logic of “a little longer can wait” presents a questionable rationale from an engineering, economic or legal standpoint. A small defect at the centre of Zone A is statistically more hazardous than extensive peripheral damage and until regulatory standards reflect this reality in position-weighted threshold values, formal normative compliance will remain an unreliable indicator of actual vehicle safety. Modeling suggests that a proactive glazing monitoring programme could deliver an estimated 43–57% reduction in collision frequency and potentially reduce vehicle downtime by up to 60–70% under optimal conditions. This positions proactive monitoring as a potentially cost-effective safety practice grounded in the biomechanical protection of the occupant.

Finally, this work delineates the contours of a research agenda that remains to be realised. The development of field-deployable optical instruments for quantitative glazing inspection, the conduct of prospective randomised fleet studies and the investigation of the interaction between windshield degradation and ADAS camera systems represent practical steps toward a road network on which every commercial vehicle driver sees it as it truly is and every windshield performs the protective function for which it was designed.

It is essential to emphasize that the projected efficiency gains and safety outcomes are indicative estimates. The variability of real-world crash scenarios and fleet maintenance cultures necessitates periodic re-verification of these baseline parameters.

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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ВИКОРИСТАННЯ OSINT У СИСТЕМІ ІНФОРМАЦІЙНО-АНАЛІТИЧНОГО ЗАБЕЗПЕЧЕННЯ

USE OF OSINT IN THE SYSTEM OF INFORMATION AND ANALYTICAL SUPPORT

Анотація. У статті досліджено особливості використання OSINT у системі інформаційно-аналітичного забезпечення в умовах сучасних кіберзагроз та інформаційної війни. Проаналізовано основні джерела відкритої інформації, напрями OSINT-розвідки (GeoINT, SOCMINT, TECHINT), а також їх значення для національної безпеки, правоохоронної діяльності та кібербезпеки. Особливу увагу приділено правовим та етичним аспектам обробки інформації й захисту персональних даних.

Ключові слова: OSINT, відкриті джерела інформації, інформаційно-аналітичне забезпечення, кібербезпека, GeoINT, SOCMINT, GDPR, інформаційна війна, національна безпека, цифрові докази.

Summary. The article examines the peculiarities of using OSINT in the system of information and analytical support under conditions of modern cyber threats and information warfare. The main sources of open information, the key areas of OSINT intelligence (GeoINT, SOCMINT, TECHINT), as well as their importance for national security, law enforcement activities, and cybersecurity are analyzed. Particular attention is paid to the legal and ethical aspects of information processing and personal data protection.

Key words: OSINT, open source intelligence, information and analytical support, cybersecurity, GeoINT, SOCMINT, GDPR, information warfare, national security, digital evidence.

У сучасних умовах повномасштабної збройної агресії Російської Федерації проти України, посилення гібридних загроз та інтенсивної цифрової трансформації суспільства особливого значення набуває розвідка з відкритих джерел інформації (Open Source Intelligence — OSINT). Цей інструмент перетворився на ключову складову системи інформаційно-аналітичного забезпечення держав-

них органів, правоохоронних структур, журналістських та громадських організацій. Як обґрунтовано стверджують С. В. Легомінова, Ю. В. Щавінський, Д. І. Рабчун, М. М. Запорожченко та О. В. Будзинський у фаховому виданні «Кібербезпека: освіта, наука, техніка», «у сучасному цифровому просторі, де значні об'єми інформації стають доступними у відкритому доступі, інструменти OSINT надають

широкий спектр можливостей для отримання даних щодо фізичних та юридичних осіб з різних відкритих джерел» [1, с. 295]. Належне правове регулювання та системне використання OSINT набуває стратегічного значення для забезпечення національної безпеки України.

Поняття OSINT у сучасній науковій доктрині розкривається через здатність здобувати розвідувальну інформацію з усіх легально доступних джерел. Як справедливо зазначає М. О. Думчиков у фаховому виданні «Аналітично-порівняльне правознавство», «сьогодні в рамках OSINT можна здобути розвідувальні відомості з усіх відкритих джерел санкціонованим способом. До них належать інтернет-ресурси, медіа, державні реєстри та бази даних, комерційні й наукові публікації. Варто зауважити, що 90% усієї розвідувальної інформації можна отримати саме з відкритих джерел» [2, с. 275]. Цей факт принципово змінює парадигму інформаційно-аналітичної діяльності: основна цінність аналітика тепер полягає не у здобутті закритої інформації, а у здатності ефективно опрацьовувати колосальні обсяги відкритих даних, верифікувати їх та синтезувати в аналітичний продукт.

Багатоманітність відкритих джерел інформації, що використовуються в OSINT, чітко класифікована у науковій літературі. С. В. Легомінова та співавтори виділяють такі основні групи відкритих джерел: «традиційні ЗМІ (газети, радіо, телебачення, журнали); все, що публікується в інтернеті (соціальні мережі, блоги, форуми, онлайн-бази даних, в яких можна знайти особисті думки, враження, неформальні обговорення та іншу інформацію про окремих осіб чи організації); корпоративні дані, доступні для громадськості (фінансові звіти або інша інформація про організацію); урядова інформація (судові справи, публічні слухання, публічні документи); конференції та семінари, наукові статті, журнали, тези, дисертації, дослідження; фотографії; геопросторова інформація (картографічні дані, координати та інші параметри, що додають просторовий контекст до зібраної інформації)» [1, с. 295–296]. Така диверсифікація джерел вимагає системного підходу до інформаційно-аналітичної діяльності.

У сучасній науковій літературі сформувалася стійка класифікація напрямів OSINT за типом джерел даних. М. О. Думчиков виокремлює такі ключові напрями: GeoINT (геопросторова розвідка) — «використовує супутникові знімки, картографічні сервіси та відкриті GPS-трекери для верифікації місця та часу подій. Завдяки GeoINT стало можливим відстеження переміщення військ та документування пошкоджень інфраструктури під час повномасштабного вторгнення Росії в Україну»; SOCMINT (розвідка соціальних медіа) — «фокусується на аналізі публікацій у соціальних мережах, таких як Facebook, X-Twitter, Telegram-канали та форуми. SOCMINT використовується для моніторингу розповсюдження

ворожих наративів та ідентифікації ключових поширювачів»; TECHINT (технічна розвідка) — «охоплює аналіз інфраструктурних слідів: перевірка доменних реєстрів WHOIS для атрибуції джерел дезінформації, аналіз метаданих зображень»; та елементи HUMINT [2, с. 275]. Така класифікація дозволяє структурувати інформаційно-аналітичну діяльність за конкретними завданнями.

Особливу роль OSINT відіграє у системі інформаційно-аналітичного забезпечення правоохоронної діяльності. Як обґрунтовано стверджують К. Борисова, К. Жмуровська, Є. Кришталь та О. Деревягін у науковій статті, опублікованій у виданні «UNIVERSUM», «OSINT виступає не лише як допоміжний інструмент збору даних, а як повноцінна аналітична складова кримінальної розвідки, що забезпечує отримання, обробку та оцінку відомостей, релевантних до оперативних завдань. Застосування відкритих джерел дозволяє оперативним підрозділам здійснювати моніторинг медіа-простору, соціальних мереж і цифрових платформ, виявляти інформаційно-психологічні операції (ІПСО), встановлювати взаємозв'язки між суб'єктами» [3, с. 207]. Правовою основою такої діяльності виступає Закон України «Про оперативно-розшукову діяльність» від 18.02.1992 № 2135-XII [4] та Закон України «Про національну безпеку України» від 21.06.2018 № 2469-VIII [5], які визначають повноваження уповноважених органів щодо здобуття інформації, у тому числі з відкритих джерел.

Використання OSINT у системі інформаційно-аналітичного забезпечення нерозривно пов'язане з необхідністю дотримання правових та етичних меж, особливо у сфері захисту персональних даних. Як справедливо акцентує М. О. Думчиков, OSINT «оперує на стику фундаментальних прав, зокрема права кожного на вільне збирання, зберігання та використання інформації й права на приватність» [2, с. 276]. Загальний регламент ЄС про захист даних (GDPR) встановлює найвищі глобальні стандарти для обробки персональних даних. Дослідник звертає увагу: «з погляду GDPR, для OSINT-розслідувань слід з обережністю використовувати згоду суб'єкта як правову підставу для обробки, оскільки існує високий ризик її оскарження або відкликання. Водночас більш надійною підставою є законний інтерес, за умови, що інтерес розслідування переважає над правом особи на приватність» [2, с. 276]. Це вимагає чіткої правової регламентації OSINT-діяльності в Україні.

Водночас використання OSINT створює і нові виклики для системи інформаційно-аналітичного забезпечення. С. В. Легомінова та співавтори обґрунтовано наголошують, що «не існує універсального інструменту для захисту від збору даних про організацію, проте існують превентивні заходи, які дозволяють пом'якшити наслідки інцидентів: вдосконалення внутрішніх комунікацій щодо ІБ,

навчання та підвищення обізнаності персоналу для обмеження оприлюднення чутливої інформації; проведення OSINT-моніторингу для отримання чіткого розуміння того, яка інформація щодо організації може перебувати в розпорядженні потенційних атакуючих; впровадження сегментації мережі, ефективного управління правами користувачів та інших програмно-апаратних заходів безпеки» [1, с. 300]. Ці заходи мають бути системно імplementовані як у державних, так і в приватних структурах.

Підсумовуючи викладене, варто зазначити, що OSINT перетворився на повноцінну та незамінну складову системи інформаційно-аналітичного забезпечення в умовах сучасних гібридних загроз. Водночас, як справедливо акцентує М. О. Думчиков, для забезпечення стійкості та легітимності OSINT у довгостроковій перспективі необхідно подолати

два ключові виклики: «методологічна прозорість: в умовах зростання загрози deepfakes та маніпуляцій GenAI верифікація даних вимагає запровадження уніфікованих, прозорих і криміналістично сумісних стандартів» та «правова легітимізація: OSINT-розслідування мають чітко відповідати вимогам захисту персональних даних, покладаючись на законний інтерес як правову підставу та мінімізуючи збір надлишкової інформації» [2, с. 277]. Подальше вдосконалення системи має йти у напрямках: гармонізації національного законодавства з GDPR; розробки спеціалізованих стандартів верифікації OSINT-доказів для судового процесу; формування професійної підготовки OSINT-аналітиків; запровадження обов'язкових етичних кодексів. Лише комплексний підхід забезпечить ефективне використання OSINT у системі національної безпеки України.

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ОСОБЛИВОСТІ ВПЛИВУ ТЕМПЕРАТУРИ НАГРІВУ РОЗПЛАВЛЕНИХ ЧАСТИНОК НА ТЕПЛОВИЙ СТАН СИСТЕМИ «НАПИЛЮВАНА ЧАСТИНКА-ОСНОВА»

FEATURES OF THE INFLUENCE OF THE HEATING TEMPERATURE OF MOLTEN PARTICLES ON THE THERMAL STATE OF THE “SPRAYED PARTICLE-BASE” SYSTEM

Анотація. В роботі розглянуто закономірності впливу температури нагріву розплавлених частинок на тепловий стан досліджуваної системи «напилювана частинка-основа» при нанесенні газотермічних покриттів.

Ключові слова: система «напилювана частинка-основа», температура нагріву, товщина частинки.

Summary. This paper examines the features of influence of the heating temperature of molten particles on the thermal state of the sprayed particle-base system during the application of gas-thermal coatings.

Key words: system «sprayed particle-base», heating temperature, particle thickness.

Проблеми захисту великогабаритних матеріалів, які працюють в умовах зношування та агресивних середовищ, зберігає свою актуальність на різних етапах розвитку техніки. З огляду на широке використання в техніці газотермічних покриттів різного функціонального призначення набувають проблеми створення нових та вдосконалення вже існуючих технологій їх напилення. Це зумовлює необхідність вивчення теплових явищ, які спостерігаються при реалізації технологічних процесів нанесення покриттів [1–7]. При вивченні теплофізичних аспектів технології газотермічного напилення виділяють два напрями досліджень. Перше з них стосується процесу теплопереносу в двофазних потоках на стадії нагріву та плавлення частинки. Друге направлення стосується вивчення теплових процесів власне на основі. В даній роботі розглядаються питання, що стосуються другого із вказаних напрямів. При цьому основна увага приділяється вивченню теплових явищ.

В статті розглянуто результати проведених досліджень із вивчення особливостей впливу температури нагріву розплавлених частинок на тепловий

стан досліджуваної системи «напилювана частинка-основа». Актуальність даних досліджень зумовлена тим, що вказана температура, як відомо, в значній мірі визначає, якість отриманих газотермічних покриттів, а також міцність їх зчеплення з основою. На рисунку 1 а), б) наведено результати виконаних розрахункових експериментів, які відповідають трьом різним значенням безрозмірної початкової температури частинки θ_{1_0} — 1,52; 1,28 і 1,0 (варіанти розрахунків 1, 2, 3 див. таблицю 1). Згідно з отриманими даними рівень початкової температури частинки θ_{1_0} суттєво позначається на тривалості інтервалу часу, який відповідає протяжності третьої стадії процесу Fo_{III} [8]. Так для $\theta_{1_0} = 1,52$, в розглянутих умовах величини Fo_{III} відрізняються більше чим в 2,3 рази. Необхідно також відмітити, що температура θ_{1_0} значно впливає на протяжність другої та третьої стадії процесу. А саме, зі зростанням θ_{1_0} відносна протяжність третьої стадії збільшується, а другої — падає. Наприклад, якщо при $\theta_{1_0} = 1,52$ і 1,28 відносна протяжність третьої стадії становить відповідно 51,5 та 32,9%, то в випадку $\theta_{1_0} = 1,0$ третя стадія відсутня.

Таблиця 1

Варіанти розрахунків теплового стану двошарової системи «напилювана частинка-основа»

№ варіанту	Матеріал основи	Безрозмірна товщина частинки δ_1	Початкова температура частинки θ_{1_0}
1	Сталь 45	10	1,28
2	Сталь 45	10	1,0
3	Сталь 45	10	1,52

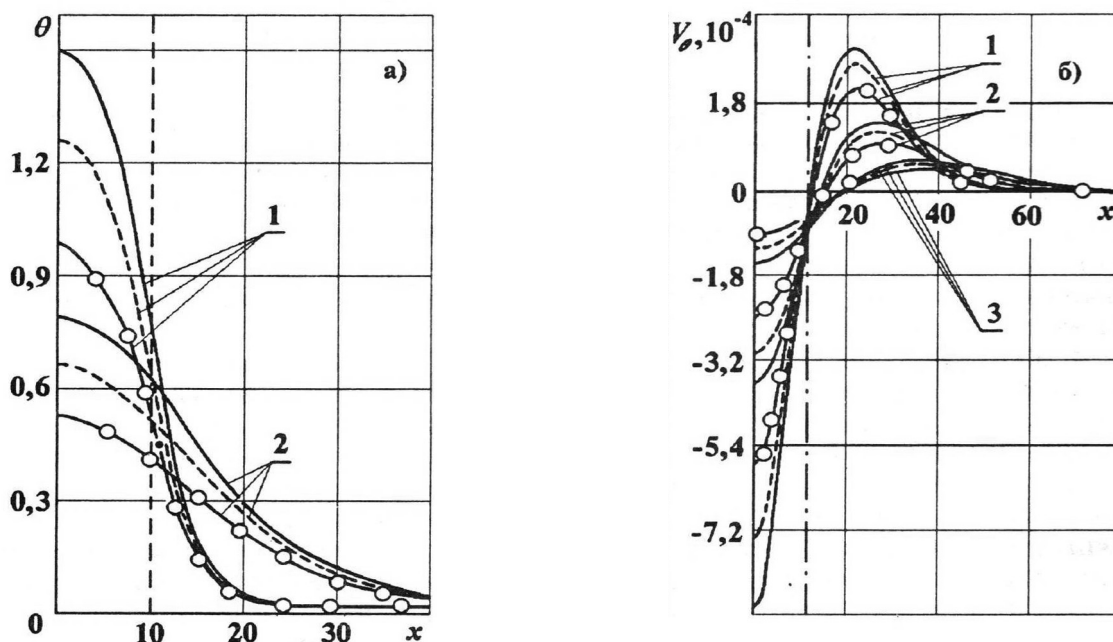


Рис. 1. Розподіл безрозмірної температури (а) та швидкості зміни температури (б) по товщині двошарової системи «частинка із сплаву $\text{Fe}_{83}\text{B}_{17}$ — стальна основа» при товщині частинки $\delta_1 = 10,0$ для різних значень початкової температури частинки θ_{1_0} ; пряма лінія $\theta_{1_0} = 1,52$; штрих пунктирна лінія $\theta_{1_0} = 1,28$; пряма лінія з кружечком $\theta_{1_0} = 1,0$ (варіанти розрахунків 1, 2, 3 див. табл. 1); а) — 1 — $Fo = 8,69 \cdot 10^{-13}$; 2 — $Fo = 4,345 \cdot 10^{-12}$; б) — 1 — $Fo = 4,345 \cdot 10^{-11}$; 2 — $Fo = 8,69 \cdot 10^{-11}$; 3 — $Fo = 1,738 \cdot 10^{-10}$

Рисунок 1а) ілюструє розподіл безрозмірної температури у системі в фіксовані проміжки часу для різних значень θ_{1_0} . Як видно з рисунку в усіх точках області, що розглядається, виключаючи незбурену зону в основі, менші значення θ_{1_0} відповідають нижчій температурі.

На рисунку 1б) наведено розподіл швидкості зміни температури V_θ ($V_\theta = \partial\theta / \partial Fo$) по товщині двошарової системи для різних значень θ_{1_0} . Згідно з отриманими даними зі зростанням початкової температури частинки збільшуються абсолютні

значення швидкості V_θ в частинці. При цьому на загальний характер залежності $V_\theta = V_\theta(x)$ рівні початкової температури покриття не впливають.

Величина θ_{1_0} впливає також і розташування границь незбуреної зони в основі. Наприклад, для $Fo = Fo_{III}$ при $\theta_{1_0} = 1,52$ значення $\Delta x_n = 160,8$ при $\theta_{1_0} = 1,0$ воно становить 293,0.

Проведені дослідження показують, що тепловий стан системи «напилювана частинка-основа» суттєво залежить від рівня температури нагріву розпиленої частинки.

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ТЕМПЕРАТУРНІ РЕЖИМИ БАГАТОШАРОВОЇ СИСТЕМИ ПРИ ВАРІЮВАННІ ДИСТАНЦІЇ НАПИЛЕННЯ

TEMPERATURE CONDITIONS OF THE MULTILAYER SYSTEM WHEN VARYING THE SPRAYING DISTANCE

Анотація. В роботі розглянуто закономірності впливу дистанції напилення на тепловий стан системи «багатошарове покриття-підшар-основа».

Ключові слова: система «багатошарове покриття-підшар-основа дистанція напилювання, пляма нагріву.

Summary. The work discusses the regularities of the influence of the spraying distance on the thermal state of the system "multilayer coating-sublayer-base".

Key words: "multilayer coating-sublayer-base" system, spraying distance, heating spot.

Проблеми захисту великогабаритних виробів, які працюють в умовах зносу в агресивних середовищах зберігає свою актуальність і на даному етапі розвитку техніки. Для вирішення даної проблеми широке застосування знаходять способи газотермічного нанесення покриттів на різні вузли тертя які працюють без самозмащування, а також в умовах граничного тертя [1–8].

Розглядається тривимірна нестационарна задача теплопровідності для багатошарової системи. При цьому основними були такі передумови. Джерело тепlopідводу вважається рухомим із постійною швидкістю у відповідності з рухом плазмотрону. Розподіл теплового потоку в плямі нагріву передбачається таким, що відповідає закону Гауса. Зростання товщини покриття після одного проходу плазмотрона не враховується. Постановка задачі ставиться в лінійній формі. Всі обмежені поверхні багатошарової системи, виключаючи поверхню тепlopідводу, приймаються адіабатними.

Робота присвячена впливу дистанції напилення l_p на тепловий стан системи «багатошарове покриття-підшар-основа». Дослідження проводились в широкому діапазоні зміни параметра l_p ($0,05 \leq l_p < 0,15$ м). Нижче наводяться дані обчислювальних експериментів, які відповідають значенням l_p : $l_p = 0,05$; $0,1$ м і $0,15$ м.

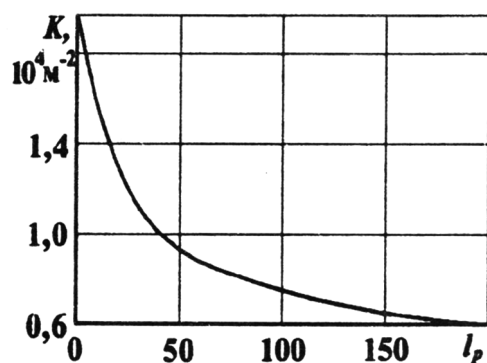
Зміна дистанції напилення l_p пов'язана із зміною коефіцієнта зосередженості теплового потоку k та ефективного коефіцієнта корисної дії (ККД) нагріву виробу цим потоком η . Вихідні дані $k = 2 \cdot 10^{-4}$ $1/\text{м}^2$, $\eta = 23\%$ при $l_p = 0,05$ м, $k = 0,95 \cdot 10^{-4}$ $1/\text{м}^2$, $\eta = 14\%$ при $l_p = 0,1$ м і $k = 0,73 \cdot 10^{-4}$ $1/\text{м}^2$, $\eta = 9\%$ при $l_p = 0,15$ м (див. рис. 1а) та б)). Розподіл безрозмірної густини підведеного теплового потоку $\bar{q}$

по плямі нагріву, визначається величинами k та η при розглянутих дистанціях напилення l показано на рис. 2а). Тут $\bar{q} = q / q_{\max}^*$, де $q_{\max}^*$ — максимальне значення густини теплового потоку при $l_p = 0,05$ м; величини $q_{\max}^*$ для всіх дистанцій напилення знаходились за співвідношенням $q_{\max}^* = Q / (\pi \cdot r_0^2)$, де Q — потужність теплового потоку; $Z = z_p / r_0$; $l = l_p / r_{0\min}$, $\bar{r}_0 = r_0 / r_{0\min}$, де $r_{0\min}$ — радіус плями нагріву при $l_p = 0,05$ м.

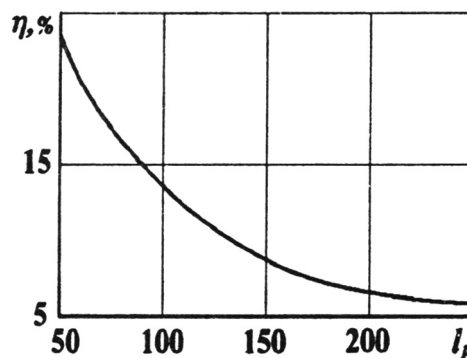
Для з'ясування впливу закономірностей коефіцієнта зосередженості теплового потоку k і ефективного ККД η — доцільним є розгляд деякої гіпотетичної ситуації, в якій зі зміною дистанції напилення змінюється тільки ефективний ККД нагріву η , коефіцієнт зосередженості k залишається незмінним. Розподіл щільності підведеного теплового потоку $\bar{q}$ при $\bar{r}_0 = 1$ для різних l , що відповідає даній ситуації ілюструє рис. 3.

Як видно із рисунку в 3 зоні, яка прилягає до максимуму тепlopідводу температурні рівні системи тим вище, чим менша дистанція напилення l . Причому велику роль відіграє збільшення плями нагріву зі збільшенням величини l . Для незмінних розмірів плями нагріву ефект зміни температурних рівнів при варіюванні дистанції напилення є менш суттєвим (зіставлення суцільних і пунктирних ліній на графіках відповідають фактичній і гіпотетичній ситуаціям).

Аналізуючи закономірності зміни температури на поверхні тепlopідводу слід відмітити також, що з віддаленням від місцезнаходження максимуму температурної функції $\theta^* = f(z)$ відмінності температур відносяться до різних дистанцій напилення (лінії 1, 2, 3 на рис. 3) помітно змінюються. Перед джерелом плазмового нагріву (по ходу його руху)

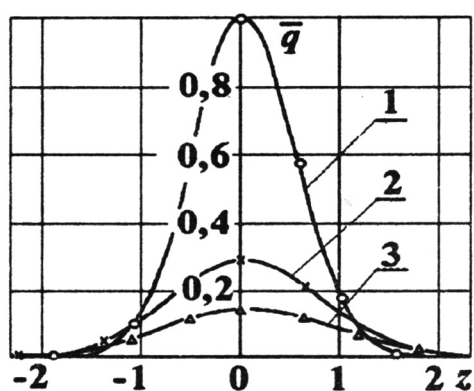


а)

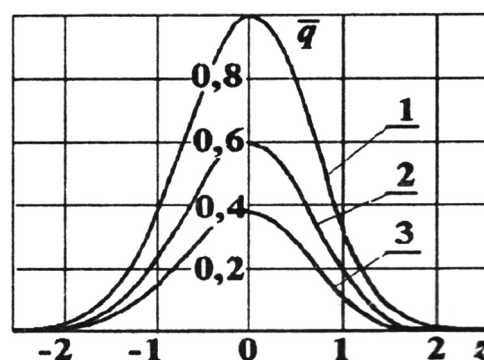


б)

Рис. 1. Залежність від дистанції наплення l : а) коефіцієнта зосередженості питомого теплового потоку двофазного струменя K ; б) ККД нагріву виробу двофазним струменем η



а)



б)

Рис. 2. Розподіл густини підведеного теплового потоку: а) при різних дистанціях наплення: 1 — $l = 7,07$ ($\bar{q}_{\max} = 1$, $\bar{r}_0 = 1$); 2 — $l = 14,14$ ($\bar{q}_{\max} = 0,29$, $\bar{r}_0 = 1,45$); 3 — $l = 21,21$ ($\bar{q}_{\max} = 0,143$, $\bar{r}_0 = 1,65$); б) при $\bar{r}_0 = 1$ для ефективного ККД нагріву виробу двофазним струменем, що відповідає різних дистанціях наплення: 1 — $l = 7,07$ ($\eta = 23\%$); 2 — $l = 14,14$ ($\eta = 14\%$); 3 — $l = 21,21$ ($\eta = 9\%$)

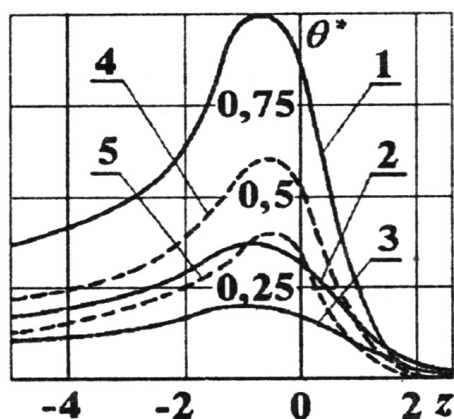


Рис. 3. Розподіл температури θ^* вздовж осі z в шарувато-неоднорідній системі «одношарове покриття-підшар-основа» при різних дистанціях наплення: 1 — $l = 7,07$ ($\bar{q}_{\max} = 1$, $\bar{r}_0 = 1$); 2 — $l = 14,14$ ($\bar{q}_{\max} = 0,29$, $\bar{r}_0 = 1,45$); 3 — $l = 21,21$ ($\bar{q}_{\max} = 0,143$, $\bar{r}_0 = 1,65$); 4, 5 — дані, що відповідають $\bar{r}_0 = 1$ та ефективному ККД нагріву виробу двофазним струменем, який відповідає дистанції наплення $l = 14,14$ і $21,21$

вбачається інверсія зіставлених температурних кривих. Останнє зумовлене тим, що при підвищенні дистанції наплення l має місце росту плями нагріву. Це підтверджується тим, що в випадку відміченої вище гіпотетичної ситуації, коли розміри плями нагріву $\bar{r}_0$ залишаються постійними незалежно від дистанції наплення, ефект вказаної інверсії не спостерігається.

ДОДАТКОВА ІНФОРМАЦІЯ

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