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From Governance to Ground-Level Outcomes: How Corporate Governance of Information Systems Shapes Public-Sector Service Delivery in South Africa

A. Latchu[1]
S. Singh[2]
[1] University of South Africa (UNISA) (Pretoria, South Africa)
[2] Cape Peninsula University of Technology (Cape Town, South Africa)

Abstract

Corporate governance of information systems (IS) is institutionalized across most parts of the public sector in South Africa, yet its practical implications for service delivery remain underexplored. Previous ICT governance literature has primarily focused on governance systems, institutional limitation, procurement infrastructure, and leadership agency. This paper shifts the focus to the service-delivery implications of IS governance. The study draws on qualitative data from 55 Government Information Technology Officers (GITOs) across national, provincial, and local government to examine how governance arrangements affect service timeliness, system reliability, organizational adoption, and operational continuity. The findings suggest that IS governance functions as an indirect conditioning factor shaping service delivery, particularly through delays in implementation, compliance-driven processes, and uneven institutional capability. At the same time, well-implemented and embedded governance practices can facilitate greater service stability and coordination. By linking ICT governance to tangible service delivery outcomes, the article contributes a downstream perspective to information systems governance research in developing-country context.

Keywords: ICT governance, public-sector service delivery, information systems governance, digital government outcomes, corporate governance of ICT

For citation:

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从治理到实际成效：信息系统企业治理如何影响南非公共服务供给

A. Latchu[1]
S. Singh[2]
[1] 南非大学 (UNISA)（南非，比勒陀利亚）
[2] 开普半岛理工大学 (CPUT)（南非，开普敦）

摘要
信息系统的企业治理在南非公共部门已广泛制度化，然而其对公共服务供给的实际影响尚未得到充分研究。现有关于信息与通信技术治理的研究主要集中于治理结构、制度性约束、采购机制以及领导力的作用。本文将关注点转向信息系统治理对服务供给的后果。研究基于定性数据，通过对国家、省级与地方层面55名政府信息技术领域管理者的访谈获得。研究结果表明，信息系统治理由于实施延迟以及不均衡的制度能力，作为影响服务供给质量的间接因素发挥作用。与此同时，已实施的治理实践也可能促进服务供给的稳定性与协调。本文将信息与通信技术治理与服务供给结果相联结，为公共部门信息系统治理研究做出了贡献。
关键词：信息与通信技术治理、公共服务供给、信息系统治理、数字政府成效、公共部门信息与通信技术治理

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Introduction

Corporate governance of information systems (IS) has become a defining feature of public-sector administration in many developing and developed countries. In South Africa, a dense architecture of legislative, regulatory, and policy instruments governs how information systems are planned, procured, managed, and overseen across government entities. These governance arrangements are intended to promote accountability, transparency, risk management, and alignment between digital investments and public-sector mandates. As a result, corporate governance of IS is now formally embedded across national, provincial, and local government institutions.

Academic research has responded to this institutionalization by examining multiple dimensions of public-sector ICT and IS governance. The literature spans governance design and framework alignment, leadership and executive involvement, compliance regimes, audit findings, and governance failure. Across these areas, studies address bureaucratic complexity, procurement processes, and accountability arrangements in relation to ICT performance. This body of research has been particularly useful in highlighting the gap between the formal intentions of governance arrangements and their practical effects.

However, much of the existing literature stops short of addressing a critical downstream question. While governance structures, behaviors, and failures are well documented, comparatively limited empirical insight exists into how corporate governance of IS affects service delivery at the ground level. Governance is often analyzed as an object of design or critique, rather than as a conditioning force whose consequences are reflected in service timeliness, reliability, relevance, and sustained operational capability. This creates an important gap in public-sector and information-systems scholarship: governance is assumed to matter, but its observable effects on service delivery outcomes remain insufficiently examined.

This gap is particularly consequential in the South African public sector, where information systems support a wide range of core service-delivery functions, including social assistance, healthcare administration, education, licensing, financial management, and regulatory oversight. When system implementation is delayed, platforms are unstable, or systems are poorly aligned with user needs, the consequences extend beyond technical performance or governance compliance. In practice, these conditions shape how public services are accessed and delivered, influencing day-to-day interactions between citizens and public institutions. Examining how governance arrangements are reflected in service-delivery experiences provides a clearer basis for assessing the practical significance of corporate governance of information systems.

This article focuses on the service-level consequences of corporate governance related to information systems. Rather than re-examining governance frameworks, leadership behaviors, or causes of failure, the analysis explores how corporate governance of IS is reflected in public-sector service delivery in practice. Drawing on qualitative evidence from senior ICT leaders across South African public-sector entities, the study examines service delivery across several outcome dimensions, including timeliness and throughput; system reliability and continuity; relevance and

citizen value; organizational capability and adoption; and cases where embedded governance practices are associated with more positive service outcomes.

The analysis considers how governance arrangements shape the pace, reliability, and practical use of digital services, as well as in internal control and compliance practices. The focus remains on the everyday conditions under which public services are delivered.

1. Literature Review: Governance and Service-Delivery Outcomes

Information systems play a critical role in facilitating the provision of administrative services, regulatory activities, and citizen-facing services in the public sector. Within contemporary public administration, these systems function as core operational infrastructures through which governments implement mandates, manage resources, and engage with citizens [Twizeyimana, Andersson, 2019]. Their performance therefore has practical implications for public service delivery, including speed, reliability, accessibility, and perceived value.

1.1. Information Systems and Public-Sector Service Delivery

Digital government research situates information systems within the broader context of service delivery, emphasizing their embedded role in operational practice and their active use in administrative processes. Prior studies document improvements in processing speed, interdepartmental coordination, data quality, and service responsiveness when digital platforms are integrated into routine administrative work [Twizeyimana, Andersson, 2019; Enaifoghe, Ndebele, 2023]. In a developing-country context, this body of research often links information systems to service access in settings characterized by limited administrative capacity and sustained demand for public services.

At the same time, empirical studies emphasize that service-delivery outcomes associated with digital systems vary across institutional and organizational contexts. As [Mojaki et al., 2025] note, although digital systems are frequently introduced to improve speed and efficiency, their impact is often constrained by institutional factors that delay implementation and limit practical use. [Ngcobo, Conradie, 2024] identify similar patterns, observing that service-delivery challenges often stem not from technological shortcomings, but from systemic conditions that slow the deployment and operational integration of information systems within public institutions. Taken together, these studies suggest that information systems alone do not guarantee improved service delivery, highlighting the importance of the institutional environments in which they are governed and used.

1.2. Governance as an Indirect Conditioning Force

Across the digital government and public administration literature, governance is more often treated as a contextual condition than as a primary object of analysis. It typically appears as an institutional backdrop shaping how information systems are introduced, resourced, and overseen, with implications for the pace and reliability of service delivery. In public-sector settings, governance arrangements influence approval processes, resource allocation, accountability mechanisms, and risk oversight, thereby affecting how system-enabled services operate in practice [Fourie, Malan, 2020].

Studies of public procurement emphasize the role of procurement processes in shaping service-delivery conditions. Public procurement refers to the procedures through which government institutions acquire goods and services [Ngcobo, Conradie, 2024]. Research highlights delays in project implementation and instances of budget underspending in contexts characterized by multiple approval requirements [Ambe, Badenhorst-Weiss, 2012; Mojaki et al., 2025].

In the South African public sector, similar delays have been observed in the delivery of infrastructure and digital services, particularly where procurement practices prioritize procedural compliance [Ngcobo, Conradie, 2024]. These findings are reinforced by the literature on ICT-related procurement. According to [Latchu, Singh, 2025b], both centralized and decentralized ICT procurement arrangements have contributed to longer project initiation periods across government departments, directly affecting service-delivery timelines. Similarly, [Mkhonza, Mpungose, 2025] identify governance inefficiencies and bureaucratic procedures within ICT procurement systems as key factors contributing to delayed system implementation. Collectively, these studies indicate that governance mechanisms influence service delivery indirectly by shaping the speed and throughput of information systems procurement and deployment.

1.3. Reliability and Continuity of IS-Enabled Services

System reliability and continuity of service delivery in the public sector are also well established in the literature. Public services in areas such as social assistance, healthcare administration, education, and public finance rely on information systems that are expected to operate in a stable, secure, and consistent manner [Dempsey et al., 2024]. The literature documents disruptions to information systems—including cyber incidents, control weaknesses, and operational oversight challenges—alongside interruptions in service provision.

Research on ICT governance in South Africa similarly addresses ICT risk management in relation to the reliability of services delivered through information systems. [Nxozi, Flowerday, 2021] report that weak ICT controls and poor corporate governance increase system vulnerability and are a frequent source of adverse audit findings, thereby undermining service continuity. Where risk management procedures are integrated into the day-to-day operation of governing processes, organizations report fewer system failures and more stable performance [Dempsey et al., 2024].

Auditor-General—based analyses provide additional insight into how ICT governance issues are reflected in service delivery. [Latchu, 2022] documents recurring ICT governance weaknesses across public entities, including gaps in disaster recovery planning, security controls, and skills capacity, alongside reported service-delivery challenges. In this body of literature, governance is conceptualized not as a performance outcome, but as the institutional framework within which information systems operate and through which sustained service delivery is enabled.

1.4. Relevance, Adoption, and Citizen Value

The literature also addresses the relevance and use of information systems in relation to service delivery. Digital government studies conceptualize citizen value in terms of alignment between information systems and service mandates, as well as their use by officials and service users [Twizeyimana, Andersson, 2019]. Other studies note that systems introduced primarily for compliance or reporting purposes tend to be less integrated into routine service-delivery practices.

South African empirical research highlights misalignment between governance arrangements and operational practice. [Latchu, Singh, 2024a] document the persistence of institutional governance forms during the period of state capture, alongside institutional paralysis and underutilized information systems. In related work, [Latchu, Singh, 2024b] describe fragmented control arrangements and audit-oriented compliance practices, combined with limited organizational attention to system adoption and service outputs.

These findings are reflected in broader public administration scholarship. [Shibambu, 2024] reports high failure rates of digital initiatives to generate citizen value in contexts where governance is reduced to symbolic compliance rather than operational enablement. Conversely, digital systems are more likely to enhance accessibility, transparency, and responsiveness in public services where governance arrangements promote alignment, enforcement, and meaningful use [Naguib et al., 2024].

1.5. Capability, Resources, and Change Uptake

Capability constraints are frequently discussed as part of the broader context in which service delivery occurs. Studies of South Africa's public sector document persistent shortages of ICT skills, limited organizational capacity, and constrained resources [Albertus, Hamman-Fisher, 2021; Enaifoghe, Ndebele, 2023]. These constraints have implications not only for system development, but also for subsequent use, maintenance, and long-term sustainability.

Several studies examine resource and skills limitations in relation to the uptake of information systems in the public sector. [Latchu, Singh, 2025a] describe cases in which limited internal capability coincided with increased reliance on external vendors in public-sector ICT initiatives. In a municipal context, [Mudzunga et al., 2025] report capacity limitations and project governance challenges in ICT initiatives, including instances of stalled or underperforming ICT-enabled services.

Across this body of work, governance arrangements are discussed in terms of how resources are allocated, skills are developed, and organizational change is managed in practice. Some studies describe contexts in which attention to capability development and system uptake corresponds with more sustained and effective use of information systems. In contrast, other accounts highlight instances where limited capability support is associated with underutilized systems, even where formal governance and compliance structures are in place.

1.6. Synthesis and Gap Identification

Taken together, the literature suggests that corporate governance related to information systems exerts a significant—yet largely indirect—influence on public-sector service delivery. Governance shapes the institutional conditions under which information systems are procured, implemented, stabilized, and used, thereby affecting service timeliness, reliability, relevance, and adoption.

Much research in public-sector management focuses on governance structures, leadership dynamics or compliance mechanisms rather than on service-delivery processes themselves. Although governance is widely acknowledged as important, fewer studies systematically examine how governance conditions are reflected in service-delivery outcomes at the ground level. As a result, service delivery is often treated as an implied consequence of governance arrangements rather than as an outcome examined in its own right.

2. Research Design and Method

This study adopts a qualitative interpretive research design to examine how corporate governance of information systems shapes ground-level public-sector service delivery outcomes. A qualitative approach is appropriate given the study's focus on how governance conditions are experienced and interpreted by senior ICT leaders responsible for the design, operation, and oversight of information systems within public-sector organizations. Rather than measuring governance effectiveness or institutional compliance, the analysis foregrounds observable service-delivery effects as reported by participants embedded within organizational contexts.

2.1. Data Source and Participants

The empirical material draws on 55 semi-structured interviews conducted with senior ICT leaders across South Africa's public sector. Participants included Government Information Technology Officers (GITOs), Chief Information Officers (CIOs), and senior ICT directors operating at national and provincial levels, as well as within public-sector organizations. These roles were selected because of their direct responsibility for information systems that underpin administrative processes and service-delivery functions. Participants were therefore well positioned to reflect on how governance conditions translate into practical service outcomes.

The interview dataset was originally generated as part of a broader doctoral study on corporate governance and information systems in the South African public sector. For the purposes of this article, only interview segments relevant to the present research focus were extracted and analyzed. Material relating to governance design, leadership behavior, procurement mechanisms, or institutional reform was included only if it directly informed service-delivery outcomes.

2.2. Analytical Scope and Coding Strategy

To maintain clear analytical separation from prior research questions, the analysis employed an RQ6-specific coding lens. Coding and interpretation were explicitly confined to outcome-oriented dimensions identified in the RQ6 framework, namely: service timeliness and throughput; system reliability and continuity; relevance and citizen value; organizational capability and adoption; and observable service-delivery outcomes. Codes related to governance instruments, executive agency, compliance

mechanisms, or causes of governance failure were deliberately excluded from the analytical frame.

Thematic analysis followed an interpretive and inductive approach, allowing patterns in service-delivery outcomes to emerge from the data while remaining bounded by the study's outcome-focused scope. Interview transcripts were examined for recurring references to how information systems affected day-to-day service delivery, operational stability, and user experience. Where governance was referenced, it was treated as contextual background rather than as an explanatory variable in its own right.

2.3. Analytical Positioning

It is important to emphasize that this article does not seek to explain why governance arrangements succeed or fail, nor does it evaluate the effectiveness of specific governance frameworks or leadership practices. Instead, the analysis is deliberately limited to examining effects rather than causes. The study explores how governance, as enacted within organizational settings, conditions service-delivery outcomes without attributing causality or advancing reform-oriented prescriptions.

By constraining the analytical focus in this way, the study maintains methodological consistency with its outcome-oriented contribution while avoiding duplication with existing governance-focused research. This positioning enables a clear examination of service-delivery consequences associated with information systems governance, without re-analyzing governance structures, leadership behavior, or institutional design.

3. Findings: Governance Effects on Service Delivery

The findings reveal how corporate governance of information systems shapes public-sector service delivery in practice. They are structured around five outcome-oriented themes that capture how governance conditions influence service timeliness, reliability, relevance, capability uptake, and positive delivery effects. Governance is treated as an enabling or constraining context, while service delivery remains the analytical foreground.

3.1. Timeliness and Throughput

Across the interviews, participants consistently described service-delivery delays as a visible consequence of governance-linked approval and procurement cycles. These delays were experienced not as abstract administrative inefficiencies, but as concrete disruptions to service throughput, budget utilization, and operational schedules.

Respondents frequently attributed delays to the centrally controlled model of ICT procurement. One participant stated: "SITA causes service delivery delays" (Interview 6). Others emphasized prolonged and uncertain procurement cycles, noting that "procurement through SITA takes anything between 1.5 to 3 years or longer" (Interview 46). Delays in approval processes were described as placing projects at risk, affecting start dates and extending overall timelines.

The complexity of governance across multiple oversight bodies was also identified as a contributing factor. Interview 14 explained that "procurement processes are very long and confusing… PFMA really impedes the organization," highlighting how differing interpretations of the Public Finance Management Act, National Treasury regulations, and SITA requirements constrain procurement processes. These dynamics resulted in delays, budget freezes, and underspending, compounded by shortages of ICT skills. Interview 27 described procurement and implementation as "a nightmare… which stems from the interpretation of the rules, particularly between SCM and IT."

Delays in claim approval were similarly linked to budget underspending and operational penalties. Interview 35 reported that "the Office is unable to spend its operating budget due to long procurement processes," while Interview 32 noted that "renewal of licences has been delayed with imminent penalties… which impacts organizational operations." In these cases, governance-induced delays translated directly into constrained service throughput, deferred functionality, and increased organizational risk.

3.2. Reliability and Continuity

Participants described service reliability as closely tied to the extent to which ICT risk management was embedded within governance routines and supported by stable leadership representation. Where governance structures actively monitored ICT risk, respondents reported more reliable system performance.

Interview 44 noted: "The committees are also very helpful in terms of helping steer the ICT unit and ensure that critical digitization and security investments are approved and holding ICT accountable for mitigating risks to an acceptable risk level and provide assurance." Similarly, Interview 38 reported: "Adoption of robust risk management frameworks and controls has reduced adverse events… I think we could enhance AGSA audits by having midyear compliance checks to spot risks early."

Respondents also linked continuity challenges to unstable ICT leadership representation. Interview 50 explained: "Prior to the merger the entity supported by aligning with the DPSA guidelines of having CIO IT representatives at EXCO. Now due to a merger this has halted but occasional representations are allowed." The same participant added: "CIO is fatigued as she has had many discussions with EXCO and the AGSA themselves but fails to get support from them. She feels that they still see ICT as a back-office support."

These accounts illustrate how governance arrangements influence whether IS-enabled services remain reliable and continuous over time.

3.3. Relevance and Citizen Value

Participants distinguished between information systems actively used to support service delivery and those implemented primarily to satisfy governance or audit requirements. Where governance emphasized formal compliance without ensuring meaningful use, systems were perceived as delivering limited service value.

Interview 22 observed: "Often, there is a gap between the IS environment and top management, either through lack of representation at executive level or through a lack of understanding in the executives charged with IS governance. This disjuncture results in a lack of support for IS programmes." This misalignment was experienced as reducing the practical

relevance of systems intended to support service delivery. Interview 50 similarly noted: "They still see ICT as a back-office support. EXCO should have training to understand digitalisation skills."

These findings suggest that citizen value is realized only when governance arrangements promote active system use aligned with operational service needs, rather than symbolic compliance.

3.4. Capability and Adoption

Capability constraints were repeatedly cited as limiting the adoption and sustainability of information systems, with direct consequences for service delivery. Participants reported significant challenges related to shortages of skilled personnel and limited internal capacity to manage ICT workload.

Interview 11 stated: "Limited resources (personnel) to oversee and execute the function… skills are also scarce." Interview 24 noted that governance and skills gaps intersect within procurement and implementation processes: "With SCM and NT guidelines involved, it slows down the delivery of IS. Having a specialist IT in SCM would assist."

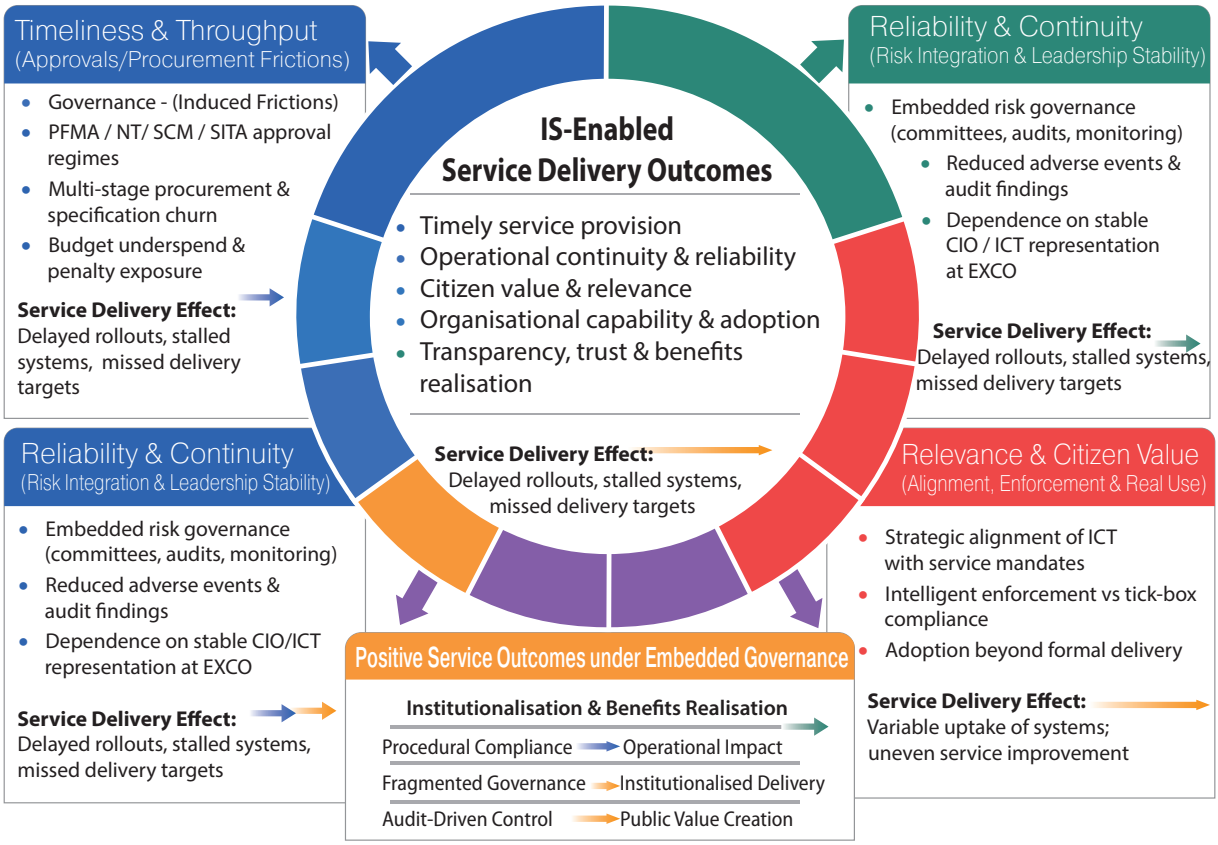
These constraints affected not only system implementation but also ongoing adoption and effective use, limiting the extent to which information systems could support sustained service delivery.

3.5. Positive Service Outcomes under Embedded Governance

Despite all these challenges, respondents identified situations in which embedded governance arrangements contributed to improved service delivery. In such cases, governance structures were described as actively supporting ICT risk management, accountability, and benefits realization.

Interview 33 reported: "The framework reduced ICT risk and made it more manageable; our audit findings decreased substantially since the governance system was introduced. The audit committee ensures proper governance, risk management and benefits realisation." Interview 38 similarly noted broader organizational benefits: "These governance structures have helped IS effectively identify, assess, and report on risks… The improved IS reputation has enhanced stakeholder perceptions of the IS department and the organisation."

These accounts illustrate the type of positive service outcomes associated with governance that is embedded and enacted in practice, without prescribing specific governance reforms or leadership interventions. The accompanying figure provides a descriptive synthesis of the service-delivery outcomes identified across the five themes. It consolidates observed outcome patterns associated with the enactment of information systems governance and does not represent a governance framework or causal model.



Source: prepared by the authors.

Fig. Descriptive Synthesis of Observed Public-Sector Service-Delivery Outcomes Associated with Corporate Governance of Information Systems

4. Discussion

The figure summarizes the empirically observed service-delivery outcomes reported by participants and serves as a descriptive reference point for the discussion that follows. Taken together, the findings indicate that corporate governance of information systems does not function merely as a distant compliance layer; rather, it is experienced through its consequences for everyday service delivery. What emerges is not a binary distinction between "good" and "bad" governance, but a patterned set of outcomes shaped by how governance is enacted, sustained, and embedded in organizational practice.

Across the five themes, a consistent pattern is evident: governance arrangements shape service delivery primarily through timing, stability, usability, and organizational readiness, rather than through formal adherence to rules or structures. Delays in approvals, procurement, and budget execution were described not as isolated administrative issues, but as cumulative constraints that slowed service throughput, disrupted operational planning, and increased financial and reputational risk. In this sense, timeliness emerges as a core service-delivery dimension through which governance is most immediately experienced by both officials and service users, echoing prior observations that administrative and digital processes are central to public value realization in government services [Twizeyimana, Andersson, 2019].

Reliability and continuity provide further insight into how governance conditions are reflected in service delivery without being framed as direct causal mechanisms. Participants did not attribute system stability to specific governance instruments; instead, they emphasized whether ICT risk oversight was sustained over time. In participant accounts, inconsistent governance attention—often associated with leadership turnover or limited executive engagement—was linked to unstable and reactive service delivery. Conversely, respondents described greater system stability in contexts where ICT controls were routinely monitored through audit and committee processes. Similar patterns have been documented in public-sector studies focused on risk management and audit practices in relation to information systems [Dempsey et al., 2024].

Accounts relating to relevance and citizen value highlight variation in how information systems were experienced within service-delivery settings. Although information systems were widely implemented across organizations, their practical contribution differed. Systems introduced primarily to satisfy reporting or compliance requirements were frequently described as underused or bypassed in day-to-day operations, with limited perceived service value. In contrast, participants reported improvements in turnaround times, service responsiveness, and user confidence where governance arrangements supported closer alignment between system functionality and operational needs. Digital government research similarly conceptualizes public value as emerging from the effective use of systems aligned with service mandates, rather than from the mere availability of technological infrastructure [Twizeyimana, Andersson, 2019; Enaifoghe, Ndebele, 2023].

Participant accounts concerning capability and adoption describe organizational conditions within which information systems are sustained in practice. Skills shortages, resource constraints, and limited internal capacity were framed not merely as technical challenges, but as structural features of the organizational environment. In several accounts, systems were reported as technically delivered but only weakly adopted, with limited internal capability constraining their use in service-delivery activities. Comparable patterns have been reported in South African public-sector studies documenting capacity limitations and supervisory weaknesses alongside poor digital project performance and service delays [Albertus, Hamman-Fisher, 2021; Ngcobo, Conradie, 2024].

The findings also indicate that governance can be associated with improved service delivery in certain contexts. Where governance was embedded, visible, and accompanied by sustained oversight and engagement, participants described improvements in transparency, system performance, and confidence in service provision. These outcomes were discussed in relation to everyday organizational routines rather than to specific governance frameworks or leadership styles. Related work [Latchu, Singh, 2024a] similarly identifies instances of symbolic compliance coexisting with limited operational enactment of governance arrangements.

Collectively, these patterns position service delivery as the arena in which governance arrangements are encountered in practice. Much of the public-sector and information-systems literature, by contrast, treats governance mechanisms, compliance regimes, or leadership roles as distinct analytical concerns. The analysis presented here instead examines how governance is reflected in observable service-delivery dimensions such as timeliness, reliability, relevance, capability, and realized service outcomes. By focusing on these observable effects rather than on explanatory causes, the study offers a closer examination of how governance enactment manifests in the everyday performance of public-sector services.

The discussion remains grounded in service-delivery outcomes, drawing on the accounts of senior ICT leaders responsible for systems that support public-sector operations. In doing so, it situates the findings within existing governance scholarship on public-sector information systems without re-examining its primary analytical debates.

5. Implications

This study has implications for both scholarship and practice by clarifying why corporate governance of information systems matters beyond formal compliance and institutional design. By foregrounding service-delivery outcomes, the analysis shifts attention to the practical consequences through which governance is experienced in public-sector organizations.

5.1. Theoretical Implications

The findings extend the ICT governance literature by shifting the analytical focus from governance structures, mechanisms, and intentions to governance consequences as experienced through service delivery. Much of the existing literature evaluates governance in terms of framework adoption, compliance maturity, leadership roles, or institutional

alignment. While these perspectives remain valuable, they provide limited insight into how governance is translated into everyday operational performance.

By demonstrating how governance conditions service timeliness, reliability, relevance, capability uptake, and realized service outcomes, this study introduces an outcome-oriented lens to ICT governance research. Governance is shown to be neither inherently enabling nor constraining; rather, its significance lies in the service-delivery conditions it produces when enacted in practice. Service delivery is positioned as a reference point through which governance arrangements can be observed in operation. In this framing, governance is examined in terms of how it is enacted and sustained within organizational settings, rather than as a set of formal institutional artifacts alone. Attention to observable service-delivery outcomes allows governance to be assessed through its practical manifestation and organizational persistence, without advancing causal claims or reform-oriented prescriptions.

5.2. Policy and Practice Implications

From a policy and practice perspective, the findings highlight the risks associated with outcome-blind governance in the public sector. Governance arrangements that prioritize procedural compliance without sustained attention to service-delivery effects may achieve formal legitimacy while producing uneven or fragile operational outcomes. As demonstrated in the findings, delays, instability, underutilized systems, and constrained capability represent not merely governance shortcomings, but tangible service-delivery risks.

The study underscores the importance of outcome-aware oversight, where the performance of information systems is evaluated in relation to service timeliness, reliability, and user value, rather than compliance alone. It does not propose a universal reform model; rather, it emphasizes the need for governance actors to remain attentive to how existing arrangements are experienced at the service-delivery level and to recognize service outcomes as a critical accountability signal.

This perspective has implications for oversight and evaluation practices within public-sector ICT environments, without advancing prescriptive reform agendas.

Conclusion

This study examined how corporate governance of information systems is reflected in public-sector service-delivery outcomes, rather than in governance structures, leadership behaviors, or compliance regimes. Drawing on the accounts of senior ICT leaders, the analysis demonstrates that governance matters most where it shapes the everyday conditions under which services are delivered. Delays, instability, uneven system use, and constrained capability are not abstract governance deficiencies, but experienced service outcomes that affect organizational performance and public value.

The findings reinforce that service delivery represents a central accountability test for corporate governance of information systems. Governance arrangements are experienced as effective or ineffective not through their formal design, but through their consequences for service timeliness, reliability, relevance, and sustained delivery capacity. Where governance is enacted in symbolic or episodic ways, service outcomes tend to be fragile and uneven. Where governance is embedded and sustained within organizational practice, more stable and dependable service outcomes are observed.

The analysis approaches service delivery as the arena in which governance arrangements are encountered in practice, rather than as a set of intended mechanisms or formal designs. In doing so, it situates governance consequences within public-sector digital environments without revisiting questions already addressed in existing ICT governance research.

Future research may examine how governance enactment and service delivery interact across different public-sector contexts. Comparative studies across sectors, spheres of government, or national settings could further illuminate how governance conditions are manifested in service experiences, while remaining attentive to contextual variation and avoiding prescriptive reform assumptions.

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About the Authors

Ashley Latchu
PhD Candidate, University of South Africa (UNISA) (Pretoria, South Africa); Head of IT, Private-Sector Organization (Pretoria, South Africa). ORCID: 0000-0002-5458-2072.
Research interests: information systems, risk and strategy, public-sector information systems, corporate governance in South Africa.
AshleyLatchu@gmail.com

Shawren Singh
PhD, Associate Professor and Head of Department, Graduate Centre for Management, Cape Peninsula University of Technology (Cape Town, South Africa). ORCID: 0000-0001-5038-0724; Researcher ID: N-3092-2014; Scopus Author ID: 56111550100.
Research interests: crime, migration, diaspora studies, feminism and gender issues, criminal justice system.
singhs@unisa.ac.za

作者信息

Ashley Latchu
博士候选人, 南非大学UNISA（南非比勒陀利亚）；私营部门信息技术主管（南非，比勒陀利亚）。ORCID: 0000-0002-5458-2072.
研究兴趣领域：信息系统、风险与战略、公共部门信息系统、南非的企业治理。
ashleylatchu@gmail.com

Shawren Singh
PhD, 副教授，开普半岛理工大学（CPUT）管理学研究生中心,系主任（南非，开普敦）。ORCID: 0000-0001-5038-0724; Researcher ID: N-3092-2014; Scopus Author ID: 56111550100。
研究兴趣领域：犯罪、移民、侨民研究、女权主义与性别问题、刑事司法体系
singhs@unisa.ac.za

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E-Commerce Development Strategy in Nigeria's Economy: Empirical Evidence from the Konga and Jumia Platforms

A.N. Omeje[1]
O. Stumke[1]
D.O. Ezeogo[2]
R. Rena[1]
[1] Durban University of Technology (Durban, South Africa)
[2] University of Nigeria (Nsukka, Nigeria)

Abstract

Nigeria is home to Africa's second-largest e-commerce market. This growth has been driven by innovations in technology, logistics, and online payment systems. This study investigates the impact of e-commerce on the Nigerian economy using Konga and Jumia as case studies. The autoregressive distributed lag (ARDL) model and monthly time-series data for the period 2017M1–2023M12 were employed. The results reveal statistically significant short- and long-run effects of e-commerce on the Nigerian economy through the activities of Konga and Jumia. Specifically, the number of users conducting transactions on Konga and Jumia, telecommunication investment in both the short and long run, and the number of internet users in the short run were found to have a statistically significant effect on Nigeria's economic growth. The study recommends that the government increase investment in telecommunications and improve internet access in order to stimulate e-commerce development, expanding digital trade both domestically and across borders, and promote economic growth.

Keywords: ARDL model, internet users, economic growth

For citation:

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尼日利亚经济中电子商务发展战略：基于Konga和Jumia平台的实证证据

A.N. Omeje[1]
O. Stumke[1]
D.O. Ezeogo[2]
R. Rena[1]
[1] 德班理工大学（南非德班）
[2] 尼日利亚大学（尼日利亚恩苏卡）

摘要

尼日利亚是非洲第二大电子商务市场。该市场的增长得益于技术、物流和在线支付领域创新的应用。本文以 Konga 和 Jumia 平台为例，分析电子商务对尼日利亚经济的影响。研究采用自回归分布滞后模型（ARDL），并使用了 2017 年 1 月至 2023 年 12 月期间的月度数据。研究结果表明，电子商务，特别是 Konga 和 Jumia 平台，在短期和长期内都对尼日利亚经济产生了统计显著影响。对尼日利亚经济增长具有统计显著影响的因素包括：在 Konga 和 Jumia 平台上进行商业交易的用户数量、电信行业投资（无论在短期还是长期）以及互联网用户数量。基于研究结果，建议政府加大对电信行业的投资并扩大互联网覆盖范围，这将有助于促进电子商务、国内和跨境贸易以及经济增长。

关键词： ARDL 模型，互联网用户，经济增长

引用格式：

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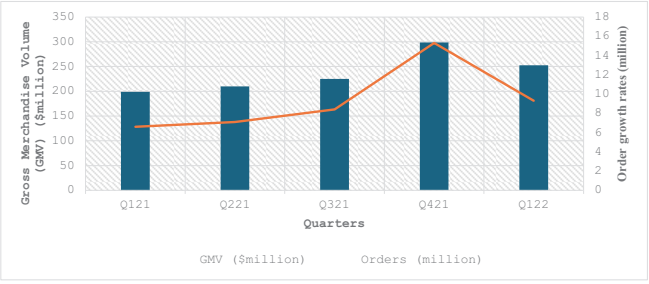
Introduction

The world has increasingly become a global village, where information technology (IT) plays a crucial role in the functioning of the globalized economy [Asogwa, 2013]. The growth of information technology has been widely recognized as influencing economic development either directly or indirectly [Toader et al., 2018]. Consequently, e-commerce has emerged as one of the most prominent applications of information technology. It encompasses methods used in the purchasing, selling, and exchanging of goods and services through computer networks and the Internet, and it has significantly transformed global economic systems [Bitrus, 2019].

E-commerce is crucial for every economy [Bitrus, 2019]. The level of economic growth in a country can, to some extent, be reflected in its response to the development of e-commerce [Oladimeji, Folayan, 2018]. For developing countries in particular, e-commerce has been identified as a significant driver of economic growth, and Nigeria is not an exception [Oladimeji, Folayan, 2018]. Gradually, e-commerce has begun to exert a notable influence on the trading system of national economies. For instance, the COVID-19 pandemic demonstrated that the importance of e-commerce for inclusive economic growth cannot be overstated. During this period, virtual shopping, also known as e-commerce, became one of the most common methods of purchasing groceries, household appliances, mobile devices, electronics, and other products [Janet, 2021].

With revenues of approximately $6.9 billion in 2021, Nigeria ranked 33rd globally in e-commerce engagement, ahead of Denmark and behind Colombia. The Nigerian e-commerce market grew by 30% in 2021, contributing significantly to the global growth rate of 15%. As a result, Nigeria recorded approximately $12 billion in online transaction volume in 2021. In Nigeria, Jumia and Konga were the leading e-commerce platforms during this period. With operations in more than 14 African countries, Jumia is the most widely recognized e-commerce platform in Nigeria. The platform offers a wide range of products, including children's items, home appliances, clothing, electronics, and other products, all of which can be delivered to customers' homes or workplaces. Jumia, a pioneer of Nigerian e-commerce founded in 2012 by Sacha Poigonnec, Raphael Kofi Afaedor, and Tunde Kehinde, generated approximately $22 million in revenue in 2021. By 2024, its revenue had reached approximately $286 million, with projected revenue of about $284 million in 2025. Jumia has given Nigeria's digital industry international recognition, thereby increasing foreign direct investment (FDI) and the sector's contribution to gross domestic product (GDP). In global rankings of internet engagement in business transactions, Jumia was ranked 1,503rd in 2020 and improved to 874th place by 2024. It also became the thirteenth most popular website in Nigeria[1]. Figure 1 illustrates the growth in the number of Nigerians using Jumia for business transactions, measured by order growth rates and gross merchandise volume.



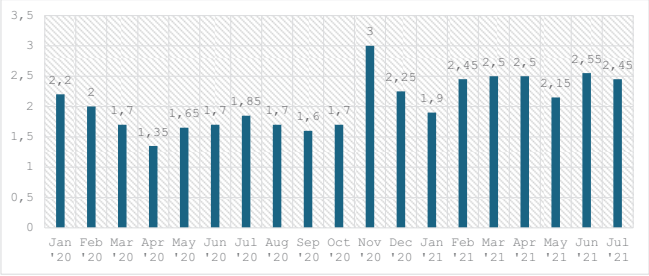
Source: authors' computation using available data from Jumia, 2023.

Fig. 1. Order Growth Rates and Gross Merchandise Volume (GMV) on Jumia from 2021Q1–2022Q1

[1] Jumia Company & Revenue 2014-2026. Ecdb.com. https://ecdb.com/resources/sample-data/retailer/jumia.

Figure 1 indicates that although the number of Nigerians using Jumia for business transactions is increasing, Nigeria has not yet fully capitalized on the opportunities embedded in the e-commerce value chain through this platform. This may be attributed to limited funding, insufficient awareness of business opportunities in the sector, and the government's inability to provide an adequate enabling environment. Through the empowerment of micro, small and medium enterprises (MSMEs), Jumia has significantly contributed to the Nigerian economy. Over the years, the company has provided a marketplace for producers, distributors, and retailers—most of whom are MSMEs—to offer their products and services to consumers. Jumia has also reduced waiting times through its logistics services, which enable merchants to ship and deliver goods efficiently, as well as through its payment services that facilitate interactions among market participants. As a result, Jumia's contribution to economic growth cannot be overstated. By reducing costs associated with marketing, leasing, and operating physical stores, Jumia has improved the viability of MSMEs and contributed to broader economic growth.

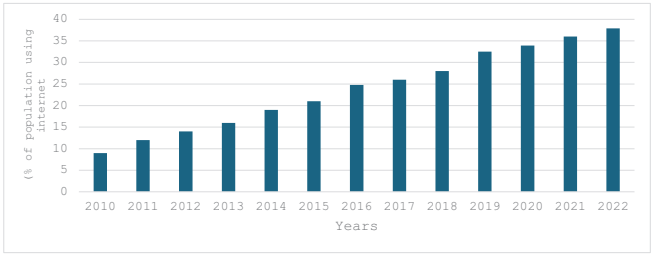
Similarly, Konga plays an important role in promoting inclusive online retail in Nigeria. Konga is among the largest online marketplaces in the country. Founded in 2012 by Sim Shagaya, the company offers a wide variety of products, including personal care items, mobile phones, clothes, shoes, healthcare products, books, home appliances, baby products, computers, and other products. Figure 2 shows that as of July 2021, Konga recorded approximately 2.5 million visits globally, 90% of which originated from Nigeria.



Source: authors' computation using available data from Statista, 2023.

Fig. 2. Konga Monthly Number of Visits from 2020M1–2021M7 (mln)

E-commerce activities in Nigeria have expanded significantly due to increasing investment in telecommunications services [Okolie, Ojomo, 2015]. In addition, the growth of e-markets has further strengthened e-commerce activities in the country. Consequently, the number of individuals accessing the Internet increased considerably between 2010 and 2021, recording growth of approximately 73% in recent years. Figure 3 presents the percentage of individuals using the Internet from 2010 to 2022.



Source: authors' computation using available data from Trading-Economics, 2023.

Fig. 3. Individuals Using the Internet (% of Population) in Nigeria from 2010 to 2022

Figure 3 indicates that the percentage of Internet users in Nigeria increased steadily from 2010 to 2022, reaching approximately 37.9% in 2022. As the twenty-first century progressed, numerous start-ups emerged within the digital economy, many of which target Nigeria's rapidly expanding base of Internet users. At present, Jumia and Konga remain the most prominent e-commerce platforms in Nigeria [Okolie, Ojomo, 2015]. Prior to the emergence of e-commerce, in the economy, consumers faced numerous constraints in traditional business transactions. Traders encountered supply chain bottlenecks, information asymmetry arose due to the presence of intermediaries, and market research required significant time and resources. At present, web-based companies such as Jumia and Konga have become new intermediaries that connect producers and consumers more efficiently.

Information technology has therefore become a key driver of global e-commerce activity. Internet services enable businesses to conduct transactions across national borders regardless of time zone differences. However, the expansion of e-commerce requires reliable technological infrastructure and stable Internet access, which remain limited in Nigeria. Nevertheless, Nigeria has been ranked as the largest and one of the fastest-growing ICT markets in Africa, as well as one of the ten fastest-growing telecommunications markets globally [Oladimeji, Folayan, 2018; Ogbonne et al., 2021]. Between the introduction of Global System for Mobile Communication (GSM) services in 2001 and 2021, the telecommunications sector contributed more than $70 billion to Nigeria's GDP. Innovation in ICT and increasing public awareness have strengthened the sector's role in economic development[2]. According to Nigerian Communications Commission (NCC), the telecommunications sector accounted for 7.7% of GDP in 2012 and increased to 14.3% by the second quarter of 2020[3]. With the exception of a slight decline in 2013, the contribution of telecommunications to GDP remained relatively stable between 2012 and 2020. According to the data, telecommunications contributed 7.7% of GDP in 2012, 7.4% in 2013, and 7.6% in 2014. In 2015, the sector's contribution increased to 8.5% of GDP, followed by 9.13% in 2016. In 2017, telecommunications accounted for 8.7% of GDP, rising to 9.9% in 2018 and 10.6% in 2019. By the second quarter of 2020, the sector's contribution increased to 14.3% of GDP, equivalent

[2] Development of Best Practices in Information Infrastructure Security Management (2021). Nigerian Communications Commission, Department of New Media and Information Security: 1-134. https://ncc.gov.ng/market-data-reports/publications.
[3] Ibid.

to N2.3 trillion, while the overall contribution of the information and communication technology (ICT) sector reached 17.5% during the same period [Olalekan, 2013]. Information and communication technology (ICT) supports the development of the e-commerce sector by creating employment opportunities, automating processes, and and enhancing transparency in various economic activities.

Despite these benefits, the expansion of e-commerce in Nigeria still faces significant challenges. Limited penetration of information technology and the persistence of the digital divide remain major obstacles to the development of the Nigerian e-commerce market [Duncombe, Heeks, 2005]. In Nigeria, there are substantial obstacles preventing the expansion of high-speed Internet access. These obstacles include the legacy of operators investing in private network deployments, which is further exacerbated by poor infrastructure quality and a complex institutional framework responsible for overseeing and promoting the development of ICT infrastructure and the telecommunications sector. Given the high costs of infrastructure development and relatively low profitability, it is difficult to extend market boundaries deeper into underserved areas, which has resulted in market failures. The lack of innovative service offerings is further intensified by the high price sensitivity of the market. Another significant barrier to Internet access in Nigeria is the high cost of broadband-enabled devices for low-income households. Other demand-side constraints include low electrification rates, the lack of locally relevant digital content, and widespread digital illiteracy. Scholars [Duncombe, Heeks, 2005; Toader et al., 2018] have argued that, in order to promote inclusive e-commerce development in Nigeria, a robust digital ecosystem must be created, digital transformation accelerated, and the critical mass of Internet users significantly expanded. Achieving these objectives requires innovative solutions, carefully designed policy interventions, and substantial financial investments. By strengthening the foundations of the digital economy through an ecosystem approach, these measures could encourage the deployment of networks in underserved areas, contribute to the reduction of broadband costs, expand complementary public access to the Internet, and stimulate demand for digital services.

Another major challenge is the large digital literacy gap, which prevents many Nigerians from fully benefiting from e-commerce opportunities. Participation in e-commerce requires digital skills at multiple levels, ranging from basic user literacy to advanced technical capabilities among producers and service providers across industries. Customer loyalty, ease of access, lower operating costs, improvements in traditional market chains, access to niche markets, greater business efficiency, automation of processes, expansion of the customer base, improvements in customer welfare, and customer education are all factors that significantly support the development of e-commerce [Okolie, Ojomo, 2015]. However, several constraints continue to affect the growth of e-commerce in the Nigerian economy. These include concerns related to business privacy and confidentiality, unreliable network availability, high establishment costs, data protection and security risks, credit-card fraud, cybercrime, limited levels of education and income, inadequate technological infrastructure [Ayo, 2011; Okolie, Ojomo, 2015], and concerns about safety in online environments [Omeje et al., 2022a]. Therefore, the primary objective of this study is to examine how e-commerce influences the Nigerian economy, using Konga and Jumia as case studies.

1. Literature Review

The literature review in this study considers both theoretical and empirical perspectives. The study first examines the theoretical literature, followed by empirical literature. These are discussed in the subsections presented below:

1.1. Theoretical Literature

The Diffusion of Innovations theory was developed by Rogers in 1962 [Rogers, 2003; Miller, 2015]. The theory explains how individuals adopt innovations and new technologies in order to perform routine activities more effectively. According to the theory, the key factors determining the adoption of innovations include relative advantage, compatibility, complexity, trialability, and observability [Rogers, 2003]. This theory focuses on the processes through which new technological ideas, methods, and artifacts move from creation to adoption and use. The fundamental concepts of the theory are based on technological innovations that diffuse over time through specific communication channels among members of a social system [Miller, 2015]. According to Rogers, any technological innovation passes through several stages: knowledge (awareness of its existence and understanding of its functions); persuasion (development of a favorable attitude toward it); decision (commitment to adopt); implementation (actual use); and confirmation (reinforcement based on positive outcomes) [Rogers, 2003; Miller, 2015].

The endogenous growth theory was developed in the 1960s with contributions from several prominent economists [Arrow, 1962; Romer, 1986; Lucas, 1988]. The endogenous growth hypothesis explains how internal forces influence long-term economic growth. It is based on the idea that improvements in human capital, knowledge, and innovation increase productivity and thereby contribute to economic growth. According to this approach, the system responsible for the production process determines long-term economic growth rather than external forces. While the theory extends the neoclassical framework by treating technological change as an endogenous outcome of public and private investments in human capital and knowledge-intensive industries (innovation), it maintains that technological advancement remains the primary driver of output growth. The endogenous growth model assumes a constant exogenous savings rate and an endogenous growth rate driven by technological progress. Technological innovation is typically represented by a factor (commonly denoted as A). The production function in this model does not exhibit diminishing returns to scale. According to the endogenous growth theory, aggregate production can increase with scale. When investments in human capital (such as education), research and development, and infrastructure are low, the economic progress of developing countries may be constrained. It is therefore assumed that investments in human capital, infrastructure, health, telecommunications, and education generate higher productivity and external economies that help offset the expected tendency toward diminishing returns.

$$Y = AK^{a+b} L^{1-a}. \quad (1)$$

According to endogenous growth theory, technological progress plays a significant role in productivity growth because it drives technological change, which in turn depends on innovation and human capital that are internal to the economy.

1.2. Empirical Literature

This section examines studies related to the subject of the study. The empirical literature reviewed in this area is divided into foreign and domestic studies.

Some studies by [Alrawashedh et al., 2022] have investigated the effect of procedures and accounting systems on the performance of Jordanian e-commerce businesses. Quantitative data collection methods and descriptive research design were used in this study. The findings revealed that the accounting and financial performance of Jordan's e-commerce sector remains uncompetitive due to the lack of government financial support , low Internet usage rates, and numerous obstacles faced by e-commerce firms in generating profits within the Jordanian market. The study therefore recommended improvements in the country's banking and Internet systems. In a related study, the impact of e-commerce development on the labor market was examined [Banescu, Manea, 2022]. A panel regression model was employed using data from 28 European countries. The results indicated that the model explained approximately 99.5% of the variation in labor market activity rates among individuals aged from 15–64. The findings suggest that the growth of e-commerce and an increase in the share of technology-oriented human capital contribute significantly to higher labor market participation. The study recommended that governments support technological advancement in the labor market by restructuring educational systems and introducing new courses that enhance competitiveness and sustainable development.

The potential of e-commerce in propelling Russian economic expansion was examined by [Karpunina et al., 2021]. Variance, covariance, and correlation analysis were employed in the study. The results indicated that Russia's economic growth patterns were significantly influenced by the emergence of e-commerce. Additionally, the dynamics of e-commerce in Russia during the COVID-19 pandemic demonstrated a notable expansion of the industry, which marked the beginning of a new phase in the country's e-commerce development. [Ibiam et al., 2017] examined the impact of e-commerce in Africa, using Nigeria as a case study and applying an ex post facto research design. The study employed an ex-post facto research design. The findings showed that although e-commerce has benefited African economies, a major challenge affecting its effectiveness is the lack of trust in online transactions across the continent. The study concluded that investment in e-commerce infrastructure in Africa, particularly in Nigeria, would accelerate economic development on the continent.

Consumer expectations and perceptions of service quality across public, private, and international banks were compared in [Navrang, Meenu, 2018]. The SERVQUAL instrument was used to measure service quality in the private banking sector. The authors found that banks face numerous challenges as a result of technological change, persistent economic uncertainty, intense competition, increasingly demanding customers, and evolving environmental conditions. The study therefore emphasized that customer satisfaction is essential for banks to remain competitive in the market. Further, the relationship between Chinese economic development and e-commerce integration was examined by [Couture et al., 2018]. The analysis combined a randomized controlled experiment (RCT) conducted in villages in collaboration with a major e-commerce company with survey data and administrative microdata. The results revealed significant benefits from e-commerce trading; however, these benefits accrued primarily to a small group of rural households, typically those that were relatively wealthier and younger. Furthermore, there was limited evidence of significant income increases for the average rural worker or producer. Instead, most benefits were observed on the consumption side, particularly in more rural markets where the cost of living declined. The authors therefore recommended further investments aimed at adapting e-commerce systems to rural communities, as the observed impacts were largely attributable to the removal of logistical barriers to e-commerce in rural markets.

Similarly, [Zatonatska, Novosolova, 2017] investigated the impact of e-commerce on Ukraine's economic growth. Economic, mathematical, and statistical estimation techniques were applied in the analysis. The results showed that e-business, although still in its early stages, has considerable growth potential, while e-commerce in Ukraine is expanding rapidly compared with many European markets. Regression analysis further revealed that electronic commerce has a significant influence on Ukraine's economic growth. The relationship between Poland's economic development and e-commerce has also been demonstrated through modeling. The comparison of models showed that Poland has a more developed e-commerce sector, although Ukraine's e-business sector is growing at a faster pace. In another study, the impact of e-commerce on the Indian economy was analyzed by [Anuj et al., 2018]. Using the Spearman rank correlation method, the study found that digital penetration in India has increased significantly, largely due to the growing use of smartphones. Internet usage in India has also increased, and the study found a relationship between the country's e-commerce growth and literacy rates. However, a negative association was observed between the expansion of e-commerce and unemployment. The study concluded that substantial government involvement and increased foreign direct investment (FDI) are necessary to sustain and expand India's e-commerce sector.

[Anjalika, Priyanath, 2018] examined the impact of commercial banks' service standards on customer satisfaction in public and private banks in Sri Lanka using survey data from 141 respondents and correlation analysis. The results indicated that, in public banks, there was a strong positive correlation between tangibility and customer satisfaction, as well as between responsiveness and customer satisfaction. Similarly, [Anvari, Norouzi, 2016] examined how the economic progress of 21 selected countries was influenced by e-commerce, research and development (R&D), and other variables. The study employed panel data and the generalized least square (GLS) regression technique for the period 2005–2013. The findings showed that both R&D and e-commerce have a positive and statistically sig-

nificant effect on GDP per capita based on purchasing power parity. Moreover, e-commerce was found to have a stronger effect on economic development than R&D. Government size and health expenditure were also found to positively influence GDP per capita.

Another study conducted by [Adisak, 2015] identified five consumer service factors influencing effective e-commerce service delivery in Thailand. Using quantitative methods and survey data, the study found that the most significant factors included service providers' commitment to protecting customer information, knowledgeable and competent bank staff, and banks' willingness to develop customer-related service capabilities. The relationship between service quality and customer satisfaction in the Malaysian e-banking and e-commerce industries was examined by [Tan et al., 2016]. Regression analysis and measuring tools such as SERVQUAL and SPSS were used in this study. The results indicated that Malaysian banking customers generally had higher expectations than perceptions regarding service quality, and the tangible dimension of service quality had the strongest influence on customer satisfaction. The study therefore emphasized the importance of maintaining high service quality standards.

In another related study, [Lili, Yan, 2014] examined the impact of e-commerce on China's economic growth. The study identified three major indicators of e-commerce development—the number of Internet users, the number of e-commerce enterprises, and the number of online shoppers—all of which were positively associated with GDP based on multiple regression analysis using the ordinary least squares (OLS) method. The study further suggested that the expansion of e-commerce significantly contributes to economic growth. It recommended that governments, businesses, and consumers prioritize e-commerce development by investing in infrastructure, employing more e-commerce professionals, and encouraging greater participation in online commerce. Another study examined the impact of China's cross-border e-commerce comprehensive pilot zones (CBECPZs) on firms' innovation capacity [Zhang, Han, 2025] using a difference-in-differences (DID) model. The findings showed that the establishment of CBECPZs significantly enhanced firms' innovation capacity, as evidenced by an increase in patent applications in emerging technological fields. Similarly, [He et al., 2026] examined the implications of regulatory innovation for digital platforms in China's data-intelligence era of e-commerce. Using a Chinese digital platform policy dataset covering the period 2000–2025 and a density-based Latent Dirichlet Allocation (LDA) algorithm, the study found that regulatory intensity was significantly correlated with both digital innovation and the value of e-commerce transactions, with statistically significant lag effects consistent with business adaptation and policy implementation.

The relationship between socio-economic development and e-commerce was also examined by [Boateng et al., 2008] using literature survey methods and descriptive statistics. The findings suggested that e-commerce has been spreading across developing countries and may contribute to achieving the global development agenda. The authors recommended that entrepreneurs, governments, consultants, and development agencies in developing countries prioritize policies that support the implementation and adoption of e-commerce initiatives. Another study by [Ziaul et al., 2005] examined how e-commerce affects economic performance. The study found that e-commerce significantly influences business costs and productivity. E-commerce was found to differ from traditional forms of commerce by increasing efficiency through greater transparency. The study suggested that firms adopting e-commerce platforms must be prepared to allow suppliers and customers access to certain internal systems. An analysis of firms' responses to the environmental impacts of e-commerce in the fashion industry was conducted by [Bertram, Chi, 2018] using secondary data. The results showed that online shopping is generally more environmentally friendly than traditional purchasing; however, intermediary factors such as excessive packaging, delivery speed, and product returns may increase waste generation and carbon emissions.

At the country level, [Yousef et al., 2022] examined why Nigerian SMEs have been slow to adopt e-commerce as a means of improving efficiency [Omeje et al., 2022b]. Survey data and descriptive statistics were used in the analysis. The findings indicated that small and medium-sized enterprises (SMEs) constitute a major component of Nigeria's productive sector. However, several obstacles hinder their adoption of e-commerce, including technological challenges, inadequate Internet security, weak regulatory support, and limited knowledge of online platforms and Internet banking systems. The study therefore recommended the implementation of effective policies to strengthen e-commerce adoption and support the sustainable growth of the SME sector. While [Omeje et al., 2022c; 2024] examined issues related to financial inclusion, [Onuora et al., 2019] investigated e-commerce adoption as a tool for economic diversification in Nigeria. The results indicated that inadequate ICT infrastructure limits the potential benefits of e-commerce for African economies. The study emphasized the importance of e-commerce for Nigeria's economic growth and recommended that the government implement policies that create a supportive environment for both domestic and foreign firms seeking to leverage e-commerce opportunities.

Similarly, [Isibor et al., 2018] examined the role of e-commerce in promoting consumer satisfaction and economic growth in Nigeria. Using paired-sample t-test and secondary data, the study found that e-commerce had only a limited effect on consumer satisfaction and economic growth. The authors recommended promoting inclusive e-commerce through digital education initiatives across the country. In another study, [Chukwuemeka et al., 2019] analyzed the impact of e-commerce on Nigeria's economic growth between 1980 and 2018 using an autoregressive distributed lag (ARDL) model. The results showed that e-commerce has a positive and statistically significant effect on Nigeria's economic growth in both the short and long run. The study recommended that the government increase investment in the e-commerce sector to accelerate economic growth. A related study by [Ukwuoma, 2019] used secondary data from 2008 to 2018 to examine the effect of e-commerce on Nigeria's economic growth using ordinary least square (OLS) regression. The findings suggested that GDP per capita and population had a negative effect on economic growth. The study recommended increased investment and the develop-

ment of a national ICT master plan to strengthen the country's digital economy.

In Nigeria, [Khan, Uwemi, 2018] also examined the influence of e-commerce schemes on the use of e-commerce services. Using survey data and descriptive statistics, the study found that consumers, employees, and suppliers significantly influence e-commerce adoption. The authors recommended that government agencies implement policies aimed at increasing e-commerce usage among stakeholders. The role of mobile broadband in promoting e-commerce and economic growth in Nigeria was examined by [Gbahabo, Ajuwon, 2019]. The study showed that mobile broadband penetration significantly promotes economic growth by stimulating the adoption of e-commerce. The results also indicated the presence of bidirectional causality between economic growth and mobile broadband development. Another study by [Adebayo, 2015] identified five consumer-related factors influencing service delivery in Nigerian e-commerce and e-banking services. Using quantitative methods and survey data, the study found that customer data protection, knowledgeable staff, and employees' willingness to assist customers were key determinants of service quality.

The long-term impact of ICT on e-commerce and economic growth in Sub-Saharan Africa (SSA) was examined by [Albiman, 2016] using nonlinear modeling and secondary data. The results indicated that Internet and mobile penetration act as major drivers of economic growth. The study further found that human capital, institutional quality, and domestic investment are important channels through which ICT contributes to economic development. Similarly, [Ibrahim, Abubakar, 2015] examined the adoption of e-commerce technology in Nigeria. Using descriptive statistics, chi-square tests, and primary data from 112 respondents, the study found that electronic payment solutions are becoming increasingly available in Nigeria. The authors recommended that policymakers develop a comprehensive regulatory framework for e-commerce in order to strengthen consumer trust.

The role of electronic commerce in promoting the growth of emerging online market firms was examined by [Adejoh, 2015]. Using descriptive and inferential statistics, multiple regression analysis, and survey data from 117 Konga employees, the study found that e-commerce significantly contributes to the development of the Konga online marketplace ($F(1,126) = 25.270$, $R^2 = 0.168$, $p < 0.05$). The results indicated that the level of e-commerce adoption explains approximately 16.8% of the variation in the development of the Konga online marketplace. The study therefore recommended the introduction of policies aimed at increasing the adoption of e-commerce in Nigeria. Using time-series data from 1970 to 2010, [Asogwa et al., 2013] examined telecommunications expenditure in Nigeria and its relationship with e-commerce and economic growth through multiple regression analysis based on the OLS estimation technique. The results showed that while unemployment negatively affects e-commerce and economic growth in Nigeria, telephony development, foreign direct investment (FDI), and trade openness have positive and statistically significant effects. The study therefore suggested that telecommunications should be properly utilized to support sustainable economic growth and that all stakeholders in emerging economies should be actively involved in this process.

In another study, [Olalekan, 2013] examined how real telecommunications investments influenced e-commerce development in Nigeria between 1980 and 2010. The findings indicated that labor employment, capital stock, real telecommunications investment, and electricity supply significantly influence both e-commerce and economic growth in Nigeria. The study recommended that the government create favorable business conditions in order to attract further investment. Finally, [Afolabi, 2012] examined the effect of globalization, accounting information technology, and e-commerce on selected Nigerian firms using descriptive statistics and survey data. The results indicated that e-commerce had no statistically significant impact on the selected firms. The study concluded that businesses should be encouraged to expand online services to both existing and potential customers. Similarly, [Ayo, 2011] investigated the opportunities and challenges associated with business-to-consumer (B2C) e-commerce adoption in Nigeria using survey data and the extended Technology Acceptance Model (TAM). The results showed that the model variables were significantly related, with intention to use being strongly influenced by task-technology fit and perceived usefulness, with coefficients of 0.2623 and 0.2002, respectively.

2. Materials and Methods

Romer's endogenous growth model (1986) forms the basis of the econometric model specification in this study. It provides an important contribution to the understanding of technological innovation and economic growth [Rogers, 2003]. The model emphasizes the role of investment in the diffusion of technology and its relationship with economic growth [Romer, 1986]. The theory attributes increasing returns to scale to aggregate production [Lucas, 1988]. It assumes that investments in infrastructure, education, skills, and ICT generate external economies and productivity improvements [Karpunina et al., 2021]. However, insufficient investment in these sectors deprives developing countries of broader social gains associated with such investments. When firms receive no direct individual benefit from these externalities, incentives for private investment formation are weakened, which may lead the unrestricted market to accumulate less than the optimal level of capital. The aggregate production function, assuming symmetry across industries in which each industry requires the same amount of labor and capital, is mathematically specified as:

$$Y = AK^{a+b} L^{1-a}. \quad (2)$$

Using Konga and Jumia as a case studies, this research employs conventional time-series analysis to empirically examine the effect of e-commerce on the Nigerian economy. For this purpose, the Autoregressive Distributed Lag (ARDL) model developed by [Pesaran et al., 2001] is used. The ARDL approach can be applied regardless of whether the variables are integrated of the same order, that is, I(0), I(1), or a mixture of both.

The ARDL model produces reliable estimates even in the presence of endogenous explanatory variables and relatively small sample sizes [Menyah, Wolde-Rufael, 2010]. Even with

small samples, the model helps address the potential endogeneity of explanatory variables. After establishing the order of integration of the variables, the ARDL procedure is implemented in three stages. The first step is to determine the optimal lag length using information criteria such as the Akaike Information Criterion (AIC), Schwarz Bayesian Information Criterion (SBIC), or Hannan—Quinn Information Criterion (HQIC). The second step involves applying the Bounds testing to determine whether cointegration exists among the variables. Once cointegration among the variables is confirmed, the ARDL framework and the corresponding Error Correction Model (ECM) are used to estimate the long-run and short-run parameters. Because the variables are integrated of order zero and order one—that is, they are stationary at level I(0) and at first difference I(1)—the ARDL approach is appropriate for examining both the long-term and short-term relationships among the variables.

Before specifying the ARDL model, the functional form of the estimable model is expressed as follows:

$$ECG = f(NPJ, NPK, NIU, TEI, NTS), \quad (3)$$

where *ECG*—economic growth proxied by GDP growth rate; *NPJ*—number of users conducting transactions on Jumia in Nigeria, *NPK*—number of users conducting transactions on Konga in Nigeria, *NIU*—number of Internet users, *TEI*—telecommunications investment, *NTS*—number of telephone subscribers.

The estimable Autoregressive Distributed Lag (ARDL) model in its econometric form is given as:

$$\mathrm{ECG}_t = a_0 + \sum_{i=1}^{n} a_j \mathrm{ECG}_{t-j} + \sum_{j=0}^{n} \theta_{1i} \mathrm{NPJ}_{t-1} + \sum_{j=0}^{n} \theta_{2i} \mathrm{NPK}_{t-1} + \sum_{j=0}^{n} \theta_{3i} \mathrm{NIU}_{t-1} + \\ + \sum_{j=0}^{n} \theta_{4i} \mathrm{TEI}_{t-1} + \sum_{j=0}^{n} \theta_{5i} \mathrm{NTS}_{t-1} + \mu_t, \quad (4)$$

where the variables are as defined above, α_0 denotes the constant term, a_i represents the parameters for the lagged dependent variable (ECG_{t-i}) in the autoregressive specification $\theta_{1,\ldots,5,i}$ represent the parameters of the lagged explanatory variables, $\sum_{i=1}^{n}$ denotes the summation notation for the lagged explained variables from $i = 1, \ldots, n$, $\sum_{J=0}^{n}$ —summation operator, μ represents the error term, and t denotes time.

Once evidence of cointegration is established, the study estimates the ARDL error correction model (ARDL-ECM) specified as (5):

$$\Delta \mathrm{ECG}_t = a_0 + \sum_{i=1}^{n} a_i \Delta \mathrm{ECG}_{t-1} + \sum_{j=0}^{n} \theta_{1i} \Delta \mathrm{NPJ}_{t-1} + \sum_{j=0}^{n} \theta_{2i} \Delta \mathrm{NPK}_{t-1} + \\ + \sum_{j=0}^{n} \theta_{3i} \Delta \mathrm{NIU}_{t-1} + \sum_{j=0}^{n} \theta_{4i} \Delta \mathrm{TEI}_{t-1} + \sum_{j=0}^{n} \theta_{5i} \Delta \mathrm{NTS}_{t-1} + \lambda_1 \mathrm{ECM}_{t-1} + \mu_t, \quad (5)$$

where Δ—difference operator, λ—speed of adjustment toward equilibrium, and ECM_{t-1}—the error-correction term.

The data used in this study consist of monthly time-series observations from 2017M1 to 2023M12. This period was selected because sufficient data are available. The variables of interest include the dependent variable, economic growth (proxied by the GDP growth rate), which was obtained from the National Bureau of Statistics[4]. The independent variables include Jumia users (NPJ), used as a proxy for e-commerce activity on Jumia, and Konga users (NPK), used as a proxy for e-commerce activity on Konga. Data were obtained from Jumia and Konga, respectively. Data on the number of Internet users, telecommunications investment, and the number of telephone subscribers were obtained from the National Bureau of Statistics[5].

Descriptive statistics summarize the general characteristics of the variables used in the regression estimation. The results are presented in Table 1.

The descriptive statistics presented in Table 1 summarize the behavior and distribution of the variables used in the regression analysis, including their mean, median, standard deviation, skewness, and kurtosis values. A total of 84 observations are included in the dataset. The variables are considered normally distributed when the probability value of the Jarque-Bera (JB)

Table 1
Descriptive Statistics

Variables	ECG	NPJ	NPK	NIU	NTS	TEI
Mean	23.29647	3.22E+08	156.2864	52.13067	2.38E+11	571.2000
Median	27.49972	3.20E+08	157.1106	42.08754	2.63E+11	547.4414
Maximum	37.50304	6.90E+08	198.1981	136.9104	3.16E+11	744.3780
Minimum	–1.027721	–4584482	104.7289	–3.621339	4.19E+10	470.7618
Std. Dev.	9.930484	2.53E+08	30.17311	44.21393	8.06E+10	78.72747
Skewness	–0.914098	0.050069	–0.120568	0.415534	–0.911454	0.650166
Kurtosis	2.812856	1.453161	1.723429	1.821626	2.668719	2.239208
Jarque-Bera	8.443318	6.006846	4.219450	5.198094	8.581860	5.674164
Probability	0.104674	0.409617	0.121271	0.704344	0.103692	0.058596
Sum	1397.788	1.93E+10	9377.183	3127.840	1.43E+13	34272.00
Sum Sq. Dev.	5818.256	3.76E+18	53714.58	115337.5	3.83E+23	365682.9
Observations	84	84	84	84	84	84

Source: authors' computation using Eviews 10.

[4] Nigerian Statistics (2024). National Bureau of Statistics Pubs. https://nigerianstat.dev.codeforafrica.org/.
[5] Ibid.

statistic exceeds the 0.05% significance level. In this case, the probability values suggest that the variables—including economic growth, the number of Jumia and Konga users in Nigeria, the number of Internet users, telecommunications investment, and the number of telephone subscribers—are normally distributed. Additionally, the skewness and kurtosis statistics further support the descriptive statistics. Skewness measures the asymmetry of a distribution around its mean. A normal distribution has a skewness value of zero. A distribution with a long right tail is positively skewed, while a distribution with a long left tail is negatively skewed. Table 1 shows that ECG, NPK, and NTS are negatively skewed, indicating distributions with long-left tails, whereas NPJ, NIU, and TEI are positively skewed, indicating distributions with long right tails.

3. Results

This study first conducted pre-estimation tests, including the stationarity (unit root) test and the bound tests for cointegration, before presenting the main estimation results. These tests are discussed below.

3.1. Pre-Estimation Tests

For the unit root analysis, the Augmented Dickey-Fuller (ADF) test was used. In this test, if the p-value exceeds 0.05, the null hypothesis of a unit root cannot be rejected. The results are presented in Table 2.

Table 2
Unit Root Test

Augmented Dickey-Fuller (ADF)			
Variables	**Level**	**First difference**	**Inference**
ECG	–3.506468*	–	I(0)
LTEI	–3.135207*	–	I(0)
LNTS	–1.739985	–6.129733*	I(1)
LNIU	–3.268363	–9.129784*	I(1)
NPJ	–13.27338*		I(0)
NPK	–4.653718*		I(0)

Notes: 1. Reported values represent the test statistics. 2. * indicates significance at the 5% level. 3. The Augmented Dickey-Fuller (ADF) tests were conducted with an intercept and trend.
Source: authors' computation using Eviews 10.

Table 2 presents the results of the unit root test, indicating that the variables are stationary at either I(0) or I(1). The Augmented Dickey-Fuller (ADF) test shows that economic growth, telecommunications investment, the number of Jumia and Konga users conducting transactions in Nigeria is stationary at level, i.e., (I(0)). In contrast, the number of Internet users, and the number of telephone subscribers are stationary at first difference (I(1)).

Given that the unit root test indicated that the variables were integrated of order I(0) and I(1), the ARDL bounds testing approach developed by [Pesaran et al., 2001] was employed to test for cointegration among the variables. The results are presented in Table 3.

Table 3
Bounds Test for the Model

Test Statistic	Value	Signif. (%)	I(0)	I(1)	Result
F-statistic	33.41735	10	2.26	3.35	
		5	2.62	3.79	Cointegrated
		2.50	2.96	4.18	
		1	3.41	4.68	

Source: authors' computation using Eviews 10.

As shown in Table 3, the calculated F-statistic (33.41735) exceeds both the lower and upper critical bounds at the 0.05 significance level. As a result, the study finds evidence of cointegration among the variables included in the analysis and rejects the null hypothesis of no cointegration, indicating the existence of a long-run relationship among the variables included in the model. Consequently, both the short-run and long-run ARDL models were estimated.

3.2. Results of the Autoregressive Distributed Lag (ARDL) Model

The bounds test confirmed the presence of cointegration among the variables; therefore, both the long-run and short-run ARDL estimates were obtained. The long-run results are presented in Table 4.

The short-run parameters of the model are presented in Table 5.

Table 4
Long-Run ARDL Regression Results

Variables	Coefficient	Std. Error	t-Statistic	p-value
ECG(–1)	0.800650	0.288647	2.773801	0.0080
NPJ	0.351928	0.120870	2.911626	0.0058
LNPJ	0.116985	0.012311	9.502477	0.0000
LNTS	0.102308	0.065401	1.564325	0.1246
LTEI	0.685079	0.070565	9.708481	0.0000
LNIU	–0.003451	0.001775	–1.944390	0.0580
C	0.407457	0.0519446	7.844159	0.0000
R^2 = 0.987061 Adjusted R^2 = 0.984249 F-statistic = 350.9264 Prob(F-statistic) = 0.000000 Durbin-Watson = 1.593805				

Source: authors' computation using Eviews 10.

Table 5
Short-Run ARDL Regression Results

Variables	Coefficient	Std. Error	t-Statistic	P-value
D(ECG(–1))	0.792236	0.288480	2.746244	0.0086
D(NPJ)	0.389739	0.125845	3.096980	0.0035
D(NPK)	0.235858	0.054398	4.335784	0.0001
D(LNTS)	0.179022	0.115703	1.547249	0.1287
D(LTEI)	0.119877	0.014113	8.494084	0.0000
D(NIU)	0.269886	0.026978	10.003929	0.0000
ECM(–1)	–0.749827	0.161987	4.629019	0.0000
C	0.071095	0.536325	0.132560	0.8952

Source: authors' computation using Eviews 10.

3.3. Post-Estimation Tests

Autocorrelation was tested using the Breusch-Godfrey serial correlation LM test, which allows testing for autocorrelation at higher lag orders.

Hypotheses:

– H_0: There is no autocorrelation;
– H_1: There is autocorrelation.

Decision rule: Reject the null hypothesis if the p-value is less than 0.05 at 5% significance level. The results of the test are presented in Table 6.

Table 6
Autocorrelation Output

Obs*Chi-Squared	2.051563
Prob. Chi-Square (2)	0.3585

Source: authors' computation using Eviews 10.

As shown in Table 6, the probability value of the chi-square statistic (0.3585) exceeds 0.05. Therefore, the null hypothesis cannot be rejected, indicating that there is no serial correlation in the residuals.

The White test was used to examine heteroskedasticity in the residuals. This test evaluates whether the variance of the residuals is constant, as required by the BLUE (Best Linear Unbiased Estimator) properties of the classical linear regression model.

Hypotheses:

– H_0: The variances are homoskedastic;
– H_1: The variances are heteroskedastic.

Decision rule: Reject the null hypothesis if the p-value is less than 0.05.

Table 7
Heteroskedasticity Output

Obs*Chi-Squared	41.82377
Prob. Chi-Square (2)	0.8660

Source: authors' computation using Eviews 10.

The probability value of the chi-square statistic in Table 7 (0.8660) exceeds 0.05, indicating that the null hypothesis cannot be rejected. Therefore, the residuals are homoskedastic, suggesting that the variance of the error term is constant.

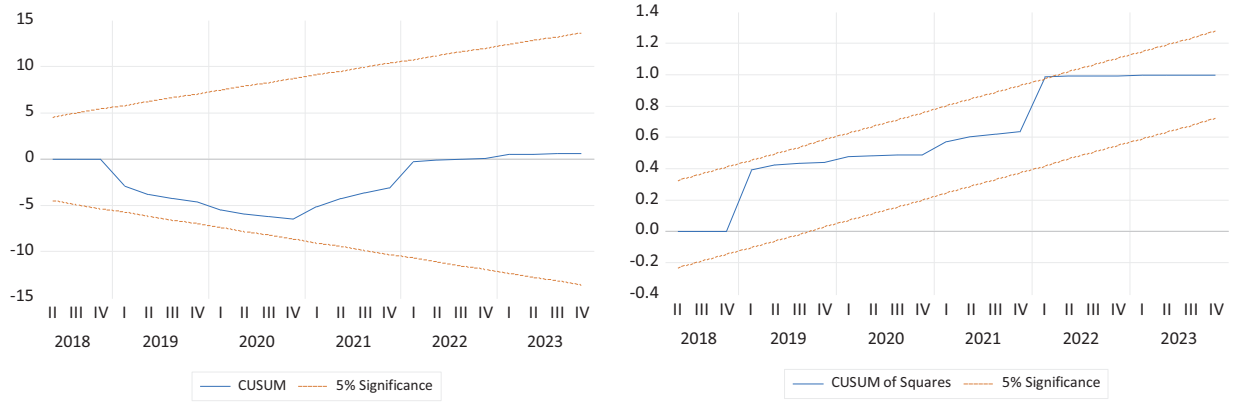
To examine parameter stability, the CUSUM and CUSUMSQ tests were applied. These tests determine whether structural breaks exist in the model and whether the estimated coefficients remain stable over time. This stability test allows us to accept the model's output. The results, presented in Figure 4, show that all coefficients remain within the 5% critical bounds, indicating that the estimated model is stable over the sample period.

The results of the CUSUM test show that the cumulative sum of recursive residuals remains within the 5% critical bounds, indicating that the null hypothesis of parameter stability cannot be rejected. Similarly, the CUSUMSQ plot remains within the 5% critical bounds, suggesting that the estimated model is stable over the sample period.

4. Discussion

In the long run, past economic growth (ECG(–1)) was found to have a positive and statistically significant effect on current economic growth, with a coefficient of 0.800650 (about 80.07%). This result is not surprising, as countries that experienced economic growth in previous periods tend to maintain policies and strategies that sustain this growth trajectory. The implication of this finding is that an increase in previous economic growth (ECG(–1)) significantly stimulates current economic growth. In the short run, past economic growth (ECG(–1)) also shows a positive and significant effect on current economic growth, with a coefficient of 0.792236 (about 79.22%). This finding similarly suggests that prior economic expansion tends to reinforce current growth dynamics. These results are consistent with the findings of [Ibiam et al., 2017; Navrang, Meenu, 2018; Banescu, Manea, 2022].

Jumia users (NPJ) showed a positive and statistically significant relationship with economic growth in the long run, with a coefficient of 0.351928. This indicates that an increase in the number of Jumia users contributes positively to economic growth in Nigeria. On average, this corresponds to approximately a 35.19% increase in economic growth. This finding suggests that improved access to digital infrastructure, including faster Internet connectivity, greater Internet penetration, the development of the Internet of things (IoT), and other channels of e-commerce



a) b)

Source: authors' computation using Eviews 10.

Fig. 4. Parameter stability tests: (a) CUSUM test, (b) CUSUMSQ test

accessibility, may significantly enhance Jumia-based transactions and strengthen Nigeria's digital economy, thereby stimulating economic growth. Similarly, in the short run, Jumia users (NPJ) have a positive and statistically significant effect on economic growth, with a coefficient of 0.389739. This indicates that increased participation in Jumia-based transactions positively influences economic growth in Nigeria. On average, this corresponds to approximately a 38.97% increase in economic growth. These findings are consistent with the study by [Karpunina et al., 2021], which found that the development of e-commerce significantly encourages economic growth.

Konga users (LNPJ) also show a positive and statistically significant relationship with economic growth in Nigeria. In the long run, the coefficient of this variable is 0.116985, indicating that an increase in the number of Konga users contributes positively to economic growth in Nigeria. On average, a 1% increase in the number of Konga users corresponds to approximately an 11.70% increase in economic growth in the long run. In the short run, Konga users (NPK) also have a positive and statistically significant effect on economic growth with a coefficient of 0.235858. This indicates that increased use of the Konga platform contributes positively to Nigeria's economic growth. On average, this corresponds to approximately a 23.59% increase in economic growth. These results are consistent with previous studies [Couture et al., 2018; Karpunina et al., 2021], which show that the that the integration of e-commerce into the economy significantly improves economic growth.

The number of telephone subscribers (LNTS) has a coefficient of 0.102308 in the long run, indicating a positive but statistically insignificant relationship with economic growth in Nigeria. Although this result conforms to a priori expectations, its statistical insignificance suggests that the increasing number of telephone subscribers alone may not be sufficient to significantly stimulate economic growth. One possible explanation is that network coverage and service quality, particularly in the rural areas, remain insufficient to generate a strong economic impact. In the short run, the number of telephone subscribers (LNTS) also shows a positive but statistically insignificant coefficient of 0.179022, indicating a positive but insignificant relationship with economic growth in Nigeria. This result may appear surprising, as it is generally expected that an increase in the number of telephone subscribers would significantly influence economic growth. However, the implication of this result is that, holding other factors constant, a 1% increase in the number of telephone subscribers leads on average to about a 17.90% increase in Nigeria's economic growth in the short run, although this increase is statistically insignificant. This finding nevertheless conforms to a priori expectations that an expansion in telecommunications services may support economic activity. It therefore suggests that the number of telephone subscribers contributes positively, though insignificantly, to economic growth in Nigeria in the short run. Similar conclusions have been reported in previous studies [Anuj et al., 2018; Bitrus, 2019; Ogbonne et al., 2021; Zhang, Han, 2025], which found that as the number of telephone subscribers increases, e-commerce activity tends to expand, thereby encouraging economic growth.

Telecommunications investment (LTEI) was found to have a positive and statistically significant effect on economic growth. In the long run, the coefficient of telecommunications investment is 0.685079, indicating that a 1% increase in telecommunications investment leads to approximately a 68.51% increase in economic growth in Nigeria. This result conforms to a priori expectations and suggests that increased investment in telecommunications infrastructure promotes the development of e-commerce activities and, consequently, economic growth. Similarly, in the short run, telecommunications investment (LTEI) also has a positive and statistically significant effect on economic growth, with a coefficient of 0.119877. This result indicates that increased telecommunications investment stimulates economic growth in Nigeria even in the short run. Therefore, a 1% increase in telecommunications investment leads to about an 11.99% increase in economic growth. This finding conforms to a priori expectations and suggests that increased investment in telecommunications infrastructure would lead to the expansion of e-commerce activities and, consequently, stimulate economic growth in Nigeria. These findings are consistent with previous studies [Zatonatska, Novosolova, 2017; Anuj et al., 2018; Bitrus, 2019; Onuora et al., 2019; Ogbonne et al., 2021; He et al., 2026].

The coefficient of the number of Internet users (NIU) is –0.003451 in the long run, indicating a negative relationship between Internet users and economic growth. Although this effect is statistically insignificant at the 5% level, it becomes weakly significant at 10% level. With a coefficient of –0.003451, an increase in the number of Internet users by one person would, on average, lead to about a 0.35% insignificant decline in Nigeria's economic growth. This result suggests that Internet penetration in Nigeria may still be insufficient to produce a strong positive impact on economic growth [Omeje et al., 2022]. Limited access to reliable Internet services and the high cost of mobile data may partly explain this outcome. These findings do not conform to a priori expectations and differ from the results reported by [Anuj et al., 2018; Oladimeji, Folayan, 2018; Bitrus, 2019; Janet, 2021]. However, in the short run, the number of Internet users (NIU) shows a positive and statistically significant effect on economic growth, with a coefficient of 0.269886. This result suggests that, in the short run, Nigerian economic growth and e-commerce activities are positively associated with the number of Internet users. The observed impact of the number of Internet users is statistically significant at the 5% level in explaining economic growth. The result further suggests that a one-unit increase in the number of Internet users would, on average, lead to about a 26.99% increase in Nigeria's economic growth. The economic implication of this result may be that, in the short run, there may be periods when Internet connectivity in Nigeria becomes faster and more reliable, allowing people in urban areas and some rural communities to access the Internet while performing online transactions. This situation could contribute to an increase in the number of Internet users in the short run. This finding conforms to a priori expectations and is also consistent with the findings of [Anuj et al., 2018; Oladimeji, Folayan, 2018; Bitrus, 2019; Gbahabo, Ajuwon, 2019; Ukwuoma, 2019; Janet, 2021].

In the long run, the constant term (C) has a coefficient of 0.407457 when all other factors are held constant. This implies that, holding all other factors constant, a unit increase in the constant term would, on average, result in about a 40.75% increase in economic growth. However, in the short run, when all other factors are also held constant (C), the coefficient of the constant

term is 0.071095, indicating that, holding these factors constant, a unit increase in the constant term would, on average, lead to about a 7.11% increase in economic growth in the short run.

Finally, the coefficient of the error correction mechanism (ECM(–1)) is –0.749827 with a p-value of 0.0000. This value indicates that the speed of adjustment is about 74.98%. This implies that deviations from the long-run equilibrium would be corrected at a rate of about 74.98% in order for the system to return to its equilibrium position. This satisfies the condition for the error correction mechanism, which requires that the coefficient of the ECM(–1) be negative in order for the system to return to equilibrium.

Conclusions

The study examined the impact of e-commerce on the Nigerian economy using Konga and Jumia as case studies, with monthly data covering the period from 2017M1 to 2023M12. The study adopted the Autoregressive Distributed Lag (ARDL) estimation technique and the bounds test for cointegration. The analytical framework was based on Romer's endogenous growth model (1986), which emphasizes the role of investment in technological diffusion and its relationship to economic growth. The theory assumes that investments, particularly in infrastructure, technology (including the Internet and artificial intelligence), education, health, and telecommunications, generate external economies and productivity improvements. The results show that the number of telephone subscribers has a positive but statistically insignificant effect on economic growth in Nigeria in both the long run and the short run. In contrast, the telecommunications investment was found to have a positive and statistically significant effect on Nigeria's economic growth in both the long run and the short run. The variables representing Jumia users and Konga users were also found to be statistically significant and consistent with a priori expectations, indicating that participation in these e-commerce platforms positively contributes to economic growth in Nigeria. Furthermore, the number of Internet users was found to be statistically insignificant in the long run, and therefore does not conform to a priori expectations in the long run, although it becomes significant in the short run.

Based on these findings, the study recommends increased government investments in Internet infrastructure, particularly in rural areas, in order to expand Internet access and increase the number of Internet users. This would enable greater participation in digital commerce and contribute more significantly to economic growth.

There is also a need to create an enabling environment for e-commerce businesses through increased investments in ICT by the government, its agencies, and other stakeholders in the country.

The results of the analysis further demonstrate that the number of Nigerians conducting online transactions on the Konga and Jumia platforms is statistically significant in explaining economic growth. Therefore, the Nigerian government should develop a comprehensive e-commerce strategy aimed at expanding the sector and formulating digital trade policies that promote both domestic and international trade through e-commerce platforms.

In addition, stronger collaboration between the government and the private sector is necessary to finance and develop a supportive digital environment, including ICT hubs and affordable Internet services that promote technological innovation, the Internet of Things (IoT), and digitization within the economy. Such initiatives would help strengthen the positive relationship between telecommunications investment and economic growth identified in this study. Adequate investment in the ICT sector would also improve digital literacy and further enhance economic growth in Nigeria.

The findings also indicate that the number of Internet users currently has a statistically insignificant effect on economic growth in Nigeria. This may be attributed to limited Internet accessibility and affordability, as well as the high cost of mobile data services provided by network operators. Therefore, the government should increase investment in Internet infrastructure to support economic growth as the global economy continues to evolve toward a more inclusive digital and artificial intelligence-driven environment.

Furthermore, public authorities should promote investment in technological knowledge among the population by supporting training and empowerment initiatives related to telecommunications technology. Efforts should also be made to increase the number of people using information and communication technologies (ICT) in order to support the achievement of the Sustainable Development Goals (SDGs) by 2030.

Finally, the government should strengthen regulatory oversight to ensure fair pricing and maintain high standards of product quality in the e-commerce market.

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About the Authors

Ambrose Nnaemeka Omeje
PhD (Econ.), Department of Auditing and Taxation, Faculty of Accounting and Informatics, Durban University of Technology (Durban, South Africa). ORCID: 0000-0002-4847-3232.
Research interests: business and economics, public, environmental and occupational health, engineering.
ambrose.omeje@unn.edu.ng

Olive Stumke
PhD (Econ.), Professor, Department of Auditing and Taxation, Faculty of Accounting and Informatics, Durban University of Technology (Durban, South Africa). ORCID: 0000-0001-8240-6298.
Research interests: accounting, auditing.
Olive.Stumke@gmail.com

Denis Onyekachi Ezeogo
Department of Economics, Faculty of Social Sciences, University of Nigeria (Nsukka, Nigeria).
deneiceonyeka99@gmail.com

Ravinder Rena
PhD (Econ.), Professor of Economics, DUT Business School, Faculty of Management Sciences, Durban University of Technology (Durban, Republic of South Africa). ORCID: 0000-0002-4156-8693; Scopus Author ID: 56441653000.
Research interests: digital platforms for crowdfunding, the BRICS and the African economy, academic freedom within the constitutional framework of South Africa, sustainable development.
ravinder.rena1@gmail.com

Равиндер Рена
PhD (Econ.), профессор экономики, бизнес-школа DUT, факультет управленческих наук, Дурбанский технологический университет (Дурбан, Южная Африка). ORCID: 0000-0002-4156-8693; Scopus Author ID: 56441653000.
Научные интересы: цифровые платформы для краудфандинга, страны БРИКС и экономика Африки, академическая свобода в рамках конституционного права Южно-Африканской Республики, устойчивое развитие.
ravinder.rena1@gmail.com

作者信息

Ambrose Nnaemeka Omeje
经济学博士，审计与税务系，会计与信息学院，德班理工大学（南非德班）。ORCID: 0000-0002-4847-3232。
研究方向：商业与经济、公共健康、环境与职业健康、工程学。ambrose.omeje@unn.edu.ng

Olive Stumke
经济学博士，教授，审计与税务系，会计与信息学院，德班理工大学（南非德班）。ORCID: 0000-0001-8240-6298。
研究方向：会计、审计。
Olive.Stumke@gmail.com

Denis Onyekachi Ezeogo
经济系，社会科学学院，尼日利亚大学（尼日利亚恩苏卡）。
deneiceonyeka99@gmail.com

Ravinder Rena
经济学博士，经济学教授，DUT 商学院，管理科学学院，德班理工大学（南非德班）。ORCID: 0000-0002-4156-8693；Scopus Author ID: 56441653000。
研究方向：数字众筹平台、金砖国家与非洲经济、南非共和国宪法框架下的学术自由、可持续发展。
ravinder.rena1@gmail.com

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Barriers to Workforce Strategy Development in the Automotive Industry: An Empirical Analysis of the Indian Passenger Vehicle Sector Using ISM and MICMAC

A. Thakran[1, 2]
R.S. Rathore[3]
N. Sanghi[4]
V. Maheshwari[5]
S.L. Sahdev[6, 7]
[1] National Taiwan University (Taipei, Taiwan)
[2] Academia Sinica (Taipei, Taiwan)
[3] Cardiff Metropolitan University (Cardiff, United Kingdom)
[4] Paybooks (Bangalore, India)
[5] Vellore Institute of Technology (Vellore, India)
[6] Alliance University (Karnataka, India)
[7] Amity University (Noida, India)

Abstract

The automotive industry in India is undergoing a rapid digital transformation, necessitating a skilled workforce proficient in emerging technologies. However, multiple barriers impede the effective adoption of such a workforce. This study aims to analyze the interrelationships and hierarchical structure of these barriers within the Indian passenger vehicle sector. Data were collected through semi-structured interviews conducted between April 2024 and July 2025 with senior professionals from leading automotive companies and academicians with established publications in the field (ABDC A- or B-ranked journals). Of the 40 potential respondents approached via email and LinkedIn, 10 provided written consent and participated in the interviews. The responses were transcribed and subjected to thematic analysis, which identified ten key barriers influencing skilled workforce adoption in the era of automotive digital transformation. Interpretive Structural Modeling (ISM) was used to establish the hierarchical structure of these barriers, while MICMAC (Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement) analysis was employed to classify them according to their driving and dependence power. The root causes appear to include poor training infrastructure, shortcomings in industry-academia collaboration, and policy inefficiencies. These root causes strongly influence other dependent barriers, such as the limited availability of digital skill sets, the high cost of upskilling, and low workforce adaptability due to organizational resistance to change. This structured understanding provides strategic insights for policymakers, industry leaders, and educators seeking to design targeted interventions to strengthen the digital workforce ecosystem in India's passenger vehicle sector.

Keywords: skilled workforce barriers, Interpretive Structural Modeling (ISM), MICMAC analysis, India, semi-structured interviews, industry-academia collaboration

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汽车工业劳动力战略制定的障碍：基于ISM和MICMAC的印度乘用车行业实证分析

A. Thakran[1, 2]
R.S. Rathore[3]
N. Sanghi[4]
V. Maheshwari[5]
S.L. Sahdev[6, 7]
[1] 台湾大学（台北，台湾）
[2] 中央研究院（台北，台湾）
[3] 卡迪夫城市大学（卡迪夫，英国）
[4] Paybooks（班加罗尔，印度）
[5] 韦洛尔理工学院（韦洛尔，印度）
[6] 联盟大学（卡纳塔克邦，印度）
[7] 安米提大学（诺伊达，印度）

摘要

当前，印度汽车产业正经历快速的数字化转型，行业亟需具备新技术应用能力的高素质人才。然而，在现阶段，人才队伍建设面临一系列障碍，制约了相关人才储备体系的有效构建。本文以印度乘用车制造业为例，分析这些障碍之间的相互关系及其层级结构。研究数据来源于2024年4月至2025年7月开展的半结构化访谈。受访者包括印度领先汽车企业的高层管理人员，以及在商业、管理与经济学领域权威国际期刊上发表过相关成果的学术界人士。研究团队通过电子邮件和LinkedIn联系了40位潜在受访者，其中10位以书面形式同意参加访谈。访谈资料经转录后，采用主题分析法加以处理，识别出影响汽车工业数字化转型背景下人才队伍建设的10项基础性障碍。在此基础上，运用ISM（解释结构模型）确定了这些障碍的层级结构，并借助MICMAC分析，根据其依赖性和驱动力对其进行了分类。研究发现，基础性障碍主要包括教育基础设施薄弱、产学互动不足以及政府政策效能不足。此外，研究还识别出若干在很大程度上受上述基础性障碍影响的次级障碍，包括具备必要数字化能力的人才短缺、技能提升项目成本过高、员工变革准备不足以及组织层面对转型的抵制等。上述结构化研究结果为政府部门、行业管理者和教育界提供了重要参考，有助于制定更具针对性的政策与措施，从而完善支撑印度乘用车制造业数字化转型的人才培养体系。

关键词： 解释结构模型（ISM）、MICMAC分析、印度、半结构化访谈、产学互动

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Introduction

The passenger vehicle sector in India is undergoing an unprecedented digital transformation driven by the rapid adoption of Industry 4.0 technologies, including automation, artificial intelligence (AI), the Internet of Things (IoT), robotics, and data analytics [Singh, Kaur, 2025]. The sector's evolution from traditional assembly lines to integrated manufacturing ecosystems reflects a global trend toward intelligent production, enhanced product design, predictive customer service, and supply chain optimization [Ojha et al., 2024; Singh, Kaur, 2025]. These changes are not merely technological; they signal a fundamental shift in how automotive companies create value and adapt to changing market demands, environmental imperatives, and consumer preferences. The Indian government's Digital India, Make in India, FAME, and Skill India programs have played instrumental roles in enabling this transformation by fostering digital infrastructure upgrades, incentivizing R&D, and encouraging industry-academia collaboration [Human Resource.., 2019; Ojha et al., 2024; Singh, Kaur, 2025].

Despite the sector's dynamic progress, Indian automotive manufacturers face significant barriers in cultivating a workforce suited to the digital era. Modern vehicle production increasingly demands data scientists, cybersecurity experts, robotic technicians, and AI specialists, yet the industry continues to experience persistent shortages of such talent [Human Resource.., 2019; Ojha et al., 2024]. The lack of specialized training infrastructure, outdated curricula in technical institutions, and limited industry-academia collaboration are major obstacles restricting the supply of skilled professionals [Human Resource.., 2019; Singh, Kaur, 2025]. These impediments are further aggravated by organizational resistance to change, the high costs of implementing digital transformation, and the need for robust IT infrastructure capable of integrating advanced technologies with legacy systems [Ojha et al., 2024; Singh, Kaur, 2025]. Small and medium-sized enterprises (SMEs) are particularly vulnerable, as limited funding and human capital make technology adoption especially challenging [Rawat et al., 2021; Ojha et al., 2024; Sharma, Paliwal, 2026].

Digital transformation has also introduced new forms of interconnectedness and complexity, especially with the advent of connected vehicles, telematics, electric mobility platforms, and cloud-based analytics [Singh, Kaur, 2025]. Case studies of leading Indian automakers such as Tata Motors and Mahindra & Mahindra demonstrate significant investments in IoT sensors, AI-driven robotics, remote diagnostics, and predictive maintenance [Singh, Kaur, 2025]. Tata Motors, for example, has implemented the iRA platform for real-time vehicle analytics and remote management, while Mahindra has developed its NEMO platform to provide seamless digital experiences for users and fleet managers [Singh, Kaur, 2025]. Maruti Suzuki and Hero MotoCorp are similarly expanding digital platforms across product development, manufacturing, and customer

support, signaling a sector-wide embrace of digital integration. However, the full benefits of these initiatives cannot be realized without a skilled and adaptive workforce capable of designing, deploying, and maintaining complex digital systems [Ojha et al., 2024; Singh, Kaur, 2025].

Barriers to skilled workforce adoption in the context of automotive digital transformation are multifaceted and deeply interconnected. High implementation costs, inadequate IT infrastructure, resistance to organizational change, insufficient legislation, data privacy concerns, and cybersecurity risks have emerged as critical challenges limiting workforce transformation [Rawat et al., 2021; Ojha et al., 2024]. For instance, advanced manufacturing facilities in urban centers have access to technologies such as automated guided vehicles (AGVs), digital twins, and real-time data analytics, yet comparable progress remains uneven in tier-2 and tier-3 cities, where basic digital infrastructure is still underdeveloped [Singh, Kaur, 2025]. Workforce readiness is further hampered by skill deficiencies: while Industry 4.0 demands expertise in data analytics, robotics, cloud platforms, and AI, many engineering and vocational programs lag behind in updating their curricula [Human Resource.., 2019; Singh, Kaur, 2025]. As a result, a persistent gap remains between industry needs and the skills imparted by traditional institutions, necessitating robust re-skilling and upskilling initiatives for the current workforce [Human Resource.., 2019; Singh, Kaur, 2025].

Organizational resistance to change is another formidable barrier. Established companies with decades-old practices and legacy systems often struggle with interoperability between conventional and modern digital solutions [Ojha et al., 2024]. Employee skepticism and reluctance to adopt new tools are common and can lead to inefficiencies or failed technology rollouts. This resistance is frequently exacerbated by the lack of involvement of middle and lower management in digital change processes. Successful implementation depends on coordinated efforts across multiple organizational levels, requiring leadership buy-in, inclusive decision-making, and robust change management strategies [Kamble et al., 2018a; Ojha et al., 2024].

Cybersecurity has come to the forefront as digital ecosystems expose vehicles, plants, and data repositories to unprecedented threats. Connected vehicles and digitally managed production lines are increasingly vulnerable to hacking, creating risks to operational integrity, customer privacy, and intellectual property [Ojha et al., 2024; Singh, Kaur, 2025]. Many Indian companies lack dedicated cybersecurity teams capable of mitigating risks, and industry-wide data protection standards are still evolving. Government initiatives encourage standardization and the strengthening of digital safety protocols, but widespread adoption remains a work in progress [Singh, Kaur, 2025].

Another layer of complexity arises from the integration of advanced data analytics and AI into vehicle production, quality assessment, logistics, and in-vehicle experiences [Ojha et al., 2024]. While digital platforms now enable real-time decision-making, predictive analytics, and product personalization, the ability to leverage these technologies is fundamentally constrained by workforce capability. The shortage of data analysts, AI experts, and digital strategists prevents companies from fully capitalizing on the potential of digital transformation [Ojha et al., 2024; Singh, Kaur, 2025].

Interpretive Structural Modeling (ISM) and MICMAC analysis have gained prominence in academic and applied research as robust methodologies for systematically investigating the structure and interrelations of barriers to workforce adoption in digital transformation [Kamble et al., 2018b; Luthra, Mangla, 2018; Ojha et al., 2024]. The ISM process enables experts to identify, rank, and map barriers according to their driving and dependent powers, ultimately yielding a hierarchy that reveals root causes and influential linkages [Ojha et al., 2024]. MICMAC analysis further categorizes these barriers into autonomous, dependent, linkage, and driving clusters, reflecting their influence within the transformation landscape. Empirical studies have shown that barriers such as geopolitical risk, lack of robust IT infrastructure, and integration challenges serve as driving forces, whereas issues like competitive pricing pressure and the risk of obsolescence tend to function as dependent variables within the ISM framework [Kamble et al., 2018a; Ojha et al., 2024].

In recent large-scale surveys, such as those employed by [Ojha et al., 2024], barriers were quantitatively ranked using Likert-scale responses, with expert validation from both academia and industry practitioners. The studies found that “integration of technology,” “cyberattacks,” and “high cost of implementation” consistently emerged as top-ranked challenges, particularly for SMEs. Expert interviews and questionnaire analyses revealed that robust IT infrastructure and geopolitical risks underpin the ecosystem’s overall capacity for digital transformation [Ojha et al., 2024]. The ISM model presented in these studies places drivers such as geopolitical risk at the base, where they influence numerous higher-level barriers within the ecosystem [Ojha et al., 2024]. These findings align with thematic observations from the Indian context, where digital transformation is hindered by gaps in infrastructure, investment, skilled talent, and cross-functional integration [Human Resource.., 2019; Singh, Kaur, 2025].

The inherent complexity of the Indian automotive workforce ecosystem demands holistic interventions. Strategic alliances between industry leaders and academic institutions are pivotal in bridging skill gaps, updating curricula, and preparing the workforce comprehensively for future demands [Human Resource.., 2019; Singh, Kaur, 2025]. Public-private partnerships in R&D, skills development, and digital infrastructure are integral to sustainable progress. Incremental adoption of modular or scalable technologies may reduce cost barriers, especially for smaller enterprises [Singh, Kaur, 2025].

This research emerges from the context of these multifaceted challenges and opportunities. By engaging practitioners and academicians through targeted semi-structured interviews, this study seeks to illuminate the core variables affecting skilled workforce adoption in the era of automotive digital transformation. Through the lens of ISM and MICMAC, the study aims to map the critical barriers, their hierarchical interrelationships, and their strategic significance for India’s automotive sector. The findings are intended to inform not only industry stakeholders but also policymakers and educators of

actionable pathways for workforce development and ecosystem enhancement.

The convergence of digital transformation and workforce dynamics in India's passenger vehicle sector is ultimately a story of adaptation, resilience, and innovation. As the sector navigates the complexities of automation, AI, connected ecosystems, and electric mobility, the challenge lies in equipping the workforce with the skills and agility required to drive the next phase of growth. Achieving this adaptation calls for a concerted effort to dismantle entrenched barriers, foster collaboration, and implement systemic change driven by evidence-based strategies. With sound leadership, forward-thinking policies, and expert-guided strategic models such as ISM and MICMAC, India's automotive sector can harness the vast opportunities of digital transformation while overcoming the persistent barriers to skilled workforce adoption [Ojha et al., 2024; Singh, Kaur, 2025].

1. Literature Review

The digital transformation of the Indian passenger vehicle sector is progressing rapidly, driven by emerging technologies woven into the fabric of Industry 4.0, encompassing artificial intelligence (AI), the Internet of Things (IoT), robotics, cloud computing, and advanced data analytics [Ojha et al., 2024; Singh, Kaur, 2025]. This transformation is altering manufacturing processes, product design, and business models, offering substantial competitive advantages. Yet, the full realization of these benefits depends on the availability and effective adoption of a skilled workforce proficient in these complex digital competencies [Human Resource.., 2019; Singh, Kaur, 2025]. The literature vividly illustrates a persistent and multifaceted set of barriers constraining the adoption of such a workforce, especially within India's passenger vehicle sector, which remains at an inflection point, balancing traditional manufacturing legacies with disruptive digital demands [Kamble et al., 2018b; Ojha et al., 2024].

1.1. Digital Transformation and Workforce Challenges in the Indian Automotive Sector

Recent studies underscore that digital transformation is more than the introduction of technology; it represents a paradigm shift requiring workforce realignment, continuous skill enhancement, and organizational cultural change. [Ojha et al., 2024] highlights the complexity of implementing Industry 4.0, wherein workforce skills not only support but also drive digital innovations, including automation, predictive analytics, and connected vehicle technologies. Similarly, [Singh, Kaur, 2025] emphasize India's governmental policy framework, such as Digital India and Skill India, which aims to synchronize workforce competencies with industry needs but faces challenges in execution and reach, particularly in semi-urban and rural manufacturing hubs lacking digital infrastructure.

Literature across the past decade points to three dominant workforce-focused barriers: skill deficits, inadequate training infrastructure, and organizational resistance to digital adoption [Kamble et al., 2018a; Ojha et al., 2024]. Skill deficiencies span core digital skills such as data analytics, cybersecurity, AI, and machine learning, as well as soft skills related to adaptability and change management [Human Resource.., 2019; Singh, Kaur, 2025]. Many technical education institutes continue to rely on curricula that lag behind fast-evolving industry requirements, perpetuating a gap between fresh graduates' capabilities and market expectations [Ojha et al., 2024]. Workforce upskilling and reskilling emerge as critical intervening forces, although current efforts remain fragmented and insufficient in scale [Singh, Kaur, 2025].

Organizational resistance, often caused by entrenched legacy systems and hierarchical corporate cultures, limits adoption momentum within automotive companies [Kamble et al., 2018a; Ojha et al., 2024]. Resistance is not only evident at the operational level but also among middle and senior managers, where fear of redundancy, unfamiliarity with digital processes, and inertia may prevail [Ojha et al., 2024]. Literature documents that overcoming such resistance requires top management support, transparent change management strategies, and inclusive communication that involves workers at all levels [Kamble et al., 2018b].

Furthermore, SMEs face unique challenges due to limited financial resources, the smaller scale of training initiatives, and uneven access to cutting-edge technology [Ojha et al., 2024]. Government subsidies and incentives, while present, tend to be skewed toward larger OEMs, creating disparities in workforce digital readiness between tier-1 manufacturers and their smaller suppliers or contractors [Singh, Kaur, 2025].

Other notable barriers discussed in the literature include cybersecurity risks associated with interconnected manufacturing environments, the lack of standardized protocols for technology integration, and policy-level ambiguities around data protection and digital labor laws [Ojha et al., 2024; Singh, Kaur, 2025]. These infrastructural and regulatory gaps exacerbate workforce uncertainties, reducing motivation to adopt new skills or invest heavily in digital transformation efforts [Ojha et al., 2024].

1.2. Methodologies in Literature to Analyze Workforce Adoption Barriers

Among the analytical techniques used to understand these barriers, Interpretive Structural Modeling (ISM) and MICMAC (Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement) analysis feature prominently in recent automotive Industry 4.0 research [Kamble et al., 2018b; Ojha et al., 2024]. ISM offers a structured method to decompose complex interrelated factors into a hierarchical model that clarifies root causes, intermediate catalysts, and dependent outcomes [Ojha et al., 2024]. MICMAC complements this by classifying barriers into autonomous, linkage, dependent, and driving clusters according to their driving and dependence power, offering stakeholders a clear roadmap for prioritizing interventions [Kamble et al., 2018b].

Literature applies ISM and MICMAC extensively in scenarios characterized by technological complexity and organizational interdependence, such as smart manufacturing ecosystems and digital supply chains [Kamble et al., 2018a; Ojha et al., 2024]. These techniques facilitate consensus-build-

ing among experts from industry and academia, revealing the multi-layered nature of barriers that might otherwise appear isolated or unrelated [Ojha et al., 2024]. For the Indian automotive sector, these models enable a nuanced visualization of how factors such as infrastructure deficits, workforce competencies, organizational culture, and policy frameworks dynamically influence one another.

1.3. Research Objectives

Building on these substantial insights, this research aims to advance understanding specifically within the Indian passenger vehicle sector, where skill adoption barriers pose a strategic bottleneck for sustained digital transformation. The objectives of this study are as follows:

1. To identify and validate the critical barriers impacting skilled workforce adoption in the era of automotive digital transformation within the Indian passenger vehicle industry.
2. To analyze the interrelationships and hierarchical structure of these barriers utilizing Interpretive Structural Modeling (ISM).
3. To classify and map the driving and dependence power of the barriers through MICMAC analysis.
4. To provide strategic recommendations for policymakers, industry leaders, and educators aimed at overcoming these barriers and accelerating workforce digital readiness.

1.4. Top Ten Variables Impacting Skilled Workforce Adoption

Based on a comprehensive literature survey and expert interviews, the top ten variables impacting skilled workforce adoption in automotive digital transformation are as follows:

- Inadequate training and skill development infrastructure

The lack of modern training centers, industry-relevant curriculum, and continuous professional development programs hampers workforce readiness [Human Resource.., 2019; Singh, Kaur, 2025].

- Organizational resistance to change

Cultural inertia and apprehension among employees and middle management obstruct the uptake of new digital processes and technologies [Kamble et al., 2018a; Ojha et al., 2024].

- Lack of industry-academia collaboration

Weak linkages between automotive firms and educational institutions result in misaligned skill development efforts and limited practical training opportunities [Ojha et al., 2024; Singh, Kaur, 2025].

- Insufficient digital literacy among existing workforces

Many current employees have inadequate exposure to digital tools and concepts, limiting their ability to adapt to Industry 4.0 environments [Human Resource.., 2019; Singh, Kaur, 2025].

- High implementation costs of digital technologies

The significant capital investment required for automation, IoT, and AI tools deters many firms, especially SMEs, from committing fully to digital workforce enablement [Ojha et al., 2024].

- Inadequate IT infrastructure and connectivity

Especially in tier-2 and tier-3 cities, poor internet connectivity and outdated digital infrastructure limit the scope of digital transformation [Ojha et al., 2024; Singh, Kaur, 2025].

- Cybersecurity concerns and data privacy

Growing cyber threats and unclear regulatory guidelines contribute to workforce hesitation and cautious adoption of digital technologies [Ojha et al., 2024; Singh, Kaur, 2025].

- Policy and regulatory uncertainties

Ambiguities in digital labor laws, data governance, and the lack of concrete government incentives hinder strategic planning for workforce transformation [Singh, Kaur, 2025].

- Limited awareness and understanding of digital transformation benefits

Both managers and employees often lack comprehensive knowledge about the potential advantages, contributing to hesitancy and resistance [Kamble et al., 2018a].

- Workforce adaptability and change management deficits

The ability to manage change effectively at all organizational levels remains limited due to insufficient leadership focus and training [Ojha et al., 2024].

1.5. Implications from Literature

The literature consistently suggests that these barriers do not exist in isolation but form a dense network of cause-and-effect relationships that must be understood holistically [Kamble et al., 2018a; Ojha et al., 2024]. For example, inadequate training infrastructure is a primary driver that exacerbates digital literacy gaps and workforce adaptability issues. Similarly, organizational resistance often stems from limited awareness and poor change management, which can be mitigated through stronger industry-academia partnerships and government incentives [Singh, Kaur, 2025]. Studies recommend that addressing these variables through targeted policies, strategic industry collaboration, and investment in scalable training solutions will prove vital to accelerating India's automotive digital transformation and workforce development [Ojha et al., 2024; Singh, Kaur, 2025]. The deployment of ISM and MICMAC analyses offers a pragmatic pathway for stakeholders to prioritize interventions and optimize resource allocation effectively.

2. Research Methodology

The research methodology for this study is structured around qualitative inquiry, employing semi-structured interviews in combination with Interpretive Structural Modeling (ISM) and MICMAC analysis to explore the interrelationships and hierarchical structure of barriers to skilled workforce adoption within the Indian passenger vehicle sector's digital transformation initiatives. This multi-step methodology is grounded in emerging best practices discussed in recent literature on automotive industry transformation and workforce agility [Debnath et al., 2023; Ruben et al., 2023; Ojha et al., 2024].

To comprehensively map the barriers and their interconnections, data collection was initiated via purposive sampling, targeting expert practitioners and academicians directly involved in or published on automotive digital transformation, with established publications in the field (ABDC A- or B-ranked journals). Potential respondents from leading automotive companies and academia were contacted via email and LinkedIn, with participation based on explicit written consent to ensure ethical com-

pliance and confidentiality [Bajpai, 2019; Singh, Kaur, 2025]. The study ultimately involved 10 expert participants out of the 40 approached, ensuring that the sample consisted of highly relevant stakeholders.

Semi-structured interviews were deployed as the primary qualitative data collection method. This technique offers a balance between guided inquiry and flexibility, allowing experts to elaborate on contextual and hidden dimensions of workforce barriers while ensuring systematic comparability across interviews [Bajpai, 2019; Horváth, Szabó, 2019; Ruslin, 2022]. Interviews were conducted from April 2024 to July 2025, each lasting approximately 60–90 minutes, and they were transcribed verbatim for detailed analysis. The use of semi-structured interviews aligns with contemporary qualitative research on industry change, where in-depth expert insights are crucial for capturing the dynamic interplay of technological, organizational, and policy-driven barriers [Bajpai, 2019; Horváth, Szabó, 2019; Singh, Kaur, 2025].

Once collected, the interview data were subjected to thematic analysis, which identified recurrent themes and distinct variables impacting skilled workforce adoption. Thematic coding was executed by two independent researchers to maximize validity and minimize bias, with disagreements resolved through consensus. From dozens of interview-derived statements, ten core variables were identified as primary barriers. These include inadequate training infrastructure, organizational resistance to change, limited industry-academia collaboration, insufficient digital literacy, high implementation costs, inadequate IT infrastructure, cybersecurity and data privacy concerns, policy/regulatory uncertainties, limited awareness of the benefits of digital transformation, and deficits in change management and adaptability.

Following qualitative coding, the ISM methodology was applied, adhering to the approach established by [Warfield, 1973] and adapted for the automotive context by recent scholars [Ojha et al., 2024; Debnath et al., 2023]. ISM supports the development of a hierarchical model illustrating how each barrier influences others within a structured matrix. First, a Structural Self-Interaction Matrix (SSIM) was developed from the expert sample, with pairs of variables systematically compared to establish directional relationships based on consensus judgments. The SSIM was subsequently used to construct initial and final reachability matrices, mathematically determining which barriers drive others and which are more dependent within the overall system [Ruben et al., 2023; Ojha et al., 2024].

Upon completion of the ISM phase, the established hierarchical order was subjected to MICMAC analysis, as introduced by [Faisal et al., 2009] and widely adopted in digital workforce studies within the manufacturing and automotive sectors [Debnath et al., 2023; Ojha et al., 2024]. MICMAC analysis groups the identified barriers according to their driving and dependence powers, classifying them into autonomous, dependent, linkage, and driving clusters for enhanced strategic clarity. Barrier variables with high driving power and low dependence, such as training infrastructure and IT investment deficits, were prioritized as strategic bottlenecks for intervention, while highly dependent variables, such as adaptability and awareness, were deemed outcomes that improve as driving barriers are addressed [Ruben et al., 2023; Ojha et al., 2024].

This mixed-method approach thus enables a comprehensive mapping of the barriers to skilled workforce adoption, linking qualitative depth and expertise with robust quantitative modeling. The integration of thematic coding, ISM, and MICMAC represents the methodological frontier in Industry 4.0 and automotive workforce research, providing both diagnostic insights and practical strategies for policymakers, educators, and industry leaders [Bajpai, 2019; Debnath et al., 2023; Ojha et al., 2024].

Ethical compliance was strictly maintained throughout the study. Participant data were anonymized and stored securely. Only experts with written informed consent were included, and the study protocol was reviewed for alignment with institutional ethical standards.

3. Research Analysis and Findings

This section presents the systematic analysis of the data collected from expert interviews. It details the application of Interpretive Structural Modeling (ISM) and MICMAC analysis to identify, structure, and classify the ten critical barriers to skilled workforce adoption within the Indian passenger vehicle sector.

The thematic analysis of expert interview transcripts yielded ten key barriers. For ease of analysis in the ISM and MICMAC processes, these barriers are assigned codes (B1 to B10), as shown in Table 1.

Table 1
Key Barriers to Skilled Workforce Adoption

Code	Barrier Description
B1	Inadequate training and skill development infrastructure
B2	Organizational resistance to change
B3	Lack of industry-academia collaboration
B4	Insufficient digital literacy among the existing workforce
B5	High implementation costs of digital technologies
B6	Inadequate IT infrastructure and connectivity
B7	Cybersecurity concerns and data privacy
B8	Policy and regulatory uncertainties
B9	Limited awareness of digital transformation benefits
B10	Workforce adaptability and change management deficits

Source: prepared by the authors.

The contextual relationships between the barriers were established based on expert opinions. The four symbols used to denote the direction of the relationship for each barrier pair (i, j) are:

- V: Barrier i leads to Barrier j;
- A: Barrier j leads to Barrier i;
- X: Barriers i and j lead to each other (mutual influence);
- O: No perceived relationship between the barriers.

The resulting SSIM is presented in Table 2.

In Table 2, the cell (B1, B2) has a 'V', meaning that experts agreed that inadequate training infrastructure (B1) leads to organizational resistance to change (B2).

The SSIM was converted into a binary initial reachability matrix using the following rules: V = 1, A = 1, X = 1, and O = 0. The transitivity of the contextual relations was then incorporated (i.e., if A leads to B and B leads to C, then A leads to C) to develop the final reachability matrix, shown in Table 3. The driving power and dependence of each barrier were calculated as the row sum and column sum, respectively.

The barriers were partitioned into different levels based on their reachability and antecedent sets. This iterative process helps determine the hierarchy, with the top level representing the least driving (most dependent) barriers.

Final level partition:

- Level I: Workforce Adaptability and Change Management Deficits (B10);
- Level II: Limited Awareness of Benefits (B9), Insufficient Digital Literacy (B4), High Implementation Costs (B5), and Cybersecurity Concerns (B7);
- Level III: Organizational Resistance to Change (B2);
- Level IV: Inadequate IT Infrastructure (B6) and Policy Uncertainties (B8);
- Level V: Lack of Industry-Academia Collaboration (B3);
- Level VI: Inadequate Training Infrastructure (B1).

Interpretive Structural Modeling (ISM) was used to determine the hierarchical relationships among the ten barriers to skilled workforce adoption in the digital transformation of India's

Table 2
Structural Self-Interaction Matrix (SSIM)

Barrier	B10	B9	B8	B7	B6	B5	B4	B3	B2
B1	V	V	V	V	V	V	V	V	V
B2	V	V	A	A	A	A	A	A	–
B3	V	V	V	A	V	V	V	–	–
B4	A	A	A	A	A	A	–	–	–
B5	A	A	A	A	A	–	–	–	–
B6	V	V	V	A	–	–	–	–	–
B7	A	A	A	–	–	–	–	–	–
B8	V	V	–	–	–	–	–	–	–
B9	A	–	–	–	–	–	–	–	–

Source: prepared by the authors.

Table 3
Final Reachability Matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	Driving Power
B1	1	1	1	1	1	1	1	1	1	1	10
B2	0	1	0	0	0	0	0	1	1	1	4
B3	0	1	1	1	1	1	1	1	1	1	9
B4	0	0	0	1	0	0	0	0	0	1	2
B5	0	0	0	0	1	0	0	0	0	1	2
B6	0	1	0	1	1	1	1	1	1	1	8
B7	0	0	0	0	0	0	1	0	0	1	2
B8	0	1	0	1	1	1	1	1	1	1	8
B9	0	0	0	0	0	0	0	0	1	1	2
B10	0	0	0	0	0	0	0	0	0	1	1
Dependence	1	5	2	5	5	4	5	5	6	10	

Source: prepared by the authors.

passenger vehicle sector. Based on expert interviews and matrix development, the ISM hierarchical order is presented in Table 4.

Table 4
Analysis of Barriers to Skilled Workforce Adoption

Level	Barrier	Role
1	Inadequate training infrastructure	Driver
1	Inadequate IT infrastructure and connectivity	Driver
2	Policy and regulatory uncertainties	Linkage
2	High implementation costs	Linkage
3	Lack of industry-academia collaboration	Linkage
3	Organizational resistance to change	Linkage
4	Cybersecurity and data privacy concerns	Linkage
5	Insufficient digital literacy	Dependent
5	Limited awareness of digital transformation benefits	Dependent
5	Workforce adaptability and change management deficits	Dependent

Source: prepared by the authors.

Drivers are foundational barriers, exerting high influence over other variables; linkage barriers interact both upward and downward; dependent barriers are more likely to be effects than causes.

Explanatory notes on ISM levels

- Level 1 (Drivers):

Inadequate training and IT infrastructure are found at the base level, signifying their critical role in influencing all other barriers. Improvements here cascade upward, enabling progress in other areas [Ojha et al., 2024].

- Levels 2–4 (Linkage):

Barriers like policy/regulation, implementation cost, industry-academia collaboration, organizational resistance, and cybersecurity are positioned centrally. Their status as linkage barriers means that actions taken here will impact multiple connected areas. For example, improving policy clarity can reduce implementation costs and incentivize collaboration [Ruben et al., 2023].

- Level 5 (Dependents):

Barriers such as digital literacy gaps, limited awareness, and adaptability are largely outcomes shaped by the preceding levels. When fundamental and linkage barriers are addressed, these dependent barriers tend to improve in tandem [Kamble et al., 2018]

The MICMAC analysis was performed by plotting the driving power and dependence of each barrier from Table 3 on a graph, categorizing them into four clusters.

MICMAC analysis was performed to assess each barrier's driving and dependency power. Below is the summary presented in Table 6.

Driving barriers (bottom row): These serve as system bottlenecks; improving them yields the strongest effect on overall skilled workforce adoption.

Linkage barriers (middle cluster): Critical transit points; any improvement or deterioration here impacts both drivers and dependents.

Dependent barriers (upper cluster): Outcomes reliant on the successful management of drivers and linkages; they are endpoints in the barrier network.

As applied in this study, ISM translates qualitative expert insights into a quantitative hierarchy, enabling the identification of root causes that must be prioritized for effective skilled workforce adoption [Ojha et al., 2024]. MICMAC's classification complements this by indicating which barriers are most likely to respond to targeted interventions and which will improve as foundational barriers are addressed. The analysis highlights that training, IT infrastructure, and regulatory clarity are the most influential levers for ecosystem change, whereas adaptability, awareness, and digital literacy function as outcomes of strategic progress. Systemic innovation, therefore, relies on concentrated action at the base and linkages of the hierarchy, with cascading benefits for dependent variables [Kamble et al., 2018a; Fauzdar, 2022].

4. Discussion of the Findings

The ISM and MICMAC analyses reveal a clear and actionable structure within this complex web of barriers.

Root Cause Barriers (Cluster IV: Independent Drivers): The analysis identifies inadequate training infrastructure (B1) and lack of industry-academia collaboration (B3) as the most powerful fundamental drivers. Experts consistently highlighted that, without modern labs, updated curricula, and strong, practical collaboration between companies and universities, the pipeline of skilled talent cannot be established. These barriers sit at the base of the ISM hierarchy, initiating a chain of effects that propagates through the entire system.

Table 5
MICMAC Clustering of Barriers

Cluster	Driving Power	Dependence	Barriers	Interpretation
I. Autonomous	Low	Low	–	No barriers fall in this cluster, indicating that all are integral to the system
II. Dependent	Low	High	B4, B5, B7, B9, B10	These are outcome barriers. They have weak driving power but are highly dependent on others. They are often the most visible symptoms of the underlying barriers
III. Linkage	High	High	B2, B6, B8	These are unstable, strategic barriers. Any action on them will have a ripple effect on other barriers and feedback on themselves. They require careful management
IV. Independent (Drivers)	High	Low	B1, B3	These are the root-cause barriers. They have high driving power and low dependence, meaning that they influence the entire system but are not themselves influenced by many other barriers. Addressing these is crucial for systemic change

Source: prepared by the authors.

Table 6
MICMAC Barrier Strength Analysis

Barrier	Driving Power	Dependency Power	Cluster
Inadequate training and skill infrastructure	High	Low	Driving
Inadequate IT infrastructure and connectivity	High	Low	Driving
Policy and regulatory uncertainties	High	High	Linkage
High implementation costs	High	High	Linkage
Cybersecurity and data privacy concerns	Medium	High	Linkage
Lack of industry-academia collaboration	Medium	High	Linkage
Organizational resistance to change	Medium	High	Linkage
Insufficient digital literacy	Low	High	Dependent
Limited awareness of benefits	Low	High	Dependent
Workforce adaptability and change management deficits	Low	High	Dependent

Source: prepared by the authors.

Strategic Leverage Points (Cluster III: Linkage Barriers): Inadequate IT infrastructure (B6), policy and regulatory uncertainties (B8), and organizational resistance to change (B2) form a critical strategic cluster. These barriers have high driving and dependence power, acting as crucial intermediaries. For instance, poor IT infrastructure (B6) directly causes high implementation costs (B5) and low digital literacy (B4). Similarly, unclear policies (B8) foster uncertainty, discouraging investment in training (B1) and technology adoption (B5). Addressing these linkage barriers can create positive feedback loops throughout the system.

Outcome Barriers (Cluster II: Dependent Barriers): The top of the ISM hierarchy and the dependent cluster in MICMAC are populated by barriers that are primarily outcomes of the deeper, driving barriers. High implementation costs (B5), insufficient digital literacy (B4), cybersecurity concerns (B7), limited awareness (B9), and, ultimately, workforce adaptability deficits (B10) are the most visible manifestations. The analysis suggests that simply targeting these dependent barriers (e.g., through awareness campaigns) will be ineffective if the root causes and linkage barriers are not simultaneously addressed.

The ISM model provides a strategic roadmap: interventions must be prioritized from the bottom up. Investing in modern training infrastructure (B1) and fostering industry-academia partnerships (B3) will alleviate pressure on IT infrastructure needs (B6) and help clarify policy requirements (B8). This, in turn, will reduce organizational resistance to change (B2), lower the perceived costs and risks, improve digital literacy, and finally lead to a more adaptable and skilled workforce (B10). This structured understanding moves the conversation from treating symptoms to addressing the core causes of the skilled workforce gap in India's digitally transforming automotive sector.

5. Recommendations and Suggestions

The ISM hierarchy and MICMAC analysis provide a clear, evidence-based roadmap for strategic intervention. The findings indicate that tackling the root causes and linkage barriers is paramount to creating a cascading positive effect throughout the entire ecosystem. The following recommendations are structured for key stakeholders: policymakers, industry leaders, and academic institutions.

Strategic recommendations based on ISM/MICMAC findings:

- For policymakers and industry: Launch a national automotive digital skills mission as a public-private partnership (PPP). This mission should be developed in collaboration with OEMs and large suppliers to establish Centers of Excellence (CoEs) for emerging technologies, including AI, IoT, Robotics, and EV technologies, within existing premier engineering institutes and ITIs. The curriculum must be co-designed and regularly updated by a consortium of industry experts to ensure relevance.
- For academia: Implement a mandatory industry immersion policy for faculty in automotive engineering and computer science departments. Encourage and incentivize sabbaticals for professors to work in R&D divisions of automotive companies to bridge the theory-practice gap.
- For policymakers: Develop a phased digital infrastructure upgrade plan for industrial clusters, especially in Tier-2 and Tier-3 cities. Provide tax benefits and subsidies for companies investing in high-speed connectivity and cloud computing infrastructure. In addition, establish a clear and stable digital automotive policy framework that clarifies data privacy, cybersecurity standards, and intellectual property rights for collaborative R&D, thereby reducing policy and regulatory uncertainties (B8).
- For industry leaders: Champion change leadership programs, not just change management. Top management must visibly sponsor digital initiatives and empower mid-level managers to become ambassadors of change. Create cross-functional digital transformation task forces that include shop-floor employees to foster ownership and reduce resistance (B2).
- For industry: Develop modular, scalable digital solutions that offer a lower cost of entry for SMEs, thereby addressing the perception of high implementation costs (B5). Implement continuous digital literacy upskilling programs for the existing workforce, focusing on practical, hands-on training rather than theoretical concepts to address insufficient digital literacy (B4).
- For all stakeholders: Launch a coordinated digital transformation awareness campaign showcasing success sto-

ries from leading Indian automakers. Use case studies to demonstrate tangible ROI, safety improvements, and job enhancement rather than merely job replacement, thereby increasing awareness and reduce fear (B9).

Stakeholder-specific action plans

For policymakers (central and state governments):

- Incentivize collaboration: Offer additional tax deductions for companies that sponsor student projects, offer internships, and collaborate with academia on curriculum design.
- Fund future skills: Expand the scope of the Skill India Mission and the FAME scheme to specifically include subsidies for advanced digital skill certification programs (e.g., in, additive manufacturing, and cybersecurity) for the automotive workforce.
- Build secure infrastructure: Prioritize the development of secure, high-bandwidth digital infrastructure in automotive manufacturing hubs as part of the Smart Cities Mission.

For industry leaders (OEMs, SMEs, Tier-1 suppliers):

- Adopt a phased approach: Instead of undertaking a full-scale transformation, start with pilot projects in one plant or department. Demonstrate quick wins to build confidence and secure wider buy-in, mitigating resistance and perceived risk.
- Invest in internal change agents: Identify and train high-potential employees to become in-house digital champions and trainers. This is often more effective than relying on external consultants and helps build long-term internal capability.
- Develop clear career pathways: Map out new digital job roles and create clear upskilling pathways for existing employees. Show how mechanics can become robotics technicians or data analysts, making the transformation an opportunity for growth rather than a threat.

For academic and training institutions:

- Revitalize curricula: Move from annual curriculum reviews to dynamic, modular curriculum updates that can incorporate new technologies as they emerge. Introduce more project-based learning with real-world problems provided by industry partners.
- Focus on soft skills: Integrate modules on adaptability, critical thinking, problem-solving, and change management into technical programs to prepare graduates for a volatile technological landscape.
- Offer executive education: Create specialized certificate and diploma programs in automotive digital transformation aimed at upskilling current industry professionals, making such programs a key revenue stream and service to the industry.

6. Conclusion and Future Scope

The digital transformation of India's passenger vehicle sector is an inevitable and powerful force. However, its success is intrinsically tied to the readiness of its workforce. This study has moved beyond merely listing challenges by providing a structural model that reveals the root causes of barriers to skilled workforce adoption.

The analysis unequivocally shows that isolated interventions will yield limited results. A synergistic effort, starting with investments in collaborative training infrastructure (B1) and industry-academia partnerships (B3), is essential to build a strong foundation. This must be supported by policies that enable digital infrastructure development (B6) and reduce regulatory ambiguity (B8), while industry leaders actively work to overcome organizational resistance (B2).

By following the hierarchical roadmap presented in this study, stakeholders can strategically allocate resources to the areas where they will have the greatest impact, ensuring that the Indian automotive workforce not only adapts to the digital era but becomes a primary driver of innovation and global competitiveness.

Future Research

Statistical validation: The developed ISM model can be statistically validated using a larger sample and techniques such as Structural Equation Modeling (SEM).

Sector-specific replication: More nuanced barriers can be identified by replicating this research specifically for either the electric vehicle (EV) ecosystem or the auto-component manufacturing sector.

Dynamic modeling: Another valuable extension is the use of System Dynamics (SD), which would help simulate the impact of policy decisions on barrier removal over time.

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About the Authors

Anjali Thakran
Research Fellow, Department of Physics, National Taiwan University (Taipei, Taiwan); Research Center for Applied Sciences, Academia Sinica (Taipei, Taiwan). ORCID: 0000-0003-1250-2166.

Rajkumar Singh Rathore
PhD, Senior Lecturer, Associate Professor, and Program Director for the MSc in Computing and IT, School of Technologies, Cardiff Metropolitan University (Cardiff, United Kingdom). ORCID: 0000-0003-4571-1888.
Research interests: IoT security, cyber-physical system security, drone networking, in-vehicle communication.

Nimish Sanghi
Co-founder, CTO, and Chief Data Scientist of Paybooks, a SaaS HR and payroll platform for the Indian market; angel investor in SaaS software and AI-driven automation across India, the United States, and Singapore; MBA, Indian Institute of Management (Ahmedabad, India), Bachelor of Technology in Electrical Engineering, Indian Institute of Technology (Kanpur, India).

V. Maheshwari
School of Information Technology, Vellore Institute of Technology (Vellore, India). Scopus ID: 57218144235.
Research interests: blockchain vulnerabilities, software testing, software security, object-oriented analysis.
maheshwari.v2014@vit.ac.in

Supriya Lamba Sahdev
PhD, Associate Professor and Deputy Director, Alliance University (Karnataka, India); Amity International Business School, Amity University (Noida, India). ORCID: 0000-0001-5141-5538.
Research interests: open innovation, fintech, blockchain, conversational AI, international business.
slamba@amity.edu

作者简介

Anjali Thakran
台湾大学物理学系科研人员（台北，台湾）；中央研究院 应用科学研究中心（台北，台湾）。ORCID：0000-0003-1250-2166。

Rajkumar Singh Rathore
博士，副教授，卡迪夫城市大学技术学院（卡迪夫，英国）"计算机与信息技术"硕士项目负责人。ORCID：0000-0003-4571-1888。
研究方向：物联网安全、信息物理系统（CPS）安全、无人机网络、车内通信。

Nimish Sanghi
印度企业人力资源与薪酬管理SaaS平台 Paybooks（班加罗尔，印度）的联合创始人、技术总监兼首席数据科学家；私人风险投资人，投资于印度、美国和新加坡的SaaS解决方案、软件及基于人工智能的自动化项目；工商管理硕士（MBA），印度管理学院（Indian Institute of Management，艾哈迈达巴德，印度）；电气工程学士，印度理工学院（Indian Institute of Technology，坎普尔，印度）。

V. Maheshwari
韦洛尔理工学院信息技术学院（韦洛尔，印度）。Scopus ID：57218144235。
研究方向：区块链技术漏洞、软件测试、软件安全、面向对象分析。maheshwari.v2014@vit.ac.in

Supriya Lamba Sahdev
博士，副教授，联盟大学（卡纳塔克邦，印度）副主任；安米提国际商学院，安米提大学（Amity University，诺伊达，印度）。ORCID：0000-0001-5141-5538。
研究方向：开放式创新、金融科技、区块链、对话式人工智能、国际商务。
slamba@amity.edu

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Engineering and Economic Education for Technological Leadership: A Manifesto for Discussion

L.D. Gitelman[1]
M.V. Kozhevnikov[1]
[1] Ural Federal University named after the first President of Russia B.N. Yeltsin (Ekateriburg, Russia)

Abstract
The article substantiates the need to significantly strengthening engineering and economic education as a critical factor in achieving innovative leadership amid digital transformation and escalating shock changes. It identifies a systemic gap between engineering, economic, and managerial training, which results in low market demand for technological solutions and limits their scalability and competitiveness. The novelty of the study lies in the development of a comprehensive methodology for engineering and economic design that fosters specialists' ability to "think from the future," that is, to engage in proactive management and the design of leadership strategies. The article presents the authors' experience in developing and using a specialized scientific and educational platform, a digital teaching-and-training complex, and simulators as tools for advanced training in relevant competencies. The recommendations formulated in the article are proposed by the authors as a discussion document for the professional community.
Keywords: digitalization, interdisciplinarity, engineering and economic design, advanced training, scientific and educational platform

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面向技术领导力的工程—经济教育:一份供讨论的宣言

L.D. Gitelman[1]
M.V. Kozhevnikov[1]
[1]俄罗斯联邦首任总统 B.N. 叶利钦命名乌拉尔联邦大学（叶卡捷琳堡，俄罗斯）

摘要
本文论证了在数字化转型加速推进和不确定性不断加剧的背景下，大幅加强工程—经济教育作为实现创新优势关键因素的必要性。研究揭示了工程、经济与管理人才培养之间存在系统性脱节，这种脱节导致技术解决方案在市场上的市场需求不足、可扩展性较弱以及竞争力不强。本文的创新之处在于构建了一套完整的工程—经济设计方法论，培养专业人员"从未来出发思考"的能力，即开展前瞻性管理和引领性战略设计的能力。文章还介绍了专业化科研教育平台、数字化教学培训综合体及模拟训练系统的开发与应用经验，这些工具被用作开展前瞻性能力培养的手段。文中提出的建议被作者作为一份纲领性文件，供专业共同体讨论。
关键词： 数字化，跨学科性，工程—经济项目，超前学习，科研教育平台

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1. The Challenge: New Priorities Misaligned with Existing Competencies

Today's economy is marked by rapid technological change unfolding in an environment of extreme uncertainty. Digital infrastructure has become ubiquitous, permeating virtually every sphere of activity. Artificial intelligence (AI), predictive analytics, and digital twins make it possible to generate solutions within seconds through the real-time processing of massive volumes of unstructured data. Through the integration of sensors, human-machine interfaces, and the Internet of Things, production systems are evolving into cyber-physical systems in which equipment can transmit real-time performance data directly to enterprise resource planning (ERP) systems, enabling more efficient asset utilization and helping prevent operational disruptions and accidents [Kravchenko, 2025; Loginov et al., 2025].[1]

The pace of these changes is so intense that science is struggling to conceptualize them, while education lags even further behind in updating knowledge, competencies, and training models adequate to this new reality.

In this context, the state's strategic objective of achieving technological leadership in key industries depends to a large extent on its ability to introduce scalable innovations quickly, at lower cost, and with minimal risk. It is no longer enough to develop equipment or technologies with superior functional characteristics. They must also prove effective throughout their entire life cycle and possess a competitive market value already embedded at the earliest stages of innovation and design. In rapidly evolving sectors such as energy, aerospace, mechanical engineering, electrical engineering, transport, and telecommunications, the competency gap is becoming a major constraint on development.

The problem becomes especially acute when an economy must rapidly transition to a new model based on advanced scientific and technological achievements, intelligent production systems, neural-network technologies, and robotics. Under such conditions, the shortage of specialists capable of formulating tasks for these highly complex systems and interpreting not only their outputs but also their decisions in the shared language of engineering, economics, and IT is becoming increasingly evident [Gitelman et al., 2024].

What is now urgently needed is engineering and economic training for innovation-oriented professionals. The old model of professional education is no longer merely outdated; it is actively impeding development and generating losses. This problem must be addressed without delay.

A vivid example of the consequences of underestimating the importance of engineering and economic knowledge and competencies in large-scale innovation projects is the failure of the energy transition in many industrialized countries [Heinberg, 2022; Gitelman et al., 2023; Ahmed et al., 2025]. A mission driven by noble goals turned into an investment failure that might have been avoided had decision-makers and their advisers possessed even a basic grounding in engineering economics.

A major reason for this outcome was the failure to account for the technological specifics of the electric power industry and for the way these specifics are linked both to the sector's economic performance and to other sectors of the economy:

1. Insufficient consideration was given to the intermittent nature of wind and solar generation.
2. The economics of energy storage were not fully assessed, including end-of-life disposal; the cost of utility-scale storage makes green energy economically unviable without substantial subsidies.
3. Energy-transition programs were poorly aligned with the technological requirements for electricity and heat at industrial enterprises, which remain major sources of harmful emissions. As a result, industry found itself caught between two imperatives: decarbonization and the inability to ensure reliable energy supply without conventional generation.
4. Policymakers ignored a fundamental principle of engineering economics: reliable power supply is never cheap, but the absence of reliability is always more expensive.

These obvious failures effectively undermined the vision promoted by advocates of the energy transition:

- In engineering design, the behavior of power systems under large-scale integration of intermittent renewable energy sources was not properly modeled; nor was sufficient analysis conducted regarding the need for flexible capacity—such as pumped-storage hydro plants, gas-fired peaking plants, and storage systems—to offset downtime at wind and solar facilities.
- In economic modeling and risk assessment, the economics of the transition were calculated on the basis of average gas prices and equipment costs, without taking their volatility into account. Nor was adequate attention paid to the fact that the decommissioning of nuclear and coal-fired power plants made EU economies more vulnerable to climatic anomalies and geopolitical shocks.
- In environmental and sustainability assessment, no full life-cycle cost evaluation of green technologies was carried out. The production of solar panels and wind turbines requires vast amounts of rare-earth metals; their extraction and processing inflict serious environmental damage on supplier regions, while the disposal of end-of-life equipment remains unresolved [Fotis et al., 2025; Uchman et al., 2026].

The energy-transition case clearly shows that every technological solution has an economic dimension [Gitelman et al., 2023], and ignoring that dimension leads to major losses. This principle should be central to the edu-

[1] See also: https://национальныепроекты.рф/upload/doklad-cifra-2025/doklad-cifra-2025.pdf.

cation of the next generation of engineers, as well as economists, managers, and IT specialists. An engineer must be able to see the economic implications of every technical decision from the moment it is conceived: payback, sensitivity to market conditions, and attractiveness to investors. An economist must understand the physical nature of the assets being evaluated, their technological constraints, operating modes, wear patterns, and failure risks. A manager must possess enough technological literacy to manage projects with a clear understanding of scientific and technological trends and stakeholder interests. An IT specialist, in turn, must understand the business consequences of architectural decisions in terms of value creation and cost reduction.

2. Principles for Organizing Engineering and Economic Training for Innovation Personnel

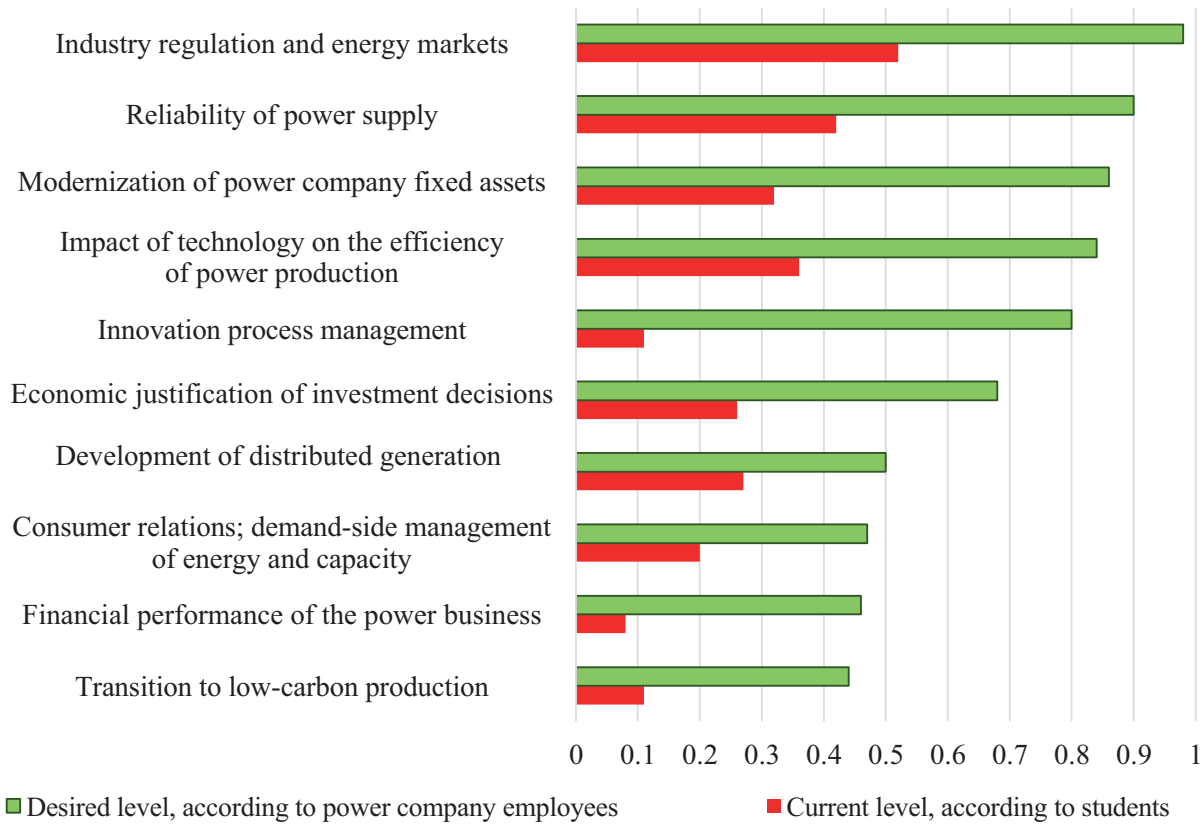
A central objective of engineering and economic training is to develop in specialists not only the ability to create a unique technical prototype, but above all the ability to ensure its market viability in large-scale production, that is, its scalability; to build an adequate business model, typically grounded in digital technologies; and to organize the innovation process effectively. This was a bottleneck in Soviet industry and remains one in Russia today: the country has still not succeeded in establishing competitive mass production in such sectors as automotive manufacturing, computer equipment, electronics, and household appliances. In highly competitive markets, it is essential to align the technical feasibility of a new product with the ability to produce it faster, at lower cost, with higher quality, and with greater consumer appeal than competing alternatives. Yet these are precisely the capabilities that engineers, economists, managers, and IT specialists are not being taught today.

As shown by the analysis presented in [Gitelman, Kozhevnikov, 2025], engineering education largely overlooks the interdisciplinary connections among technology, ecology, economics, and management, as well as topics of immediate relevance to modern industries, such as demand-side management and the energy transition (Figure 1).

At the same time, according to practicing specialists, these issues should be covered in far greater depth and scope, while the growing importance of competencies related to organizing innovation processes points to their relevance and acute shortage not only among engineers but also among managers at all levels (Table 1).

Let us formulate the key principles of a new type of engineering and economic training.

It is fundamentally important to begin this training in the



Source: compiled by the authors.

Fig. 1. Depth of Consideration of Engineering and Economic Issues in the Electric Power Industry Development

first year of study. As psychological research suggests, once a person has developed, by the age of 25–30, a mode of thinking based on rigid dichotomies that treat engineering and economics as mutually exclusive categories, it becomes extremely difficult to retrain them to think in interdisciplinary terms [Phan, Ngu, 2021; Ionescu et al., 2023]. By contrast, engineering and economic thinking is the ability to recognize the interdisciplinary nature of any professional decision. Specialists with this type of thinking, who are especially in demand in today's labor market, ask questions at the intersection of disciplines, such as: "How can a reliable design be developed within budget while ensuring an acceptable operating cost?" and "How can a project be made profitable while taking technological constraints and production risks into account?"

This kind of hybrid thinking cannot be developed in the later years of study simply by adding a course such as "Economics for Engineers" to the curriculum, because by that stage the student's intellectual lens has already been formed: they are accustomed to viewing a problem from only one perspective, either technical or economic. From the first year onward, therefore, students should simultaneously deepen their understanding of:

- their industry, including how value chains are organized and who the key players are;
- technologies and the specific features of production organization, including the main business processes, how the product is created, what it is made of, what costs are involved, and what physical, chemical, and software-related constraints must be taken into account. An engineer who has never been inside a production shop and an economist who does not understand how the production cycle is organized will speak different professional languages and make decisions that cannot be implemented;
- real business problems, including unmet customer needs and the reasons why some technologies gain market traction while others do not.

The main task for the student here is to see and understand how disciplinary fields intersect and enrich one another. They should not have to wait until the senior years to encounter special interdisciplinary courses. Engineering-and-economic thinking takes shape when, already in the first year, while studying, for example, strength of materials, a future engineer sees that the strength equation is linked to the choice of material, the choice of material is linked to its cost, and cost is linked to the market price of the product. A future manager or economist, when studying the fundamentals of investment management, should be able to see the real technological constraints behind financial indicators. Thus, choosing a cheaper solution that appears profitable in the short term may ultimately lead to lower equipment reliability, increased risks of accidents and operational disruptions, and, consequently, growing losses and declining trust on the part of consumers and investors over the long term.

Table 1
Main Barriers in Managerial Practice in the Electric Power Industry

Deficiency	Share of respondents reporting a pronounced manifestation of the deficiency (%)	
	2020	2025
Lack of competencies in innovation process management (investment appraisal, assessment of expected benefits and risks, employee engagement, teamwork)	42	72
Insufficient efforts to attract and develop young specialists for work on innovation projects	70	68
Lack of knowledge and practical experience in implementing digital tools and IT solutions in the company's operations	47	54
Poor understanding of the benefits that additional products and services, including digital ones, can bring to a power company beyond its core operations	72	46
Inability to respond in a timely manner to market changes and consumer needs	25	40
Lack of a project-based thinking and project management skills	48	38
Inconsistent and contradictory managerial decisions caused by a poor understanding of the interests of key stakeholders	17	36

Source: compiled by the authors.

These linkages must be embedded in the curriculum from the outset. Only then will students come to understand that engineering and economics are inseparable dimensions of the outcomes by which their work will ultimately be evaluated. That is why a model engineering-and-economic program should introduce students, from the very beginning of their studies, to the operation of advanced industrial facilities, helping them enter the profession and develop a real understanding of their industry and its connections with other sectors of the economy. In fields such as the electric power industry, nuclear power, petrochemical production, and transport, where reliability, environmental safety, and the human factor are of paramount importance, this sense of the industry is especially critical—and it cannot be developed in just one or two years.

A substantial expansion of enterprise-based practical training, with students involved from the early years of study in both operational and innovation-related tasks relevant to their future profession, is a policy decision that needs to be made at the state level.

Table 2 presents an example of a forward-looking specialist degree program for engineer-economists in the electric power industry. The program is balanced in its combination of fundamental and applied training as well as in its set of disciplines. It fosters an integrated understanding of the logic of scientific and technological progress and equips students with the tools needed to implement relevant innovation projects.

A strong emphasis on interdisciplinarity is built into the curriculum from the first year of study, enabling students to:

– develop an understanding of technologies and production systems as complex and socially responsible objects of management;
– learn to analyze the interrelationships among engineering, technology, ecology, economics, and management, including advanced IT systems and digitalization, in order to make sound decisions on business development, business process improvement, and the development of companies' areas of activity.

Table 2
A Fragment of the Engineering and Economics Degree Program Framework for the Electric Power Industry

<table>
<tr><th rowspan="2"></th><th colspan="5">Years of Study</th></tr>
<tr><th>Year 1</th><th>Year 2</th><th>Year 3</th><th>Year 4</th><th>Year 5</th></tr>
<tr><td>Key Disciplines</td><td>Introduction to the Field
Patterns of Scientific and Technological Development
General Mathematics
Economics and Organization of Energy Markets</td><td>Организация энOrganization of Power Production
Advanced Digital Technologies and AI
Applied Mathematics and Statistics</td><td>Economics of the Industry
Business Infrastructure of the Power Industry
Financial Mathematics
Investment and Risk Management</td><td>Production Asset Management in Power Companies
Strategic Management Under Uncertainty
Framing Engineering and Economic Problems
Investment Project Management
Personnel and Team Development</td><td>Business Analytics
Power Industry Engineering and Consulting</td></tr>
<tr><td rowspan="4">Main Active Learning Methods</td><td colspan="4">Interdisciplinary business simulations</td><td>Internships at power facilities</td></tr>
<tr><td colspan="3">Innovation-focused company visits</td><td rowspan="2">Workshops led by senior executives</td><td rowspan="3">Pre-defense presentations of final projects at power companies</td></tr>
<tr><td rowspan="2">Professional challenge tasks</td><td rowspan="2">Power production improvement projects</td><td>Analysis of companies' financial statements</td></tr>
<tr><td>Quantitative case studies</td><td>Management case studies</td></tr>
<tr><td>Type and Duration of Practical Training</td><td>Research internship (4 weeks)</td><td>Technical internship in a production unit of a power company (4 weeks)</td><td>Internship in the chosen specialization within a functional unit (4 weeks)</td><td>Engineering and economic internship in corporate management (8 weeks)</td><td>Pre-graduation internship combined with with managerial shadowing (16 weeks)</td></tr>
</table>

Source: compiled by the authors.

A related issue is the training of engineering personnel and the need to strengthen its engineering-and-economic component. As noted above, any engineering decision aimed at improving the technological level of production is inherently also a techno-economic decision. Ultimately, such decisions are evaluated in terms of the balance between their economic, environmental, and social outcomes and the financial resources required to achieve them. Engineering education must therefore include the corresponding organizational and economic dimensions. The most important of these are outlined below using the electric power industry as an example.

1. Industry organization and energy markets. The system of state regulation and governance in the industry. The effectiveness of market reforms in the electric power sector. Long-term industry development programs.
2. Efficiency of power production. Relationships between the technical characteristics of power installations and the environmental and economic performance of power companies.
3. Availability and reliability as the core functional characteristics of power facilities. The effect of availability on the economics of a power company. Assessing the cost-effectiveness of expenditures aimed at improving reliability. Advanced approaches to organizing maintenance and repair.
4. Production asset management. Renewal of the fixed assets of power companies. Equipment modernization, reconstruction, and technical upgrading of power facilities.
5. Financial resources of power companies.
6. Economic justification of investment decisions and projects. Taking technical and price risks into account when evaluating investment projects.
7. Innovation process management. Stages of the innovation process in a power company. Advanced technological innovations for power plants and grid companies. The impact of these changes on the profitability of power companies, production costs, and electricity prices. Energy engineering as an advanced tool for innovation process management.
8. Transition to low-carbon production.
9. Development of distributed generation.
10. Demand-side management of energy and capacity.
11. Digital transformation of power production and management.

It should be emphasized that engineering training remains incomplete unless the economic component of students' graduation projects is developed to a professional standard under the supervision of leading faculty members from specialized departments of economics and management. Without this component, the graduation project fails to develop the most important competency: the future engineer's ability to justify why a particular technical solution merits investment and how it will affect business performance. As a result, graduates enter the profession without having learned to connect engineering thinking with economic outcomes.

3. Special Emphasis on Fundamental Knowledge

A matter of ongoing debate is the so-called fundamental core of engineering-and-economic education. In our view, it should encompass three priority areas:

1) the scientific and technological foundations of industrial production, including digitalization, without which it is impossible to develop an integrated understanding of the objects and tasks of one's professional activity, recognize key development trends, or prepare even for the near future;
2) the methodology of innovation activity;
3) the design of complex systems and systems engineering [Gitelman et al., 2022b].

These areas define the content of the corresponding core disciplines needed in the education of engineers, managers, and economists alike (Figure 2). As a result, the content of fundamental training changes substantially across levels of education: at the undergraduate level, the focus is on specific fields of knowledge such as economics, engineering, and computer science, whereas at the master's level attention shifts to complex objects and processes, including the development of complex systems, strategic analytics, and future-oriented design.

An alternative structure for the fundamental component is also possible. In this approach, the curriculum is built around a relatively small number of core required courses that foster systems thinking and provide the mathematical foundation needed to address complex problems, as is common at leading universities worldwide [Reynolds, 2024]. These courses are complemented by a range of electives that broaden students' intellectual horizons and encourage greater flexibility of thought (Table 3).

Effective implementation of a stronger fundamental component would, of course, require changes in the set of entrance examinations and a higher admission threshold.

Under the Soviet education system, students entering either engineering or economics were expected to have a strong foundation in mathematics and the natural sciences. Even specialized economics institutes treated physics and advanced mathematics as essential subjects, recognizing that industry, energy, and transport cannot be managed effectively without an understanding of the physical processes that underpin them.

Today, most Russian universities admit applicants to economics and management programs with only a basic level of mathematics, and physics is often not required at all. As a result, many graduates have little understanding of technological constraints, are unable to estimate

	SCIENTIFIC AND TECHNOLOGICAL FOUNDATIONS OF PRODUCTION IN THE INDUSTRY	METHODOLOGY OF INNOVATION	DESIGN OF COMPLEX SYSTEMS. SYSTEMS ENGINEERING
TYPE OF KNOWLEDGE	Engineering-and-economic knowledge of the specific features and development patterns of particular production systems, markets, and industries	Understanding of the principles and methods used to study new paradigms of the innovation process	Mastery of methods for managing complex cyber-physical systems throughout their life cycle
FUNDAMENTAL DISCIPLINE	Power industry: economics, organization, and management	Management of innovation processes and projects	Fundamentals of systems thinking
AUTHORS' TEXTBOOKS AND ELECTRONIC MATERIALS	 	 	 

Source: compiled by the authors.

Fig. 2. The Author's Experience in Delivering Fundamental Training

production costs realistically, base managerial decisions on abstract reasoning, and struggle to work effectively with engineers. At a time when technological leadership and sovereignty have become national priorities, this situation is untenable. In our view, admission to economics and management programs should therefore require advanced mathematics, physics, and computer science, given the central role of digital technologies in the modern world.

China offers a revealing contrast. Admission to economics and management programs—especially at leading universities that train highly qualified specialists—typically requires strong preparation in advanced mathematics and the natural sciences. The gaokao, the national university entrance examination, includes mathematics and physics as core subjects for most engineering-and-economics tracks [Zhang, Pecheritsa, 2025]. The United States does not have a single national admissions standard, but leading universities generally expect applicants to undergraduate programs in economics and management to have a strong secondary-school background in mathematics, sometimes including introductory calculus, as well as in the natural sciences;

Table 3
Proposed Structure of Fundamental Training

Type of Discipline	Cource Title	Purpose
Core	Systems Analysis and Complexity Theory	Develops the ability to view systems holistically and understand the interrelationships among technical, economic, and organizational subsystems
	Mathematical and Simulation Modeling	Provides a common language and toolkit for describing, forecasting, and testing techno-economic processes without risking disruption to real-world production
Elective	Decision Theory under Uncertainty	Introduces tools for risk analysis, multicriteria decision-making, and scenario-based reasoning
	Life-Cycle Management of Complex Systems	Integrates design, economics, and management across the full life cycle of complex systems
	Fundamentals of Production Technology and Organization	Develops an understanding of technological constraints and real-world production processes
	Innovation Economics and R&D Management	Connects engineering creativity, economic efficiency, and innovation management
	Digital Transformation and Cyber-Physical Systems	Integrates digital technologies with production systems and economic decision-making
	Methodology of Interdisciplinary Research	Develops the ability to synthesize knowledge across fields and formulate problems at the intersection of disciplines

Source: compiled by the authors.

and at engineering schools that train future managers, physics is a required subject [Bouchrika, 2026].

4. Engineering and Economic Education in International Practice

An analysis of the curricula of engineering and economic programs offered by foreign universities reveals several major types [Gitelman et al., 2022a].

In programs designed to provide broad-based preparation for future managers, the curriculum can be broadly divided into two blocks: traditional subjects, such as finance and economics, accounting, quality management, human resource management, and operations management; and interdisciplinary subjects focused on the technological dimension of business, including systems engineering, innovation development in engineering and management, information and analytical systems, business modeling, and the management of industrial and business development projects.

Programs intended to prepare managers for specific industries characterized by greater technological complexity require students to study the technological specifics of production alongside the organizational and economic aspects of innovation activity.

Of particular interest to us are advanced programs aimed at training innovation-oriented specialists capable of developing, mastering, testing, and implementing the technologies of the future in engineering, IT, and the environmental sector. Illustrative examples include programs offered by Stanford University and the Massachusetts Institute of Technology (MIT).

Stanford's engineering management program is organized around six research areas that are directly integrated into the curriculum at both the undergraduate and graduate levels: computational social science; decision-making and risk analysis; operations research; organizations, technology, and entrepreneurship; policy and strategy; and quantitative methods of financial analysis. Among the key learning outcomes are mastery of mathematical methods, the ability to plan and conduct experiments, and the ability to design complex systems using systems engineering tools.

At MIT, the System Design and Management program is organized into three components. The first consists of core courses in engineering and management totaling 36 credit units. The second includes required advanced courses—12 credit units in engineering and 12 in management. The third comprises student electives, with a broad selection of approximately 150 engineering courses, 50 management courses, and 30 interdisciplinary courses.

The architecture of such programs is generally based on the principles of STEM, understood as the integration of Science, Technology, Engineering, and Mathematics [Gromova et al., 2025; Torralba, Membrillo-Hernández, 2025]. STEM is viewed as a concept of interdisciplinary, problem-based learning that engages students in:

- activities related to the design, development, and operation of technological systems;
- case-based discussions of current issues in science, technology, and the social sphere;
- addressing the challenges faced by specific industries and companies through the application of fundamental scientific knowledge and an understanding of technological development;
- individual and team-based work on problems characterized by a high degree of uncertainty.

In recent years, one of the main forces shaping engineering and economic education worldwide has been the rapid advance of digital technologies. In China, for example, the state has explicitly defined the digital economy as a driver of technological leadership, artificial intelligence as a source of competitive advantage, and higher education that integrates cutting-edge digital and AI technologies as a key engine of innovation [Chentsova, Chentsov, 2023]. A striking example is Chongqing University of Science and Technology, where students in the School of Civil Engineering are trained through a multi-level integration of AI tools, including digital twins for assignments, neural-network-based generation of images and digital avatars for case development, and simulation platforms for visualizing financial evaluations[2].

The American approach is equally instructive. One of the defining trends in the United States today is close collaboration with industry combined with a strong emphasis on AI-related career pathways.

Texas A&M University, together with the Microsoft AI Economy Institute, is implementing a project titled "The Evolving Role of Universities in the Age of AI: Opportunities to Advance AI Literacy through Interdisciplinary Curriculum Design." The project examines how universities can prepare students for the labor market by embedding competencies in big data, machine learning, and AI ethics into academic programs[3].

At Carnegie Mellon University, the master's program in business technology strategy prepares specialists to apply AI to breakthrough challenges at the intersection of engineering, economics, and information technology. As part of dedicated project-based practicums, students develop neural-network models for analyzing market trends, simulation environments for testing complex scenarios using large language models, and AI assistants to support decision-making in dynamic and uncertain environments[4].

The Chinese and American examples discussed above confirm that the future of engineering and economic edu-

[2] Deng Y. Chongqing University Launches AI-Powered Courses. https://app.ichongqing.info/mixmedia/a/202503/12/WS67d18bdfe4b0f27cb3591f03.html.
[3] Texas A&M Energy Institute Partners with Microsoft AI Economy Institute to Advance AI Literacy and Workforce Readiness. https://energy.tamu.edu/news_item/texas-am-energy-institute-partners-with-microsoft-ai-economy-institute-to-advance-ai-literacy-and-workforce-readiness/.
[4] Signature Initiative: Collaborative AI. https://tepper.pantheon.cmu.edu/tepper/about/strategic-plan/signature-initiative-collaborative-ai.

cation lies in embedding digital tools and artificial intelligence at its core.

5. A Method for Aligning Engineering and Economic Education with Technological Leadership

The method of the Engineering and Economic Project of technological leadership (hereinafter, EEP), developed at the Department of Energy and Industrial Management Systems of Ural Federal University, is built around a vision of the future of an industry or enterprise. It identifies the competencies needed to realize that vision, addresses the resulting skills gap through anticipatory training, and turns engineering and economic education into both a methodological framework and a practical instrument for implementing a leadership strategy[5].

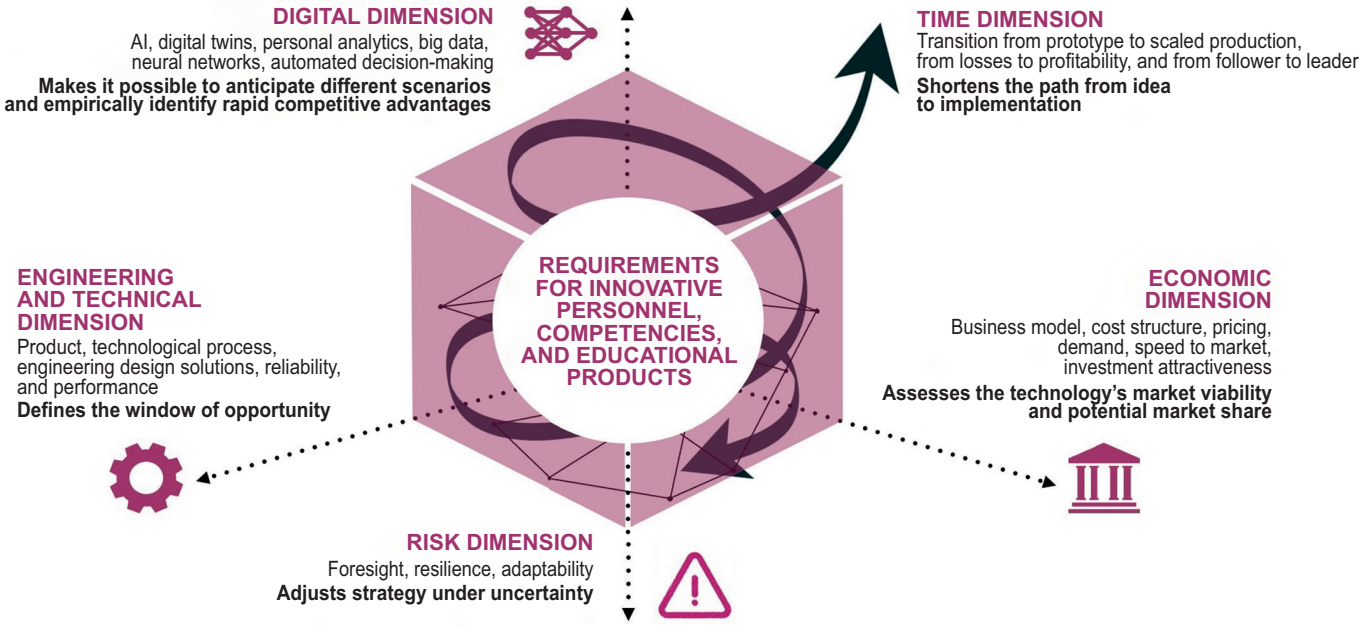
As noted in our earlier publications [Gitelman, Kozhevnikov, 2025; Gitelman et al., 2025], EEP performs an integrating function by aligning the economic interests of producers and consumers when assessing the market viability of engineering solutions. In this context, the EEP is described as a multidimensional model in which four different coexist and influence one another in real time (Figure 3).

A distinctive feature of the EEP method is that it structures the innovation process around a forward-looking logic that the authors describe as "thinking from the future." Unlike a conventional techno-economic feasibility study, it is closely linked to anticipatory management [Gitelman, 2020], oriented toward future conditions, and built on scenario-based modeling under uncertainty. Rather than being evaluated against a single baseline forecast, a project is assessed across multiple possible futures shaped by technological change, regulatory shifts such as the introduction of a carbon tax, fluctuations in fuel and resource prices, changing consumer preferences, and other risk factors.

It is important to emphasize that, unlike the conventional engineering and economic approach, in which engineers develop technical solutions, economists assess them mainly in cost terms, and environmental specialists address environmental consequences only after implementation, the EEP method requires specialists from different fields to work in an integrated way from the earliest conceptual stage. Each technical solution is therefore assessed simultaneously against several groups of criteria, including:

- technical criteria: reliability, safety, compliance with standards, and digital maturity;
- economic criteria: total cost of ownership over the asset life cycle, payback, and sensitivity to external factors;
- environmental criteria: carbon footprint, environmental impact, recyclability, and compliance with current and anticipated regulatory requirements (Figure 4).

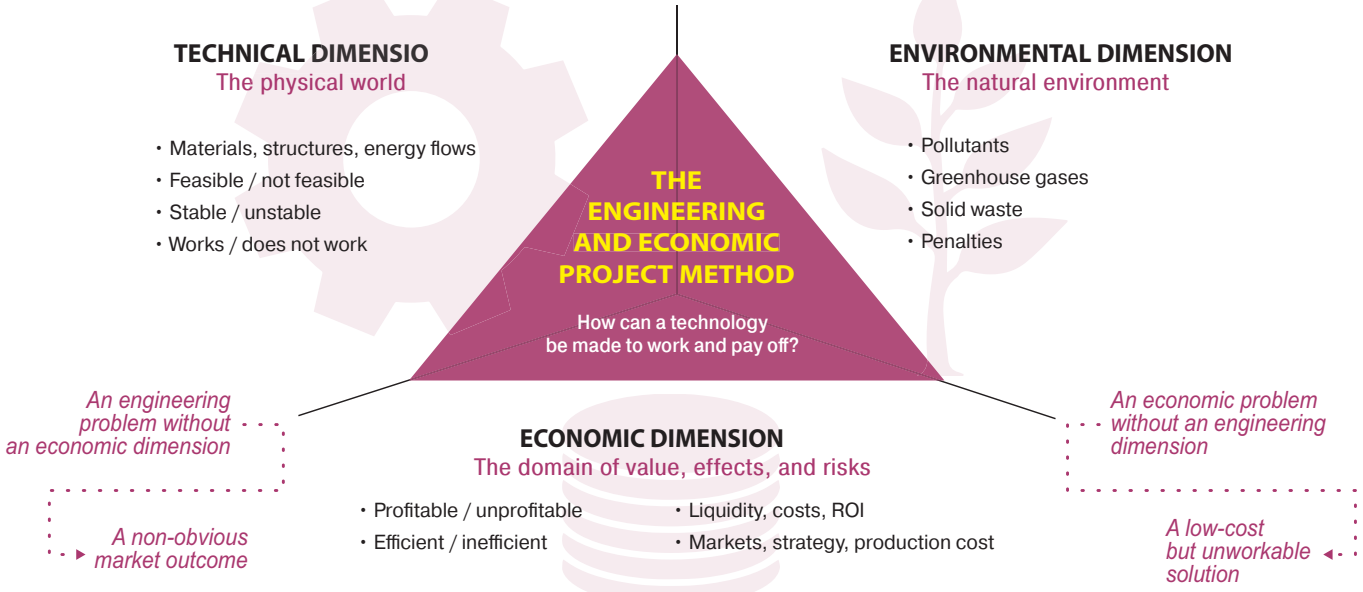
The EEP method creates a fundamentally different educational architecture and makes anticipatory training for technological leadership possible. This is achieved through



Source: compiled by the authors.

Fig. 3. Engineering and Economic Design as a Multidimensional Model

[5] A detailed account of the theoretical foundations and functional capabilities of the EEP is provided in the authors' two forthcoming books, The Engineering and Economic Project: Innovation Personnel and Solutions for Technological Leadership and The Engineering and Economic Project: A Guide to Developing Competencies for Technological Leadership, both of which are currently in press and scheduled for publication in the second quarter of 2026.



Source: compiled by the authors.

Fig. 4. The EED Method: Integrating Engineering Thinking and Market Perspective

a set of interrelated mechanisms embedded in the method itself.

The first of these is specially organized anticipatory problem framing, that is, the systematic identification and formulation of future challenges [Gitelman, 2020]. Traditional education typically gives students problems that already have known solutions. In effect, the past is passed on to the present in the form of ready-made answers. EEP reverses this logic. Instead of solving tasks with predetermined outcomes, students are placed in future-oriented problem situations—challenges industry is likely to face in 5, 10, or 15 years. Using digital tools, they model the production systems of tomorrow while taking into account expected technological shifts, changes in market conditions, the emergence of new materials, new regulatory requirements, and logistical constraints.

The second mechanism is an active innovation process. Students learn to treat the analysis of complex change, continuous problem framing, and the transformation of problems into projects as a normal part of their work. This places particular emphasis on teamwork in a digital environment. The digital platform continuously introduces new variables: energy prices change, a cheaper material appears, new environmental restrictions are imposed, or a competitor launches a breakthrough technology. Each time, students must recalculate the economics of their project and look for new engineering solutions. At the same time, they must collaborate with peers and consult experts, including AI tools, on specific issues. This is how competence in team-based innovation activity is developed.

The third mechanism is the development of a future-driven vision through digital twins. Within the EEP framework, a digital twin helps students conceptualize a product and a production system that will be both effective and in demand under projected future conditions. An AI assistant supports this process by analyzing global trends, identifying the competencies and decisions likely to become critical in the medium term, forecasting possible risks and bottlenecks in emerging technologies, and modeling alternative market scenarios.

The fourth mechanism is integration with systems engineering. Systems engineering offers a toolkit for working with complexity, including holistic vision, requirements management, and architectural thinking. The EEP method complements this toolkit with approaches for assessing efficiency and risk, total cost of ownership, and predictive analytics. Combined with contemporary information technologies, this synthesis enables specialists to design engineering solutions on the basis of a unified techno-economic model that takes account of both economic consequences and market dynamics. The result is a multiplier effect: the thinking of interdisciplinary teams becomes oriented toward the real-world feasibility of projects aimed at future leadership.

Our work in this area has been summarized in monographs [Gavrilova et al., 2017; 2024] and is currently being implemented through the courses Systems Engineering for Managers, Interdisciplinary Industry Linkages, and Production Asset Management System. Students learn to shift their focus from day-to-day operational measures to asset performance over the life cycle and its contribution to prof-

itability—an especially urgent task given the pressing need for systemic industrial modernization.

For example, the course Production Asset Management System develops the following key engineering and economic competencies:

- Techno-economic modeling: the ability to build digital twins that connect the physical parameters of assets, such as efficiency, wear, and vibration, with economic parameters such as repair costs and residual value.
- Life-cycle management: an understanding of how decisions made at the design stage will affect costs over the next 10–20 years.
- Data science: the use of predictive analytics and machine-learning methods to forecast failures and optimize maintenance schedules.
- Fundamentals of financial management applied to assets: repair budgeting, evaluation of investments in specific modernization measures, tax treatment, and depreciation charges, all understood in conjunction with the engineering characteristics of the assets involved.
- Systems thinking: the ability to see an asset as part of a production system in which the downtime of one component affects the entire value chain.

Thus, integrating EEP and systems engineering into educational courses develops cross-cutting competencies that enable graduates and trainees to view assets within a unified framework of technology, economics, and risk; justify investments on the basis of total cost of ownership rather than purchase price alone; work effectively in interdisciplinary teams; and adapt quickly to changes in technology and the market.

6. A Digital Platform for Developing Innovation-Oriented Specialists

Engineering and economic training aimed at developing the competencies required for technological leadership in a digital environment must itself be delivered in a high-tech format aligned with the values and expectations of younger generations. The use of digital twins and simulation platforms makes it possible to model different scenarios, learn from mistakes without serious consequences, and see the long-term effects of decisions. In many industries, including electric power, where the cost of error is especially high, it is essential that students learn to work with real data, interpret modeling results, and make decisions under conditions of uncertainty.

This issue has become especially urgent in light of the rapid advance of AI. Specialists must do more than simply use off-the-shelf AI tools: they need to understand their limitations and combine machine-based analysis with expert judgment. This, in turn, requires academic programs to include dedicated modules on data analysis, machine learning, and AI ethics.

In this regard, the authors' efforts are focused on developing a specialized digital platform for engineering and economic education to support both student training and the development of enterprise personnel reserves. The platform includes the following components:

1. A teaching-and-training complex: a system that integrates educational content, teaching methods, and information support for the study of theoretical issues, research work, and the development of engineering and economic projects (Figure 5).

2. The "Ahead of Time" knowledge base for 24/7 self-study, containing hundreds of electronic resources prepared by department faculty, as well as completed student projects, all of which can be automatically matched to a specific project-and-research topic or learning task.

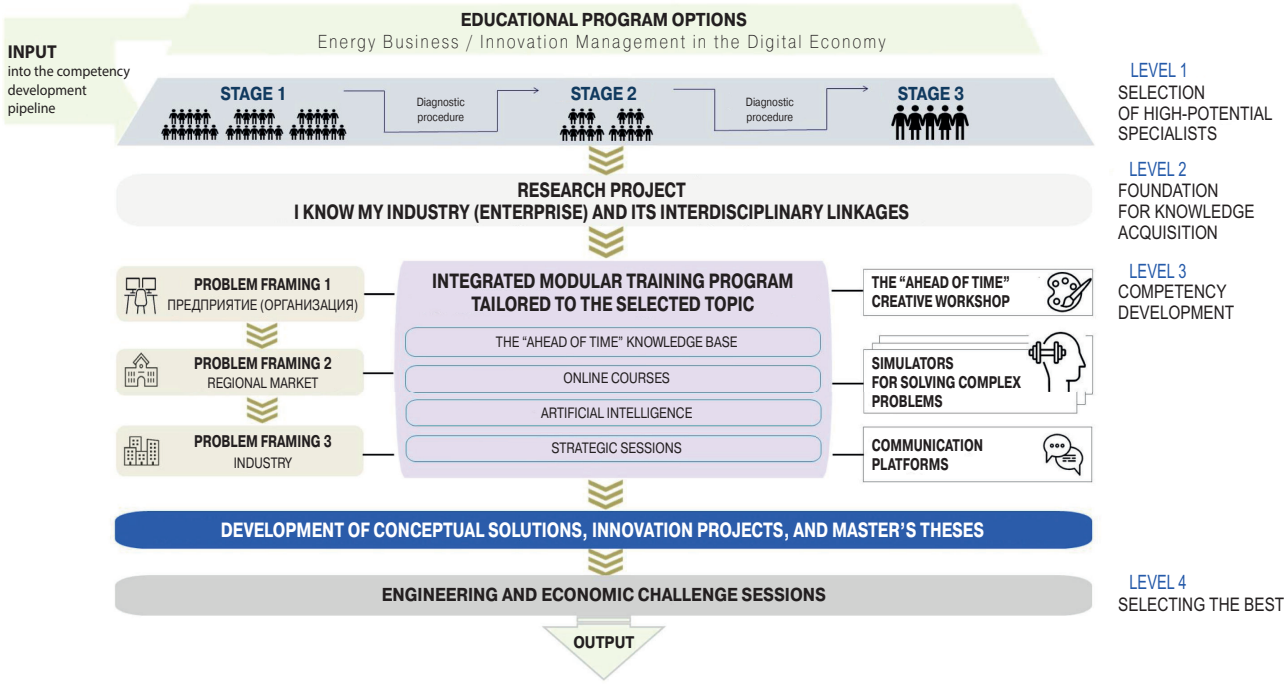
3. A portfolio of online courses that makes it possible to quickly assemble modular educational products tailored to different tasks, competencies, and students' professional interests.

4. Digital simulators for solving complex problems: tools for the intensive development of innovation competencies through electronic interfaces (computer applications) and interactive dialogue with AI, machine-learning systems, expert consultants, and members of the student's own team (Figure 6).

The simulator contains a thematic set of innovation projects and current challenges, and work within it takes the form of developing innovative solutions on a selected topic. To organize a creative yet goal-oriented process, different scenarios of teamwork are used. These include multiple stages that can vary depending on the topic, the scale of the problem being addressed, and the composition of both the innovation participants and the project team.

A range of digital simulators is used in teaching-and-training sessions, and the set is updated as new topics are introduced. The simulators currently in use include "Transformations for Achieving Technological Leadership," "Regional Electric Power Reform After Twenty-Five Years: Assessing the Results," "A Power Company Strategy for Technological Leadership," "Engineering and Economic Problem Framing for Stimulating Innovation," "Process Management as a Foundation for Digitalization," "Innovation Personnel as a Driver of Technological Leadership," "Enterprise Asset Management: Priorities for Anticipatory Management," "Competencies for Modernizing the Electric Power Industry," "Rethinking the Mission of an Enterprise Seeking Technological Leadership," and "Risk Analysis of an Innovation Solution."

5. A set of original technologies for the continuous development of competencies across the full educational pathway, from school, technical school, or college through to master's and doctoral study.

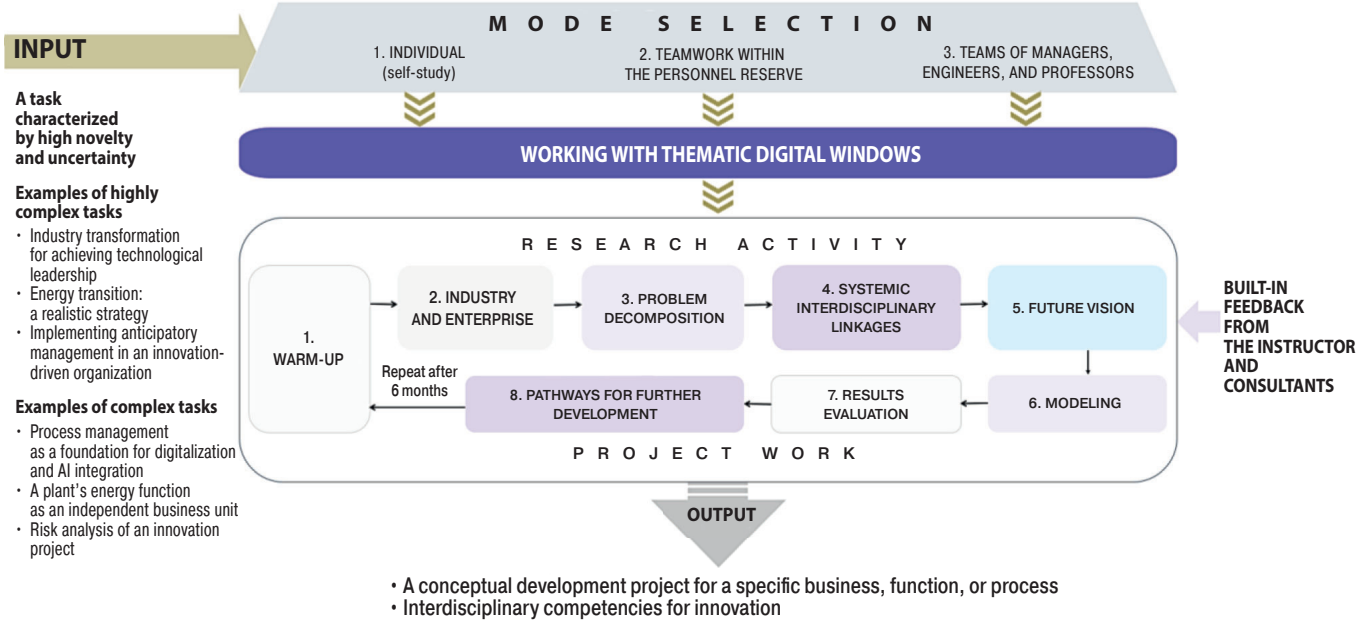


Source: compiled by the authors.

Fig. 5. Organization of Student Work in the Teaching-and-Training Complex

6. A network of communication platforms, including virtual ones, linking the department with leading enterprises and academic partners from different countries and from cities across Russia to exchange best practices and innovative ideas.

At the heart of this research and educational platform is the digital knowledge base "Ahead of Time." It includes materials corresponding to the department's various research areas, as well as to project-and-research work carried out by students and business teams (Figure 7). Students re-



Source: compiled by the authors.

Fig. 6. Structure of the Digital Simulator

port that it is highly effective for completing learning tasks that require non-standard solutions at the intersection of different subject areas.

The service not only enables users to obtain relevant information quickly and efficiently for the courses they are taking, but also helps them gather empirical data, expert opinion, and analytical materials for project work. This is achieved through dedicated search tools that allow materials to be filtered by thematic tags, resource type, author, and keywords in Russian, English, and Chinese.

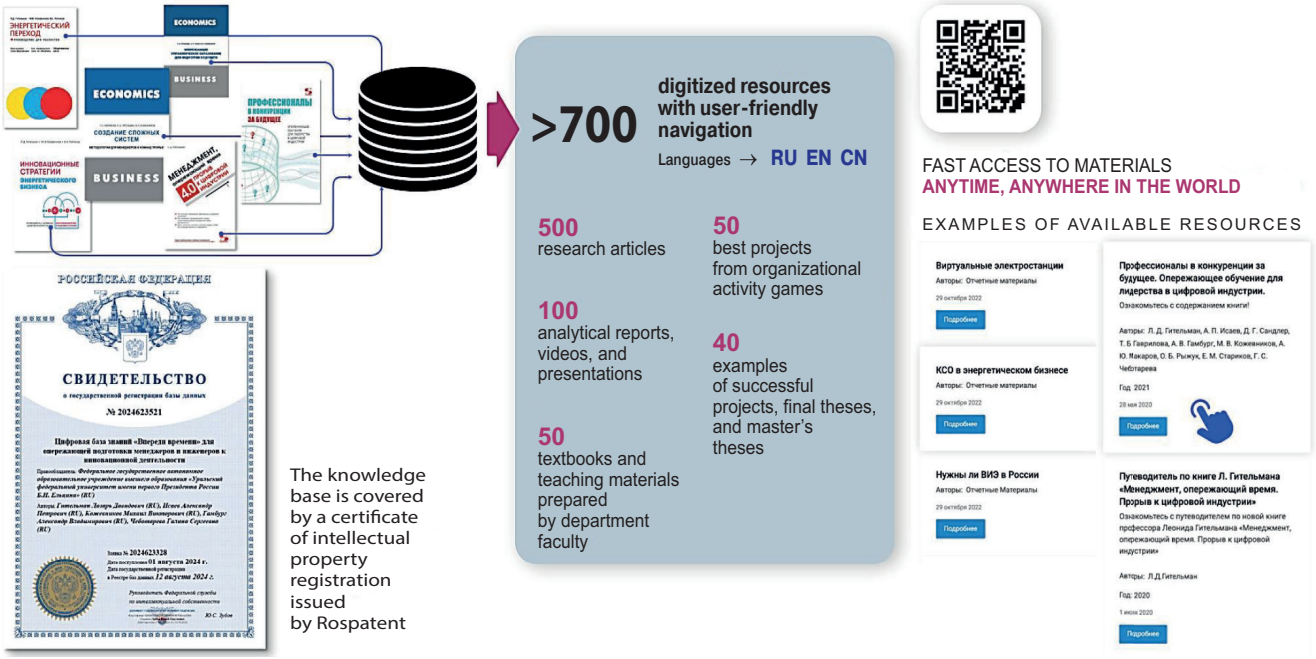
The distinctive features of the knowledge base are as follows:

– 95% of the resources have been prepared by department faculty;
– the content is specifically focused on developing students' engineering and economic competencies, above all systems thinking, and on helping them master the interconnections among engineering, technology, ecology, economics, finance, and management;
– all resources are aligned with specific courses within the department's educational offerings; targeted discipline-based searches greatly facilitate theoretical preparation and significantly improve the effectiveness of independent study;
– the service is adapted for international students: the menu and the key characteristics of resources, including titles, abstracts, and keywords, are available in both Russian and English, while some of the most important materials are also available in Chinese.

The knowledge base helps restructure the learning process by freeing up time for work on the most challenging issues facing a given industry or enterprise. This creates the conditions for a more progressive balance within the educational process: 20% discussion of problems, 25% research and analytics, 35% design, and 20% exposure to advanced practice.

The following forward-looking components of the platform are currently under development:

- Digital twins: full digital replicas of real production facilities in which each piece of equipment has its own economic model, including hourly operating cost, energy consumption, and depreciation; each material "knows" its own price and logistics parameters; and every decision is instantly translated into an economic outcome. Students can reconfigure the production process and immediately see how cash flow changes.
- AI assistants: intelligent agents embedded in every element of the platform. They analyze the history of decisions, forecast consequences, highlight risks, and propose alternatives. AI thus becomes more than a tool: it becomes a co-creator of solutions, expanding human cognitive capacity and enabling users to evaluate hundreds of times more scenarios than would be possible manually.
- An end-to-end digital trajectory: the platform records each student's digital footprint, including what decisions they made, what mistakes they made, and how quickly they learned to balance technology and



Source: compiled by the authors.

Fig. 7. Structure of the «Ahead of Time» Engineering and Economic Knowledge Base

economics. This becomes an objective portfolio that is clear and meaningful to employers. By looking at the student's learning trajectory, an enterprise can already understand whom it is hiring and what kinds of tasks can be entrusted to that person.

Thus, the department's platform becomes a full-fledged working environment in which users can find relevant information exactly when they need it, model the consequences of decisions in digital simulators before those decisions are made, and quickly connect with outside experts, colleagues, and instructors.

This is precisely the logic built into the architecture of the platform: to serve as a provider of tools through which specialists can, to a considerable extent, acquire the competencies they need on their own.

Conclusion

We believe the article has shown that contemporary engineering, economic, and management education is not aligned with the challenges the country now faces. The role of engineering and economic education is therefore becoming increasingly important. Without it, technological leadership will remain a slogan rather than an imperative for survival in an aggressively competitive environment. The problem has become acute and requires an immediate response.

The solutions proposed here affect a wide range of stakeholders, from students and university faculty to business employers and public authorities. They therefore call for broad discussion and a degree of consensus across both the academic and business communities.

With this in mind, the authors propose the following questions for discussion:

1. How can the engineering, economic, and humanities components of education be balanced so as to cultivate the culture and competencies required of a new generation of technological leaders?

2. What qualities and competencies should a university graduate possess in order to engage in breakthrough innovation suited to the era of digital technologies and AI?

3. How can interdisciplinarity, along with the corresponding tools and competencies, be implemented in practice under conditions of acute shortages of qualified instructors, digital laboratory infrastructure, and shared university–industry platforms for the experimental testing of new developments?

4. Should the mathematical component of education—and, in some cases, natural science training, especially in physics—be substantially strengthened, with corresponding changes to the entrance examinations required of applicants?

5. To what extent does engineering and economic training require a substantial—indeed, manyfold—increase in practical training, together with a move away from the overly formal approach still common in both universities and business? In the same vein, should engineering and economic issues relevant to real production be introduced from the first year and studied in conjunction with other disciplines, both theoretical and applied?

6. What organizational barriers might hinder the implementation of a new model of engineering and economic education?

7. How broadly applicable is the proposed educational model? Can it be used across different industries?

8. Would it be advisable to begin with pilot projects in anticipatory engineering and economic education, and what sequence of steps would be needed to scale up the resulting experience?

9. Is there now a need to include engineer-economist as an official degree track within the system of higher education specialties?

10. Finally, should the model of specialized engineering and economic faculties or institutes, as it existed in the Soviet period at the country's leading universities, be revived on a fundamentally new basis?

These may not be all the questions that arise for the reader. Yet the problem is so complex that both the range of issues and the answers to them may vary. We hope that constructive support for, or criticism of, the position advanced here will help generate sound solutions.

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About the Authors

Lazar D. Gitelman
Dr. Sci. (Econ.), Professor, Professor, Department of Energy and Industrial Management Systems, Ural Federal University named after the first President of Russia B.N. Yeltsin (Ekaterinburg, Russia). Web of Science ResearcherID: AHB-8473-2022; Scopus Author ID: 55806230600.
Research interests: energy business in the electric power and heat power sectors, proactive management, organizational transformations, management education.
ldgitelman@gmail.com

Mikhail V. Kozhevnikov
Dr. Sci. (Econ.), Associate Professor, Head of the Department of Energy and Industrial Management Systems, Ural Federal University named after the first President of Russia B.N. Yeltsin (Ekaterinburg, Russia). Web of Science ResearcherID: AAB-6693-2020; Scopus Author ID: 55805368400; ORCID: 0000-0003-4463-5625.
Research interests: knowledge-intensive services, innovative industrial development, management education.
m.v.kozhevnikov@urfu.ru

作者简介

Lazar D. Gitelman
经济学博士，教授，俄罗斯联邦首任总统 B.N. 叶利钦命名乌拉尔联邦大学能源与工业企业管理系统教研室教授（俄罗斯叶卡捷琳堡)。
WOS Research ID: AHB-8473-2022；Scopus Author ID: 55806230600。
研究方向：电力与热力能源行业中的能源业务、前瞻性管理、组织变革、管理教育。
ldgitelman@gmail.com
Mikhail V. Kozhevnikov
经济学博士，副教授，俄罗斯联邦首任总统 B.N. 叶利钦命名乌拉尔联邦大学能源与工业企业管理系统教研室主任（俄罗斯叶卡捷琳堡)。
WOS Research ID: AAB-6693-2020；Scopus Author ID: 55805368400；ORCID: 0000-0003-4463-5625。
研究方向：知识密集型服务、工业创新发展、管理教育
m.v.kozhevnikov@urfu.ru

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Strategy for Implementing Hybrid Power Supply Systems in Large-Scale Construction Projects

M.Yu. Mokshin[1]
O.N. Rimskaya[2]
[1] National Research Nuclear University MEPhI (Moscow, Russia)
[2] Federal Register of Experts in Science and Technology of the Russian Federation (Moscow, Russia)

Abstract

The organization of power supply at construction sites in Russia, particularly in remote and climatically challenging regions, is characterized by a high dependence on diesel generators for temporary power supply. Fuel delivery is associated with increasing costs, price volatility, and a significant environmental footprint. This article examines the use of hybrid power supply systems (wind turbines, solar photovoltaic panels, and battery storage) as an alternative to conventional diesel-based power supply schemes. Hybrid energy solutions combining diesel generators with renewable energy sources can improve the reliability and economic efficiency of power supply. Rising fuel prices, environmental concerns, and the growing availability of renewable energy technologies are stimulating the adoption of hybrid power supply systems at large construction sites. The methodological framework of this study includes calculations of the Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), and Net Present Value (NPV), as well as sensitivity analysis with respect to fuel price fluctuations and wind conditions. The article also presents a comparative analysis of Russian and international practices, demonstrating the increasing role of hybrid power supply systems in the construction sector. The results indicate the high investment attractiveness of hybrid technologies and their potential for scaling up within national programs for economic and construction sector development.

Keywords: construction site power supply, hybrid power supply systems, wind turbine, solar photovoltaic system , LCOE, IRR, NPV, economic efficiency

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大型建设项目混合供电系统实施战略

Mokshin M.Yu.[1]
Rimskaya O.N.[2]
[1] 国立核能研究大学"莫斯科工程物理学院"（莫斯科，俄罗斯）
[2] 俄罗斯联邦科技领域专家联邦名录（莫斯科，俄罗斯）

摘要

俄罗斯建筑工地能源供应的组织特点，尤其是在偏远地区和气候条件复杂地区，面临的一个突出问题是临时供电对柴油发电机的高度依赖。燃料运输不仅会推高成本，还会带来价格波动和更大的生态环境负担。本文探讨了采用混合能源供应系统（风力发电装置、太阳能电池板和蓄电池）替代传统柴油供电方案的可行性。在这种背景下，将柴油发电机与可再生能源相结合的混合能源解决方案正发挥越来越重要的作用。燃料价格上涨、生态环境问题以及可再生能源技术的日益普及，正在推动混合能源系统在大型建筑项目中的应用。研究的方法论基础包括平准化度电成本（LCOE）、内部收益率（IRR）和净现值（NPV）的测算，以及对燃料价格变化和风力条件变化的敏感性分析。文章还对俄罗斯及国外相关实践进行了比较分析，展示了混合能源系统在建筑领域日益重要的作用。研究结果表明，混合能源技术具有较高的投资吸引力，并具备在国家经济和建筑业发展规划框架下实现规模化推广的潜力。

关键词： 建筑工地能源供应，混合能源系统，风力发电装置，太阳能发电站，平准化度电成本（LCOE），内部收益率（IRR），净现值（NPV），经济效益。

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Introduction

Global energy consumption continues to increase due to population growth, economic development, and improvements in living standards and life expectancy. As a result, the demand for new and more efficient technologies in the energy sector is steadily growing. One of the most prominent trends in the development of modern power systems is the adoption of energy-efficient technologies, which enable reductions in energy costs while mitigating the environmental impact of industrial activity. Key drivers of this trend include the relatively low cost of fossil fuel extraction, geopolitical instability, and the increasing volatility of national economies worldwide [Ageev, 2018].

Improving energy efficiency and promoting resource conservation have therefore become critical challenges for most countries. In response, new energy policies have been developed over recent decades that emphasize the deployment of hybrid power supply systems integrating renewable energy sources (RES). In such systems, conventional power generation technologies are combined with renewable energy sources, including solar photovoltaic (PV) systems, wind turbines, and other RES-based technologies.

According to the Energy Strategy of Russia through 2030[1], the strategic objectives associated with the development of RES and the use of locally available fuels include reducing anthropogenic environmental impacts, improving the efficiency of fossil fuel utilization, decreasing fossil fuel consumption, protecting public health and quality of life, lowering energy transmission and distribution costs, expanding the national fuel and energy resource base, and strengthening energy security through the decentralization of power supply systems.

The Ministry of Energy of the Russian Federation supports the development of hybrid power supply systems based on RES as part of national policy aimed at diversifying the country's energy mix, improving its environmental performance, and strengthening national energy security. Hybrid systems combining RES with conventional generation technologies or battery storage represent a promising technological pathway for the sustainable development of national energy infrastructure.

The Russian power system has traditionally been dominated by thermal power plants (TPPs), hydropower plants (HPPs), and nuclear power plants (NPPs). However, over the past decades the share of RES has been gradually increasing, creating favorable conditions for the deployment of hybrid power supply solutions, particularly in remote and isolated areas as well as at large construction sites.

Comprehensive statistical data on hybrid energy systems are currently unavailable both globally and in Russia. Nevertheless, their development is closely linked to the increasing share of RES in national energy balances. Available statistics therefore reflect this trend indirectly, primarily through indicators describing the expansion of renewable power generation capacity. As of 1 August 2025, the total installed capacity of RES-based power plants in Russia amounted to 6.64 GW (Figure 1). The structure of installed RES capacity is dominated by wind and solar power plants, accounting for 2.57 GW and 2.55 GW, respectively, while small hydropower plants with capacities of up to 50 MW contribute 1.31 GW. In addition, the country operates power plants based on biomass, biogas, landfill gas, municipal solid waste, and geothermal energy, with a combined installed capacity exceeding 200 MW[2]. Although the share of RES in Russia is increasing gradually, renewable energy already accounts for approximately 29% of global electricity generation worldwide.

Thus, countries around the world, including Russia, are gradually entering the fourth energy transition and aim to achieve carbon neutrality by 2050, increasing the share of RES-based power generation [Mokshin et al., 2025].

1. Research Background

Hybrid power supply systems (hereinafter referred to as HPSS) are based on a unified technological principle that makes it possible not only to reduce fuel consumption but also to improve the quality of electricity supply, thereby increasing the operational reliability of power systems and reducing environmental impacts.

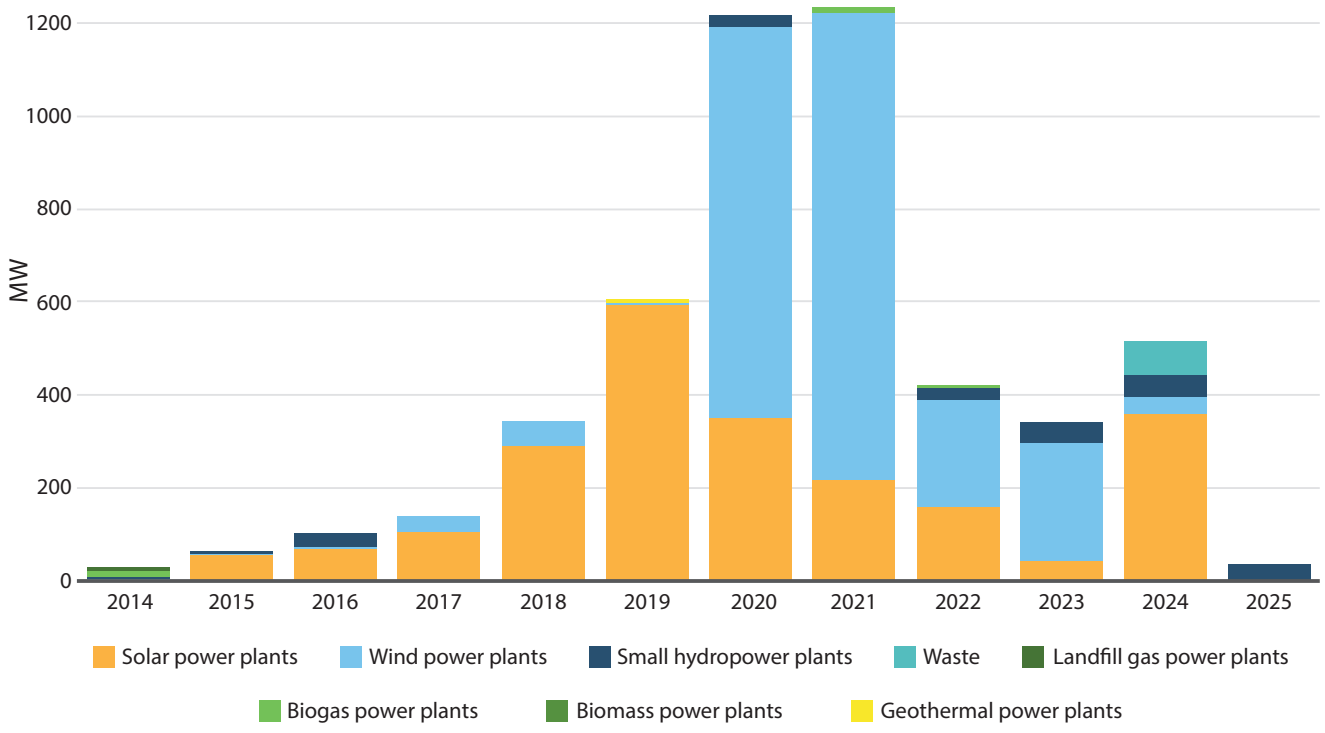
One proposed solution is the deployment of HPSS, which can significantly reduce power supply costs and improve the stability of power supply. An example of a successful pilot project is provided by the village of Menza in Zabaykalsky Krai of the Russian Federation, where HPSS provide local residents with uninterrupted electricity supply [Sharkova et al., 2025].

However, the widespread deployment of such systems in Russia is constrained by technological, economic, and infrastructure barriers, including the low level of localization of critical components such as lithium-ion

and insufficient adaptation of equipment to severe climatic conditions [Kapustina et al., 2025]. Russia is characterized by a clear division of the year into cold and warm seasons and by significant temperature fluctuations within each season. Climatic conditions in Russia affect the operation of virtually all types of power plants. The operating conditions of power plants are closely linked to natural factors that determine fuel and water supply, emission dispersion, the efficiency of cooling systems, as well as the number of sunny days per year and wind potential in different regions.

The Unified Energy System of Russia includes seven interconnected regional power systems—Eastern, Siberian, Ural, Middle Volga, Southern, Central, and North-Western—which are linked to regional power systems within the

[1] https://normativ.kontur.ru/document?moduleId=1&documentId=145742#h1708.
[2] https://rreda.ru/industry/statistics/.



Источник: https://rreda.ru/industry/statistics/.

Fig. 1. Commissioning Dynamics of Renewable Energy Power Plants in Russia

constituent entities of the Russian Federation and operate as an integrated complex providing electricity generation, transmission, and distribution across the country. However, about 700,000 people living in remote regions of the Russian Federation do not have access to power grids and rely on diesel generators for electricity generation. Diesel fuel is delivered to remote areas slowly and with considerable logistical difficulty, while electricity generated from diesel fuel is expensive.

The cost of electricity supplied from the Unified Energy System of Russia to industrial consumers is comparable to the cost of power supply from their own generating facilities, including the capital costs of their construction. Against the background of rising electricity and heat tariffs, this stimulates the development of distributed generation and encourages some consumers to move away from centralized power supply. As a result, an increasing number of consumers are considering the establishment of their own electricity generation facilities.

Thus, the key technical and economic characteristics and challenges of energy-isolated territories of the Russian Federation include:

– the predominant use of low-capacity diesel generators (up to 1 MW);
– high electricity production costs caused by the relatively low efficiency of diesel generators;
– a significant share of household expenditures on utilities, which, according to [Kapustina et al., 2025], may reach 70%;
– high costs associated with the maintenance of power transmission lines [Kapustina et al., 2025].

Given these factors, the development and operation of hybrid power supply systems in remote regions of the country represent a particularly relevant research topic.

Although the Government of the Russian Federation has approved the General Scheme for the Placement of Electric Power Facilities up to 2035[3], the transition to the deployment of hybrid power supply systems is not explicitly addressed in this document.

The application of hybrid power supply systems integrating RES has both advantages and disadvantages, which will be discussed in this article.

The objective of this study is to investigate the application of hybrid energy-efficient technologies in power supply systems at remote industrial sites, such as construction projects, and to identify ways to improve their efficiency.

The power supply of temporary construction sites is one of the key challenges facing the construction industry. In remote regions such as the Arctic, the Far East, and the Far North, up to 80–90% of temporary power demand is supplied by diesel generators. Fuel costs, transportation ex-

[3] https://www.garant.ru/products/ipo/prime/doc/71599734/.

penses, and high maintenance costs significantly increase overall construction costs.

The issue of construction site power supply is closely linked to the development of construction technologies, infrastructure, and the broader economy. In the early stages of construction development, electricity was supplied through temporary generators and low-voltage temporary networks, which were unsafe and inefficient. Later, large industrial construction projects introduced more reliable solutions, including temporary transformer substations, mobile diesel generator units, and improved cable systems, ensuring safe and stable electricity supply at construction sites.

The use of hybrid power supply systems at construction sites has been studied in international practice for more than two decades. In Russian scientific literature, however, research has focused primarily on general energy systems and renewable energy sources, while the specific features of power supply for construction projects have received considerably less attention. This article seeks to partially fill this research gap by examining the application of hybrid power supply systems in the context of power supply for remote industrial and construction sites.

Within the framework of this study, a comprehensive approach was applied to evaluate the effectiveness of domestic autonomous hybrid power generation units (AHPGU) designed to provide power supply for isolated and hard-to-reach territories of Russia. To determine the level of localization of production of system components, an expert assessment method was employed, based on an analysis of production chains and technological processes of domestic enterprises. The information base of the study included official statistical data from the Ministry of Energy of the Russian Federation on the state of power supply in isolated and remote territories, industry reports from ROSNANO and the International Renewable Energy Agency (IRENA), thematic reviews by professional associations, and scientific publications in the fields of distributed generation and hybrid power supply systems.

2. Overview of Industrial Hybrid Power Supply Systems

A promising area of application of hybrid systems based on RES with a fuel substitution level of at least 50% and small installed capacity in Russia is the power supply of approximately 100,000 facilities and small isolated settlements across the country, including regions of the Far North and the Far East. These facilities include cellular communication infrastructure, meteorological stations, lighthouses, autonomous technical and navigation posts, pipeline route consumers along oil and gas pipelines, electrochemical protection stations for pipelines, valve control nodes, farms, hunting and fishing facilities, border posts, and other special-purpose installations [Vasilevsky et al., 2017].

Within the framework of this article, a hybrid system is understood as an autonomous power supply system with several sources of electrical energy (generators) using at least two different power generation technologies.

Compared with traditional power supply systems for isolated consumers based on diesel generator units, hybrid systems provide several advantages. These include not only a reduction in fuel consumption and the cost per kilowatt-hour but also a significant reduction in service and maintenance requirements. This is particularly important for the deployment of autonomous power supply systems for various purposes in remote territories characterized by difficult terrain and severe climatic conditions.

In international practice, several types of hybrid power supply systems have been developed and are currently operating in different countries, including the Russian Federation:

1. 1. Solar-hydropower plants use solar energy to pump water from a lower reservoir to an upper reservoir, creating potential energy that is subsequently converted into electricity when the water is released.

A notable technological solution is the world's only floating solar platform located in Portugal at the Alto Rabagão dam. Projects involving the installation of solar modules on the downstream slopes of dams are also known in Japan, including installations at the Kotani (5 MW) and Gongen (1.76 MW) dams. The largest solar-hydropower plant in the world (850 MW) is located in China and represents a striking example of hybrid hydro-solar generation integrated with the nearby Longyangxia hydropower plant (1280 MW) and coordinated with its operation[4]. In Russia, the possibility of using dam structures and adjacent areas of hydropower plants for the installation of solar modules has not yet been considered.

2. A hybrid wind-hydropower plant combines wind turbines with a pumped-storage hydropower facility to ensure stable electricity generation.

In 2022, the Swedish energy company Vattenfall commissioned the first hybrid power plant "Haringvliet" in the Netherlands, which integrates solar photovoltaic generation, wind generation, and an energy storage system. The facility consists of a solar PV plant with a capacity of 38 MW and a wind power plant with a capacity of 22 MW (six turbines), complemented by 288 lithium-ion batteries installed in 12 maritime containers[5].

3. 3. A floating hybrid solar-wind power plant represents a new and technologically complex solution developed by SolarDuck (Netherlands) in cooperation with Italian partners. The Corigliano project with a capacity of 540 MW is planned to be constructed off the southern coast of Italy in the Ionian Sea and commissioned in 2028.

4. Battery energy storage systems continue to be widely used and successfully developed. When operating

[4] https://econet.kz/articles/178271-gibridnaya-energetika.
[5] https://www.in-power.ru/news/alternativnayaenergetika/44487-vvedena-v-stroi-gibridnaja-vetro-solnechnaja-elektrostancija-s-nakopi.html.

in hybrid mode with a diesel generator, they provide a high level of efficiency and help reduce operational costs. When used as standalone equipment, battery energy storage systems also represent an environmentally sustainable solution, as they allow energy generated from renewable sources such as solar PV panels and wind turbines to be stored and supplied when required[6].

5. A unique hybrid energy concept involving energy generation from marine algae is planned in Germany[7]. A building designed for the International Building Exhibition in Hamburg in 2014 features a façade covered with bio-adaptive louver panels containing marine algae. Each panel functions as a flat bioreactor containing algae. In addition to providing a suitable environment for algae growth, these panels create shading for interior spaces. The bioreactor also captures thermal energy released by the algae, which is subsequently collected and used to meet the building's energy needs.

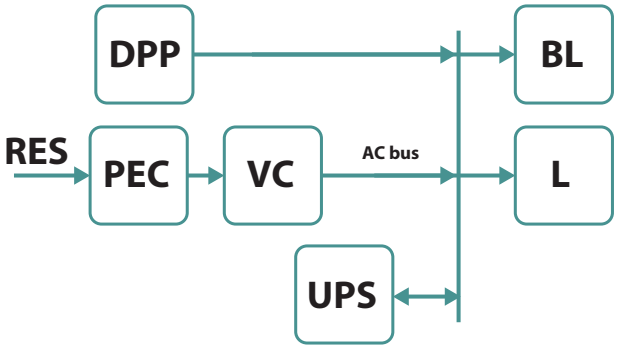
Within the context of hybrid systems, it is also important to consider the demand of the construction industry for a reliable energy source, particularly during the construction of large industrial facilities in remote locations. This demand can be met only through the deployment of autonomous hybrid power supply systems located near the construction site.

Currently, temporary power supply for construction sites in Russia is typically provided through two main solutions depending on the required capacity[8]:

1) connection via a temporary transformer substation;
2) deployment of on-site power transformers.

In recent years, generators have played a key role in providing electricity at all stages of construction, serving as the primary, backup, or emergency power source in locations remote from centralized power supply systems. The choice of generator type depends on the characteristics of the construction project, its power demand, fuel availability, and environmental requirements. In most cases, diesel power plants and diesel generator units are considered universal and reliable options during the design of construction site electrification projects. However, the use of generators as the sole source of power for electricity supply, lighting, and dewatering at construction sites is not always justified under current conditions due to high fuel costs, noise generation, harmful atmospheric emissions, the need for preventive maintenance, and voltage fluctuations that may damage equipment. Additional challenges include the limited capacity of generators and the decline in operational and economic efficiency associated with high fuel consumption, the need for regular maintenance, and the risk of downtime.

Within the framework of this study, a hybrid power supply system for a large construction project is defined as a system designed to fully or partially replace electricity supplied from the urban power grid while simultaneously functioning as an uninterruptible power supply source (Figure 2).



Note. DPP — diesel power plant, RES — renewable energy sources, PEC — primary energy converter, VC — voltage converter, UPS — uninterruptible power supply, L — load, BL — ballast load.
Source: [Trofimova, Zatsepina, 2023].

Fig. 2. Hybrid Power Supply System with a Backup Diesel Power Plant

Hybrid power supply systems involve the use of multiple energy sources. Electrical energy is generated using solar photovoltaic panels, wind turbines, or other conversion technologies. Thermal energy for heating systems, domestic hot water supply, and industrial processes can be generated using solar thermal collectors (flat-plate and evacuated tube), geothermal systems, and other thermal energy conversion technologies. The integration of different RES technologies and the use of a unified control system to ensure their coordinated and efficient operation constitute the basis of a stable hybrid power supply system [Meirbekova, Myrzabek, 2022].

Among the key advantages of hybrid power supply systems for large construction projects are the following [Kamanina et al., 2023]:

- diversity of energy sources (solar, wind, hydropower, thermal energy, biomass, diesel fuel, etc.), allowing the system to optimally utilize available resources depending on specific conditions and operational requirements;
- enhanced reliability, since the use of multiple sources reduces the risk of outages or operational failures and ensures that electricity demand can always be met;
- significant cost reduction when more than one energy source is used, provided that careful system design is undertaken to select the most suitable energy generation technologies for the given conditions;
- reduced environmental impact, as hybrid systems incorporating RES make electricity generation more environmentally sustainable;

[6] https://www.atlascopco.com/ru-kz/construction-equipment/resources/generators-guide/why-battery-based-hybrid-energy-storage-solutions-represent-the-future.
[7] https://www.vzavtra.net/eko-zdaniya/pervoe-v-mire-zdanie-s-energoobespecheniem-ot-morskix-vodoroslej-budet-postroeno-v-germanii.html.
[8] https://энерготрест.рф.

- flexibility and adaptability, since hybrid power supply systems can be adjusted to different climatic conditions and customer requirements through integrated battery energy storage systems (BESS);
- reduction of electricity losses, as BESS integrated into hybrid systems enable surplus electricity generated during periods of low demand to be stored and subsequently supplied to the network;
- independence from centralized power supply, since hybrid systems can be deployed in remote and hard-to-access locations where connection to the power grid is not feasible.

Practical experience shows that when battery energy storage systems are used in autonomous hybrid power supply systems, several specific factors must be taken into account. In particular, the service life of battery energy storage systems in autonomous RES-based energy systems may be shorter due to uneven power generation caused by weather variability and seasonal fluctuations. For this reason, when designing hybrid power plants based on RES technologies, it is necessary to consider the climatic conditions of the region and to select energy storage technologies that meet the requirements for durability, reliability, and economic efficiency. According to a group of Russian researchers led by Professor V.A. Zubakin, the classification of hybrid energy systems depends on the operational objectives defined by the customer [Zubakin et al., 2024]. At modern construction sites, hybrid power supply systems are increasingly used as an optimal solution for the electrification of remote rural areas [Ogunlana, 2017] and isolated construction sites where expansion of the centralized power grid is technically difficult and economically inefficient. Depending on the characteristics of the facility and the required power parameters, several sources can be combined to provide electricity for modern construction sites, including grid connection, generators, solar photovoltaic panels, and wind turbines[9].

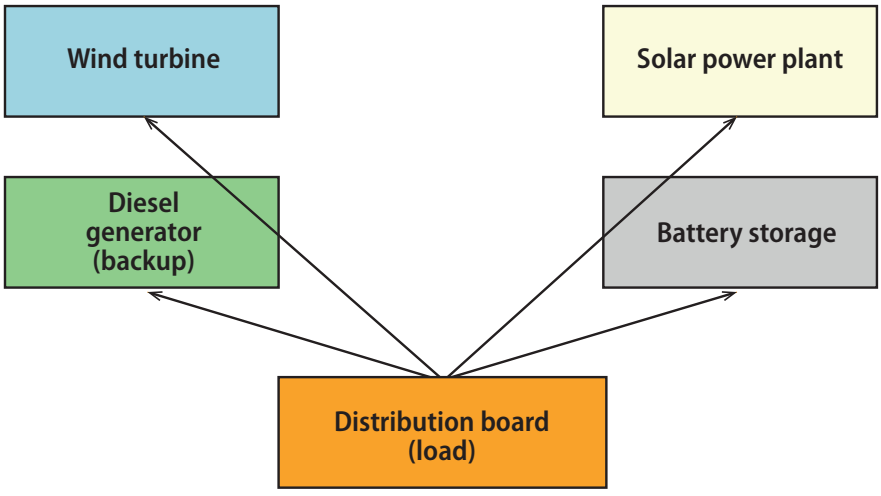
Each of these energy sources has specific characteristics and limitations that must be considered when designing a construction site power supply system. For example, low temperatures typical of many regions of the Russian Federation pose a serious challenge for electrical equipment. Battery capacity decreases rapidly, cables become brittle, and generators may fail. Addressing these challenges requires the use of modern materials and technologies that are resistant to subzero temperatures.

The ability of electrical substations to operate autonomously is a critical factor when construction sites are located far from existing power grids. In such conditions, the role of backup power sources—such as diesel generators and battery energy storage systems—becomes particularly important and must be carefully considered and integrated into the overall power supply design.

In recent years, the decarbonization of the construction industry and the transition to sustainable technologies have received increasing attention. The Low-Carbon Development Strategy of the Russian Federation up to 2050[10] explicitly emphasizes the need to reduce the carbon footprint of the construction sector. This highlights the importance of identifying alternatives to diesel-based generation for temporary construction site power supply.

3. Research Methodology

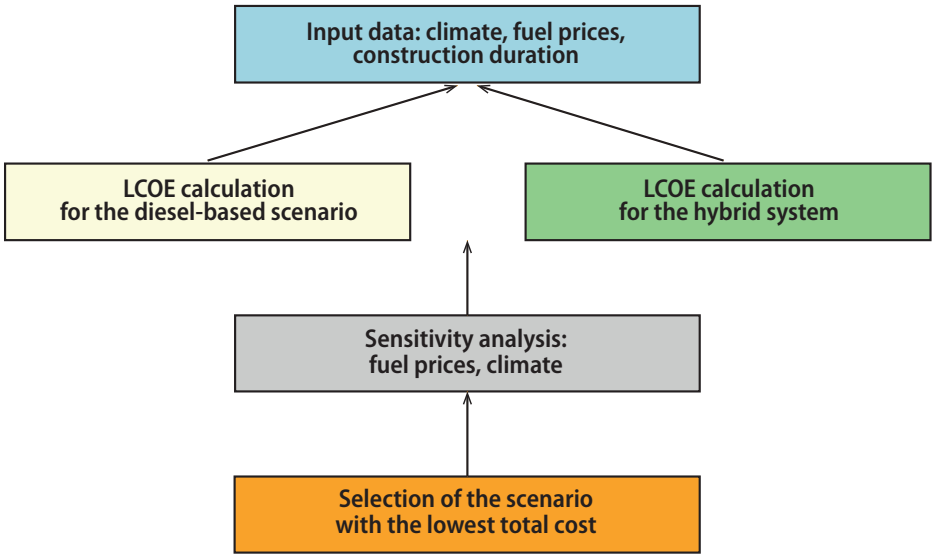
The object of the study is the power supply of large construction projects located in remote areas.



Source: compiled by the authors.

Fig. 3. Hybrid Power Supply System Architecture for a Construction Site

[9] https://energy-systems.ru/main-articles/proektirovanie-elektriki/effektivnoe-proektirovanie-elektrosnabzheniya-stroitelnoy-ploschadki-klyuchevye-aspekty-i-luchshie-praktiki.
[10] http://government.ru/docs/43708/.



Source: compiled by the authors.

Fig. 4. Algorithm for Selecting the Optimal Power Supply Scenario for a Construction Site

The subject of the study is automated hybrid power supply systems for large construction sites implemented in different countries worldwide.

All construction equipment—cranes, hoists, drilling rigs, most types of concrete mixers, air heaters, and lighting systems—operates on electricity. Interruptions in electricity supply or a complete shutdown of power supply lead to construction delays and negatively affect construction quality, ultimately resulting in financial losses.

Power supply for remote construction projects has a specific characteristic: the need for the rapid deployment of electricity supply of standard quality to mobile electrical loads, together with the ability to regulate electrical loads to ensure the mobility of construction machinery and equipment [Orlov, 2016]:

Within the framework of this study, two power supply scenarios for large construction projects are compared. The first scenario represents the conventional diesel-based approach, relying on diesel generators and fuel delivery logistics (Figure 3). The second scenario involves a hybrid power supply configuration consisting of a Condor Air 10 wind turbine, AXITEC AC-375MH/144V solar photovoltaic modules, Delta GX 12-200 battery energy storage units, and a Growatt inverter (Figure 4).

3.1. Methods of Analysis

The evaluation of the economic performance of industrial energy systems is widely addressed in the scientific literature. Particular attention is given to economic indicators such as LCOE, IRR, NPV, profitability, and payback period [Mokshin, 2024].

In Russian practice, the evaluation of energy projects most commonly relies on indicators such as the capacity utilization factor and the payback period. At the same time, the Levelized Cost of Energy (LCOE) is also applied in analytical assessments, including those used by the industry regulator—the NP Market Council Association, which represents participants in the wholesale electricity market.

It is therefore recommended to incorporate the LCOE metric into Russian evaluation practice, taking into account CO_2 emission costs and sustainability considerations. This approach is consistent with the methodology proposed in [Zubakin, Zhukov, 2024]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}, \quad (1)$$

where $CAPEX_t$ — capital expenditures in period t, $OPEX_t$ —operating expenditures in period t, F_t —fuel costs in period t, E_t —electricity generated in period t, r —discount rate, t —period index, n —number of periods.

A sensitivity analysis was conducted with respect to the following parameters:

- changes in diesel fuel prices (±30%);
- variations in wind speed (±20%);
- construction project duration (6–24 months).

Figure 3 illustrates the architecture of a hybrid power supply system for a construction project. It also reflects the logic used to compare two alternative power supply scenarios (diesel-based and hybrid) and to select the option with the lowest total cost.

3.2. Results

The economic efficiency assessment of the power supply systems is presented in Table.

Table
Economic Efficiency of Power Supply Systems

Indicator	Diesel-Based Scenario	Hybrid System
Annual costs (mln RUB)	16.4	6.25
Cost savings (mln RUB)	–	10.15
NPV(mln RUB)	–	> 10
IRR (% per year)	–	170
Payback period (years)	–	< 1

Source: compiled by the authors.

The environmental performance of the power supply systems was also assessed:

- diesel-based scenario: >150 t CO_2 per year;
- hybrid system: <20 t CO_2 per year;
- emission reduction: more than sevenfold.

A sensitivity analysis of the power supply systems was conducted:

- if diesel fuel prices increase by 30%, cost savings increase to 12 mln RUB;
- if wind speed decreases by 20%, the economic effect remains positive (cost savings of 7.5 mln RUB);
- if the construction site operates for 24 months, the IRR remains at 145–150%.

3.3. Validation and Discussion of Results

The comparative analysis shows that hybrid power supply systems provide clear advantages and make it possible to:

- reduce the cost of temporary power supply by 40–60%;
- increase the investment attractiveness of construction projects;
- reduce the environmental footprint.

Similar effects have been reported in the application of hybrid systems for power supply at large industrial facilities in several countries:

- Germany—cost savings of 35–50% when hybrid systems are used [Jacobson et al., 2022];
- China—cost reductions of up to 60% at construction sites in north-western regions [Zhao et al., 2023];
- United Arab Emirates—carbon emission reductions of up to 70% [Kumar et al., 2022].

The main risks associated with the operation of hybrid systems include the high cost of battery storage and their dependence on climatic conditions. However, when solar and wind generation are properly combined and supported by modern energy management systems, these risks can be significantly reduced.

Figure 3 presents a schematic representation of a hybrid power supply system for a construction site, illustrating the integration of renewable energy sources (wind turbines and solar power plants), battery storage, and a backup power source within the overall power supply architecture of the facility. The flow diagram shows the sequence of analysis: from initial input data to the calculation of LCOE for the diesel-based and hybrid scenarios, followed by sensitivity analysis and the selection of the power supply configuration with the lowest total cost.

Conclusion

The analysis of domestic practice shows that combining renewable energy sources with backup generation units to form hybrid power supply systems can ensure more cost-effective, environmentally sustainable, and reliable electricity supply under varying demand conditions compared with the use of single-source energy systems.

One of the key issues in designing a hybrid system for temporary construction site power supply is determining the optimal composition and capacity of its components in order to meet the required load while minimizing capital and operating costs. The implementation of hybrid power supply systems for temporary construction sites can significantly reduce costs and improve the environmental sustainability of construction activities. Within the framework of the authors' "Wind Map"[11] project, a model scenario was developed for a construction site with an estimated load of 100 kW and an analysis horizon of 12 months. The results indicate that annual cost savings exceed 10 million RUB, the internal rate of return exceeds 170%, and CO_2 emissions are reduced by more than sevenfold compared with the diesel-based scenario.

Most countries and companies have set the goal of achieving carbon neutrality by 2050 through the integration of green technologies into national energy systems. The global transition from traditional energy generation methods to alternative energy sources is expected to lead to significant structural changes in the global economy. In the long term, these changes may result in the loss of a substantial number of jobs, social unrest, and subsequent economic crises.

[11] "Wind Map" is a digital tool designed to optimize the costs of temporary power supply at construction sites, developed on the basis of the authors' analytical calculations. A project presentation is available upon request.

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About the Aurhors

Mikhail Yu. Mokshin
Postgraduate Student, Faculty of Business Informatics and Integrated Systems Management, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia. ORCID: 0000-0002-0985-2192; Web of Science Researcher ID: LRC-2876-2024; SPIN: 8914-1453; Author ID: 1230549.
Research interests: wind energy, green energy, energy cost management in industry and the energy sector.
mokshin.my@mail.ru

Olga N. Rimskaya
Cand. Sci. (Econ.), Associate Professor, Expert listed in the Federal Register of Experts in Science and Technology of the Russian Federation, Moscow, Russia. ORCID: 0000-0002-1548-0815; Scopus Author ID: 5581148210; Web of Science Researcher ID: 583440; SPIN: 4185 4532; Author ID: 583440.
Research interests: global economy, digital economy, innovation, labour economics, lifelong learning, human resource management, labor motivation and incentives, humanitarian crisis issues.
olgarim@mail.ru

作者信息

Mikhail Yu. Mokshin
商业信息学和综合系统管理学院研究生，国立核能研究大学莫斯科工程物理学院(俄罗斯，莫斯科）。ORCID: 0000-0002-0985-2192; Web of Science Researcher ID: LRC-2876-2024; SPIN: 8914-1453; Author ID: 1230549.
科学兴趣领域：风能、绿色能源、工业和能源领域的能源成本管理。
mokshin.my@mail.ru

Olga N. Rimskaya
经济学副博士，副教授，俄罗斯联邦科技领域专家名录专家（俄罗斯莫斯科）。ORCID: 0000-0002-1548-0815; Scopus Author ID: 5581148210; Researcher ID: 583440; SPIN: 4185 4532; Author ID: 583440.
科学兴趣领域：世界经济、数字经济、创新、劳动经济、终身教育、人力资源管理、劳动动机与激励、人道主义危机问题。
olgarim@mail.ru

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Enterprise Information Security Strategy: Monitoring and Management

T.A. Rudakova[1, 2]
O.Yu. Rudakova[2]
[1] Altai State Technical University named after I.I. Polzunov (Barnaul, Russia)
[2] Altai State University (Barnaul, Russia)

Abstract

The security of an economic entity's information and the infrastructure that supports it remains one of the key challenges at the current stage of economic relations. Unauthorized access to information, accidental or malicious impacts on information, and third-party intrusion into the operation of the supporting infrastructure threaten to reduce economic benefits and cause damage to economic entities, both legal entities and individuals. Under these conditions, one of the tasks of an organization's economic security service is to prevent threats and mitigate risks related to unauthorized access to sensitive and financial information about the enterprise and to employees' personal data. The objective of the study is to develop methodological recommendations for organizing the process of managing enterprise information security risks. In the course of the study, the authors obtained the following scientific results: the elements of information security (information protection, access restriction, encryption, security system, two-factor authentication, information transfer, document forgery, verification of the vulnerability of the information source, and information authenticity) were examined comparatively, considering both their current state and their historical development; information on participants involved in information theft and methods of unauthorized access was systematized; factors limiting compliance with personal data protection principles were analyzed; and information security risks were systematized in the context of object-vulnerability-threat. The practical significance of the research results lies in the possibility of integrating them into an organization's management system and developing an internal control system to minimize threats and mitigate the risks of unauthorized access to sensitive and financial information and employees' personal data.

Keywords: personal data, sensitive and financial information, risks of unauthorized access

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企业信息安全保障战略：监测与管理

T.A. Rudakova[1, 2]
O.Yu. Rudakova[2]
[1] 波尔祖诺夫阿尔泰国立技术大学（巴尔瑙尔，俄罗斯）
[2] 阿尔泰国立大学（巴尔瑙尔，俄罗斯）

摘要

经济主体信息及其保障该信息运行的基础设施的安全性，仍然是当前经济关系发展阶段面临的挑战之一。对信息的未授权访问、对信息的偶然或恶意影响，以及第三方侵入相关支撑基础设施的运行，都会导致经济利益受损，并对经济主体—无论是法人还是自然人—造成损害。在这种背景下，组织经济安全部门的任务之一，就是防范威胁并控制企业敏感信息、财务信息以及员工个人数据遭受未授权访问的风险。本文旨在提出关于企业信息安全风险管理流程组织的方法建议。研究过程中，作者取得了以下成果：从比较视角考察了信息安全各项要素—包括信息保护、信息访问限制、加密、安全系统、双因素认证、信息传输、文件伪造、信息来源脆弱性检验以及信息真实性—的现状及其历史演变；系统梳理了信息窃取及未授权访问信息的方式；分析了制约个人数据保护原则落实的因素，并在"对象—脆弱性—威胁"框架下系统归纳了信息安全风险。研究结果的实践意义在于，可将其整合到组织管理体系和内部控制体系建设中，以最大限度减少针对敏感信息、财务信息和员工个人数据的未授权访问威胁，并控制相关风险。

关键词： 个人数据，敏感信息与财务信息，未授权访问风险

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Introduction

The global digital transformation of the economy is accelerating the development of information technologies and the integration of innovative solutions across economic sectors and public administration. For active participants, this creates competitive advantages, reduces costs, improves service quality, enhances production efficiency, and increases economic returns in the short term, with similar benefits expected in the future. At the same time, these positive developments are accompanied by negative effects, most notably the growing information vulnerability of economic entities.

Within the economy, information serves both as an object of exchange and as a source of data about business entities. Under current conditions, the task of those generating information is not only to ensure its accuracy but also to protect it from unauthorized interference. This includes safeguarding both the data itself and the infrastructure that supports it—what is commonly referred to as information security. Most researchers and practitioners dealing with the assessment of data security and supporting infrastructure agree that unauthorized access to business data remains a persistent risk. The ability to predict and prevent such incidents depends on multiple factors, while effective management of these risks helps minimize potential damage. In August 2025, the Russian analytical platform TAdviser conducted a survey among experts and business representatives. According to the results, "two out of three Russian companies (67%) can be breached within less than a day, and in more than 60% of cases, an incident capable of disrupting business operations can be successfully executed."[1]. These findings suggest that the level of cybersecurity claimed by businesses is substantially lower than the level of protection actually required, while risks and threats continue to be underestimated. At the same time, the time required to compromise a target system continues to shrink. Developers of innovative information security solutions attribute this situation to several factors.

First, management often prioritizes tasks such as timely reporting to investors and government institutions, conducting audits, obtaining positive audit opinions on financial statements, ensuring management efficiency, and maintaining business continuity.

As a result, information protection and control over unauthorized access tend to receive less attention. The rapid pace of technological development and the increasing use of advanced IT solutions in illicit activities make information systems more vulnerable. Moreover, the convenience of modern technologies often reduces their resilience. This creates an illusion of manageable risk at the management level. However, experts highlight persistent weaknesses in information security, including issues related to identification and authentication, as well as privilege management—such as excessive access rights in Active Directory, service accounts without multi-factor authentication, outdated or reused passwords, and persistent VPN access for contractors. Additional vulnerabilities include legacy Windows environments, unmanaged updates, and weak network segmentation, where the compromise of a single user device can lead to the failure of critical systems[2].

Information security, along with the challenges and factors limiting the legal protection of data, including personal data, has been widely studied in both domestic and international research. For example, the impact of big data technologies and related tools on personal data protection was analyzed in [Savelyev, 2015]. Information security and payment card industry standards were examined in [Borhalenko, 2015]. A bibliometric analysis of phishing attacks and WhatsApp[3] crelated threats using VOSviewer was presented in [Sujiwana et al., 2024]. International legal regulation of the digital environment was discussed in [Yastrebova, 2025]. Cybercrime and its regulation in countries of the Global South were analyzed in [Tsyplakova, 2025]. The role of intelligent systems in decision-making within the legal framework was explored in [Selivanova, Konopiy, 2025]. The use of explainable artificial intelligence for detecting attacks on corporate networks was proposed in [Yaz, Süzen, 2023]. The importance of human and social factors in monitoring information security risks was emphasized in [Van Deursen et al., 2013]. A quantitative model for assessing information security risks was proposed in [Jouini, 2015]. The role of financial and non-financial information in cybersecurity was analyzed in [Cristea, 2020]. Finally, [Lee, 2011] proposed a model for optimizing returns on investments in customer information security.

1. Unauthorized Access to Information

In Russian dictionaries, the term "to authorize" is defined as "to grant permission." Accordingly, information obtained without the consent of its owner may be considered stolen. Unauthorized access to information in the context of digital transformation represents a serious threat affecting both individuals and organizations, regardless of their size, ownership structure, or industry. This issue has attracted the attention of researchers since the early days of computing. The actors involved in in-

[1] https://clck.ru/3Pt26q/.
[2] Ibid.
[3] Owned by Meta, an organization recognized as extremist and banned in the Russian Federation.

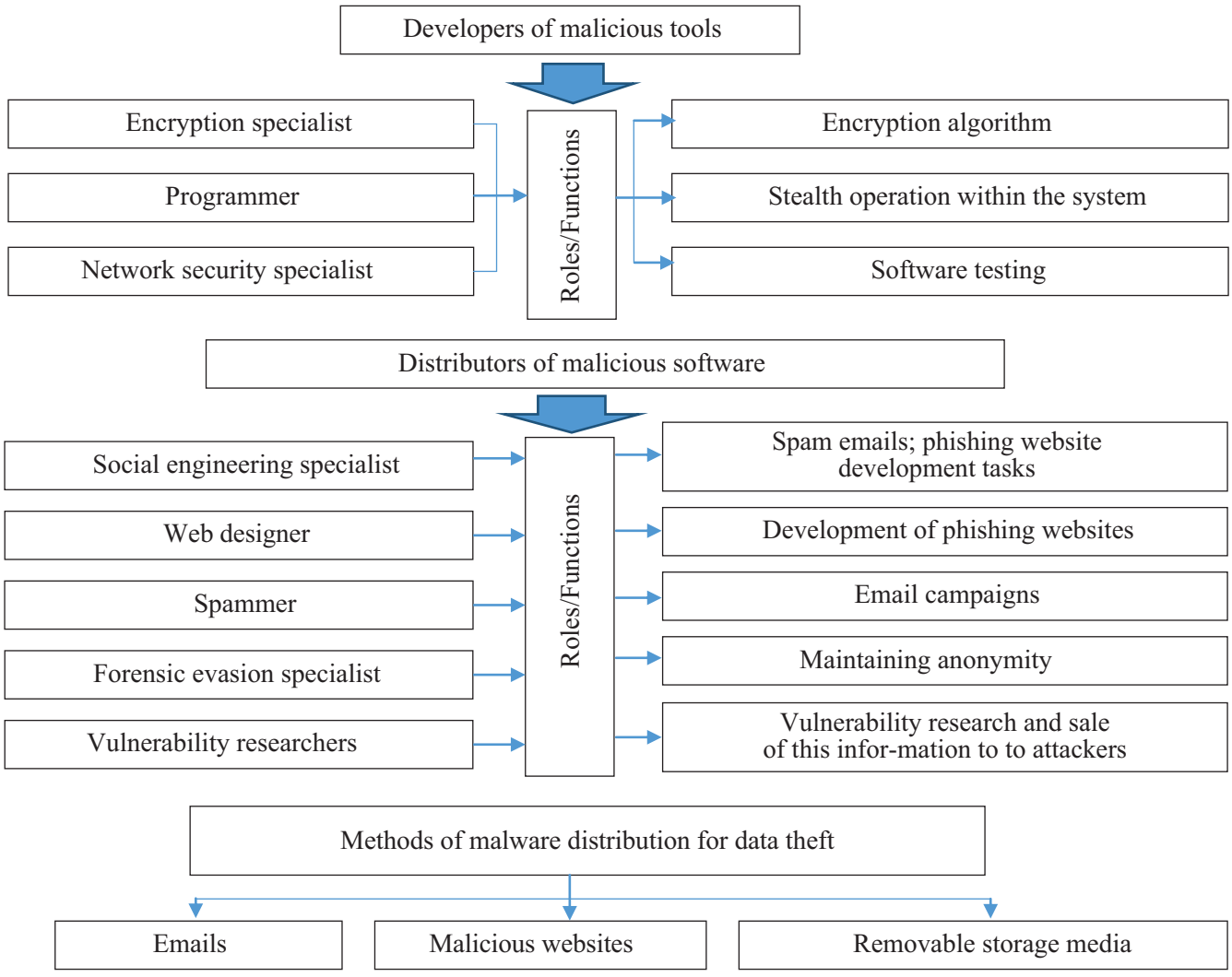
formation theft and the methods used to obtain data are presented in Figure 1.

The process of information theft typically involves the creators of malicious tools, distributors of malware, target objects, and access channels to data storage systems. These tools may be developed by a single specialist or a team possessing expertise in encryption algorithms, stealth techniques, and software testing. The distribution of malicious software is carried out by social engineering specialists, web designers, spammers, and experts responsible for maintaining anonymity and identifying software vulnerabilities.

2. Technological Innovation and the Risks of Information Leakage

The main channels through which information may be accessed include email in the absence of spam filtering and antivirus protection, malicious websites visited by users, applications downloaded to devices, and removable storage media that may be infected with malware. In all such cases, the primary source of vulnerability is the user of the device, whether a personal computer, tablet, or mobile phone.

In 2025, a ransomware strain capable of embedding itself in processor microcode was reported. At a confer-



Source: compiled by the authors.

Fig. 1. Actors Involved in Information Theft and Methods of Unauthorized Access

ence, K. Baik, Senior Director of Threat Analytics at Rapid7, described this threat and noted that he had developed a proof-of-concept malware sample capable of modifying the microcode of AMD Zen processors, which are used in a wide range of devices, including desktop computers, laptops, servers, and embedded systems. Because such malware remains invisible to conventional security tools, it represents a particularly serious threat. In Baik's view, cybersecurity professionals have become overly focused on advanced technologies, including artificial intelligence, while neglecting basic cybersecurity practices and longstanding security weaknesses[4].

The range of technological innovations in information acquisition, storage, and transmission has recently expanded to include tools based on generative artificial intelligence, of which there are now more than two thousand. These tools are used across a wide variety of fields. Their adoption is rapid and continues to gain momentum, while platforms built around them are developing at high speed. This points both to their broad practical use and to their substantial potential to transform socioeconomic processes.

According to the Big Data Association in cooperation with the consulting company B1 and TAdviser, the big data market showed strong growth in 2024 compared with 2023. Nearly all segments—services, application software, and infrastructure—grew by 26% to 33% (Table 1).

Within the services segment, the highest growth rate is seen in analytics and DaaS (Data as a Service) (Table 2).

The highest growth rate in the software segment—139.9%, or RUB 13 billion—is observed in analytical software (AI platforms) (Table 3).

Table 1
Big Data and Artificial Intelligence Market in Russia

Indicator	Market Size (RUB bln)		Growth	
	2023	2024	Absolute (RUB bln)	Relative (%)
Services	179	239	60	133.51
Application Software	95	127	32	133.68
Infrastructure	53	67	14	126.41
Total	327	433	106	132.41

Source: compiled by the authors based on TAdviser: https://www.tadviser.ru/a/910779.

Table 2
Services Segments of the Big Data and Artificial Intelligence Market in Russia

Indicator	Market Size (RUB bln)		Growth	
	2023	2024	Absolute (RUB bln)	Relative (%)
IT consulting, business consulting, data labeling, and model training support	85	105	20	123.5
Analytics and DaaS				
Advertising data products	44	67	23	152.2
Non-advertising data product	50	67	17	134

Source: compiled by the authors based on TAdviser: https://www.tadviser.ru/a/910779.

Table 3
Software in the Big Data and Artificial Intelligence Market in Russia

Indicator	Market Size (RUB bln)		Growth	
	2023	2024	Absolute (RUB bln)	Relative (%)
Application Software	29	39	10	134.48
Digital infrastructure	22	29	7	131.81
AI platforms	33	46	13	139.39
BI, EPM, and IBP analytics, geoinformation systems, search software, and software for intelligent content processing	11	13	2	118.18

Source: compiled by the authors based on TAdviser: https://www.tadviser.ru/a/910779.

[4] https://cnews.ru/link/a640902.

The use of generative artificial intelligence tools by employees to perform professional tasks creates a risk that personal, payment-related, and sensitive information may be transmitted through uploaded files and prompt content. This should not be regarded as unauthorized access to personal data or corporate information; rather, it reflects a lack of corporate culture and unprofessional employee conduct resulting from ineffective internal control and risk management systems.

This creates a need for business organizations to develop internal policies governing the use of generative artificial intelligence tools. Otherwise, personal data leaks may result in financial losses, including a fine of RUB 15 million for a first incident and up to 3% of a company's turnover in the event of a repeated breach where the responsible party cannot be identified.

The capabilities of modern innovative technical solutions are largely determined by the volume of information stored in digital devices, as socioeconomic processes have increasingly moved into the online environment. The amount of data is growing exponentially, and conventional tools are no longer capable of handling it effectively. This is where generative artificial intelligence, and tools built on it, become relevant: they can generate any information contained in the underlying data sets, though not always with the consent of individuals, in the case of personal data, or of legal entities, in the case of sensitive and financial information. This is inherent in big data analytics technologies, which comprise tools and methods designed to process and structure continuously expanding and rapidly changing data flows and thus provide the foundation for the use of generative artificial intelligence tools [Savelyev, 2015].

Today, information plays a central role in both business activity and public administration. It has rightly come to be treated as a commodity—often referred to as "the new oil" [Arthur, 2013]—and is now regarded as one of the factors of production. The quality and volume of this asset allow those who possess it, provided they have the necessary technical capabilities, to occupy a key position in the value chain, increase productivity, reduce costs, and thereby contribute to the growth of industries that support data analysis, including both technology and related services.

3. Information Security: A Historical Perspective

The need to protect information in storage and transmission from unauthorized interference and misuse has long required information creators not only to ensure the authenticity of documents but also to restrict unauthorized access to them. This is evidenced by studies of early cryptographic practices, which show that concerns about information security have existed for centuries (Table 4).

Firewalls—systems that monitor and filter network traffic to prevent unauthorized access to a device or computer network—have replaced the wax, parchment, and threat of execution once used in the fourteenth century to ensure the secure delivery of information from sender to recipient. Today, one of the main means of transmitting and exchanging large volumes of data remains email, whereas historically this function was performed by messengers. In the past, unauthorized access to information was constrained through homophonic encryption of messages written on parchment, which increased their unpredictability, or entropy. Encryption, or encoding, remains a means of protecting information today. Historically, the design of a cipher was the responsibility of its creator. In diplomatic correspondence, homophonic ciphers were widely used: letters were replaced with symbols, and the same letter could be represented by different symbols. At the same time, the limited literacy of the person carrying or encoding the message often prevented them from understanding its content. Information was also protected against loss and interception by sending duplicate messengers and dividing the key to the protected information among them [Larin, 2010].

Today, access to information is restricted through differentiated access rights, individual passwords, two-factor authentication when logging into an account, and biometric systems. In earlier periods, these functions were performed by wax seals and the sender's handwriting. In modern conditions, information transmitted through telecommunication channels is protected by software tools such as antivirus programs. In the past, double envelopes were used, with one containing non-essential information and the other the message intended for the recipient. Letters were often duplicated to increase the chances of successful delivery, and secret markings were used to make intercepted messages more difficult to exploit. The authenticity of information was confirmed by a wax seal attached to the letter; such seals were possessed by persons of rank, including bishops, dukes, and kings. The modern analogue of this mechanism is the electronic signature, which may be protected in different ways depending on the owner and the significance of the document being certified.

Nevertheless, regardless of the tools available at a given stage of social and economic development, information forgery has always existed. This was done by altering the text of a letter written on parchment or paper, either by modifying it directly or by inserting additional text after it had been signed.

Modern society faces supply chain attacks, in which cybercriminals exploit vulnerabilities in software or hardware supply chains to gain access to the systems of a target organization. In such cases, information becomes accessible and may be used for extortion or blackmail. One current way of combating cybercrime is vulnerability identification through bug bounty programs, that is, open initiatives aimed at discovering vulnerabilities in software products. This may be compared with reports of forged coats of arms and seals in earlier periods: if such reports proved false, the informant could be severely punished for providing inaccurate information in a denunciation.

4. Information Security Standards and Personal Data Protection

Establishing an information security system is one of management's priority tasks. The regulation of this area is based on applicable national and international standards. In Russia, the basic rules governing standardization and the application of national standards were established by Federal Law *On Technical Regulation*[5] and State Standard GOST R 1.0-2004 *Standardization in the Russian Federation. Basic Provisions*. National information security standards were developed with reference to international experience and standardization practices. The currently applicable standard GOST R ISO/IEC 27005-2010 *Information Technology. Security Techniques. Information Security Risk Management* refers to international standards only where no equivalent national standard exists. Since national standards are regularly updated, the correct application of GOST R ISO/IEC 27005-2010 requires continuous monitoring of changes in the relevant national documents.

Personal data protection requirements are established both by international law and by national regulations. It should be noted that the international community began addressing the problem of unauthorized access to personal data much earlier than Russia did. The Convention for the Protection of Individuals with regard to Automatic Processing of Personal Data was adopted by the Council of Europe in Strasbourg in 1981, becoming the starting

Table 4
Information Security Elements: Modern Practices and Historical Analogues

Concept	Modern Practice	Historical Analogue
Information protection	Antivirus software	Double envelopes containing non-essential and important information, duplicate letters, secret markings, and steganography on parchment
Restriction of access to information	Access control through individual passwords	Division of decryption keys among messengers
Encryption	Encoding information to prevent unauthorized access	Homophonic encryption designed to make message content less predictable
Security system	Firewalls, which monitor and filter network traffic to prevent unauthorized access to a computer network or device	Wax, parchment, and the threat of execution for messengers
Two-factor authentication	Two different factors used to verify identity when logging into an account or system; biometrics	Wax seals used to secure letters; handwriting
Information transmission	Mail and email	Messengers
Information tampering / falsification	Supply chain attacks, in which attackers exploit vulnerabilities in software or hardware supply chains to gain access to a target organization's systems	Tampering with written documents by altering the text after signature
Vulnerability assessment	Bug bounty programs for identifying vulnerabilities in software products	Reports of forgeries of coats of arms and seals
Information authenticity	Electronic signature	Wax and sealing-wax seals

Source: compiled by the authors.

[5] https://www.consultant.ru/document/cons_doc_LAW_40241/.

point for the adoption of national laws and a series of EU directives across Europe.

The Russian legal framework was supplemented by Federal Law No. 152-FZ of 2006 *On Personal Data*[6], which entered into force in 2007 following Russia's ratification of the Council of Europe Convention in 2005.

This suggests that the legal framework contains a substantial body of provisions governing personal data protection. At the same time, doubts remain as to whether these requirements are consistently observed by all participants in information exchange, both at the stage of data collection and processing and at the stage of data transfer and generation. Individuals voluntarily disclose personal data not only to employers and state institutions, which assume responsibility for protecting such information, but also through messengers, online platforms, and internet resources. As a result, personal data become part of big data sets and may be used to generate new information by combining them with other data unrelated to either the original purpose of disclosure or the stated purposes of personal data processing (Table 5).

Failure to comply with the principle that personal data must be processed only for the purposes for which they were collected may result from a number of factors. These include the employer's technical capacity to handle employees' personal data and store copies of HR documents; the qualifications of personnel who have access to such data; employees' digital literacy; the use of generative artificial intelligence tools in the performance of professional tasks involving personal data; failure by employees to observe digital hygiene practices; and the absence of any guarantee that the economic entity providing storage space for personal data on its platform will remain in operation until the end of the contract term, whether because of voluntary closure or compulsory insolvency proceedings.

An increasing number of organizations are using cloud technologies in workforce management. Once a contract has been concluded, responsibility for the security of HR documents shifts to the cloud service provider, which creates certain information security risks for the client organization. This is because the cloud provider owns the relevant infrastructure. Although storing data in a public cloud offers clear advantages, it does not relieve the organization of its obligation to comply with information security and personal data protection requirements. On the contrary, it requires organizational and technical measures that ensure long-term document retention and continued accessibility. Not all cloud-based HR document management solutions are capable of preserving the legal validity of documents, including electronic signatures, and not all can ensure long-term storage. Therefore, the client organization must be able to export such documents and place them on its own server.

Table 5
Personal Data Protection Principles with Barriers to Their Compliance

Principle	Barriers to Compliance
Voluntary consent of the individual, provided that the operator discloses the purpose of processing	The large volume of information provided by the operator on the purposes of processing, which is difficult to review when accessing the resource The complexity of the way this information is presented by the personal data operator, which may require legal knowledge on the part of the individual
Personal data must not be combined with other sources to generate new information	The logic of big data analytics, which is based on data reuse The accumulation of personal information voluntarily left on websites, online platforms, messengers, and other digital resources
Personal data must be processed in accordance with the operator's stated purposes for collection	Technical limitations Staff qualifications Staff digital literacy Failure of the operator's employees to follow digital hygiene practices The need to ensure business continuity on the part of the economic entity leasing out cloud storage space Phishing

Source: compiled by the authors.

[6] https://www.consultant.ru/document/cons_doc_LAW_61801/.

An analysis of regulatory documents and academic sources leads to the rather discouraging conclusion that unauthorized access to personal and sensitive information remains a pressing issue for all participants in socioeconomic relations and market activity under current conditions and is unlikely to lose its significance in the near future. This is due to the transformative processes taking place in both the economy and society under the influence of digitalization, the migration of information into cloud environments, the adoption of new technological advances in the era of big data, and the development of generative artificial intelligence tools. Digitalization is a long-term process, and each new stage of technological development will bring new challenges, generate new problems, and create new tasks for its participants.

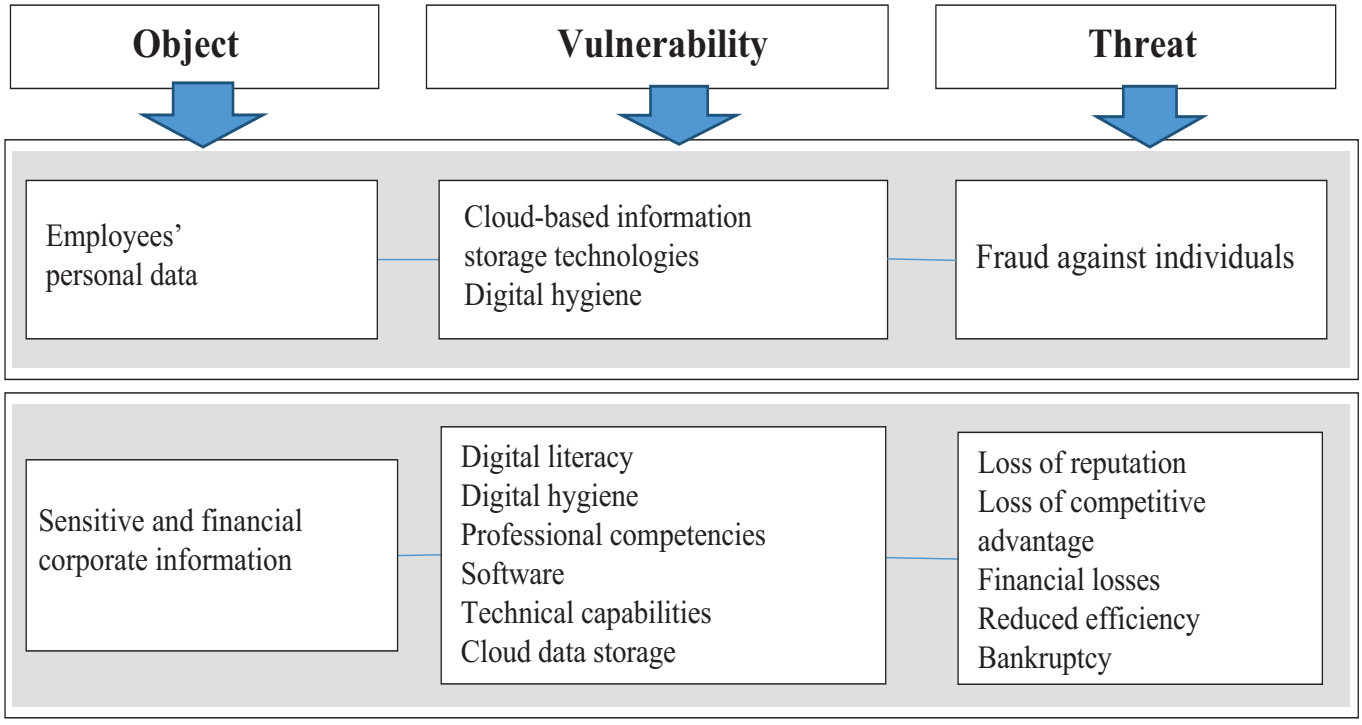
At the present stage of socioeconomic development, unauthorized access to information, its underlying causes, and ways of preventing it should be regarded as fundamental challenges. Participants in socioeconomic relations must be prepared to address them. Above all, this concerns the competencies required of everyone involved in information exchange. Leaders of organizations and public institutions need competencies not only in management but also in building information security systems at both the corporate and personal levels. This, in turn, requires continuous monitoring of developments in information security technologies and of measures aimed at restricting unauthorized access to employees' personal data. Individuals, with due regard to age-related characteristics and other limitations, should also be taught the basic rules of digital hygiene. Since information is now a commercially valuable asset, management must ensure that this value is protected in both a direct and a broader sense by identifying the relevant priorities and tasks.

5. Monitoring and Management of Information Security Risks in an Enterprise

From an information security perspective, risk management should begin by identifying the asset at risk, assessing the vulnerabilities of the relevant tool or resource, and determining the potential threats and adverse consequences associated with those vulnerabilities (Figure 2).

The second stage in organizing the management process should focus on specifying the relevant objects, describing their vulnerabilities, and identifying potential threats and the consequences of their realization for the organization (Table 6).

The allocation of responsibilities for monitoring and overseeing information security assets across an organization's divisions, or responsibility centers, and among individual managers may depend on a number of factors, including the size of the business, its financial resources,



Source: compiled by the authors based on [Lapina et al., 2024].

Fig. 2. Components of Information Security Risk

Table 6
Information Risk Management Framework

Object	Vulnerability	Threat	Risks
Human resource management			
Personnel with the required competencies	Insufficient qualifications in information technology	Poor digital hygiene; accidental or deliberate disclosure of information to third parties	Reputational; financial
Information risk management			
Software	Origin (foreign or domestic)	Lack of a software license or difficulties in obtaining or renewing one	Information loss; data recovery costs; financial losses caused by business interruption during migration to alternative software (revenue loss, profit loss, fines, penalties)
Technical infrastructure capacity	Insufficient capacity to store large volumes of information	Contractual limits on mandatory long-term storage of large volumes of information in cloud repositories	Loss of access to information that must be retained long term (including HR records)
Electronic documents	Unauthorized access; limited retention periods	Loss of legal validity of electronic signatures when HR and other documents are stored in the cloud on leased services	Loss of access to information intended for long-term retention
Personal, sensitive, and financial information	Insufficient protection against unauthorized access	Theft, falsification, blackmail	Reputational, financial

Source: compiled by the authors.

the specifics of its organizational structure, staffing, and related considerations.

Both historical experience and current business needs suggest that information security, as a component of an economic entity's broader economic security, will remain one of the most urgent tasks in the short term. This is driven by the rapid growth in the volume of information, the migration of key business and social processes to the internet, and the increasing role of information as a valuable asset in both commercial activity and public administration. Information technologies have made it possible for many processes and social interactions to move online, thereby enabling intrusion into individuals' private lives and reshaping the boundaries of personal space. A number of regulations have been developed to govern the handling of corporate and personal information and to prevent unauthorized access, distortion, and fraudulent use. However, these measures are no longer sufficient in view of the rapid development of information technologies and the emergence of innovative technical solutions that make it possible to exploit internet-based information with a digital footprint. To organize effective efforts aimed at minimizing threats and containing potential information risks, an economic entity needs more than legal expertise alone.

Within the management system, the following measures should be prioritized:

1. Objects requiring close attention within the organization's risk management system should be identified, together with their vulnerabilities, potential threats, and the likely consequences of those threats.

2. Powers and responsibilities for monitoring and analyzing events involving the organization's information and employees' personal data should be clearly allocated among divisions and personnel in order to prevent unauthorized access to sensitive and financial information and to personal data.

3. Employees should be regularly informed about current methods of unauthorized access to private and corporate information and should continuously develop the competencies needed to counter such threats. Failure to observe digital hygiene practices increases the likelihood of financial risks not only for the organization but also

for the individual and may also result in administrative liability under Article 13.11 of the Code of Administrative Offenses of the Russian Federation.

The development and continuous improvement of employees' competencies in handling sensitive information and personal data should become an integral part of the organization's human resource management system. This will help ensure that the economic entity operates within the legal framework governing personal data protection, minimize violations of employees' personal boundaries, and reduce risks of various kinds, including financial ones.

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About the Authors

Tatyana A. Rudakova
Cand. Sci. (Econ.), Associate Professor, Department of Economics, Altai State Technical University named after I.I. Polzunov (Barnaul, Russia); Associate Professor, Department of Economic Security, Accounting, Analysis and Audit, Altai State University (Barnaul, Russia). ORCID: 0000-0002-8735-7058.
Research interests: digital finance, economic security, risk management, accounting and analytical aspects of bankruptcy, reliability of accounting and reporting information, risks of the real sector of the economy.
aleks_rudakova@mail.ru

Oksana Yu. Rudakova
Cand. Sci. (Econ.), Associate Professor, Head of the Department of Management, Business Organization and Innovation, Altai State University (Barnaul, Russia). ORCID: 0000-0001-9714-2483.
Research interests: anti-crisis management, change and development management, economic security, management consulting, innovation.
rud-oksana@yandex.ru

作者简介

Tatyana A. Rudakova
经济学博士，副教授，伊·伊·波尔祖诺夫阿尔泰国立技术大学经济学系（巴尔瑙尔，俄罗斯）；副教授，阿尔泰国立大学经济安全、会计、分析与审计系（巴尔瑙尔，俄罗斯）。ORCID: 0000-0002-8735-7058。
研究方向：数字金融、经济安全、风险管理、破产的会计与分析问题、会计报告信息的真实性、实体经济部门风险。
aleks_rudakova@mail.ru

Oksana Yu. Rudakova
经济学博士，副教授，阿尔泰国立大学管理、商业组织与创新系主任（巴尔瑙尔，俄罗斯）。ORCID: 0000-0001-9714-2483。
研究方向：危机管理、变革与发展管理、经济安全、管理咨询、创新。
rud-oksana@yandex.ru

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The Concept of Top Management Teams: A Systematic Review of the Research Discourse

V.K. Taysaeva[1, 2]
[1] Moscow State Institute of International Relations (MGIMO University) (Moscow, Russia)
[2] Ministry of Economic Development of the Russian Federation (Moscow, Russia)

Abstract
The personal maturity and professional competence of top management teams (TMTs) are increasingly recognized as critical factors for ensuring organizational sustainability and competitiveness in contemporary strategic management research. This study presents a systematic review of the academic literature examining top management teams and their contribution to the strategic success of organizations. A total of 41 publications indexed in the Web of Science and Scopus databases between 1980 and 2025 were analysed. The review findings indicate that research on the TMT concept is predominantly characterized by the use of quantitative methodologies and a focus on economically developed countries. At the same time, several important areas remain underexplored, including the transformation of top management teams in organizations pursuing long-term strategic orientations, the internal cognitive and behavioral processes within teams, and the specific features of TMT functioning in companies operating in emerging economies. The identified research gaps highlight the need for further empirical and qualitative studies aimed at deepening the understanding of the mechanisms underlying the formation and transformation of top management teams and their influence on organizational strategic resilience.

Keywords: Upper Echelons Theory, strategic management, organizational sustainability, organizational competitiveness

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高层管理团队概念：研究话语的系统性综述

V.K. Taysaeva[1, 2]
[1] 俄罗斯外交部莫斯科国立国际关系学院（莫斯科，俄罗斯）
[2] 俄罗斯联邦经发展部（莫斯科，俄罗斯）

摘要
在当代战略管理研究中，高层管理团队（Top Management Teams, TMT）的个人成熟度与专业胜任力日益被视为组织保持韧性与竞争力的关键因素。作者对关于高层管理团队及其对组织战略成功贡献的学术文献进行了系统性综述。研究样本纳入了 1980 年至 2025 年期间来自 Web of Science 和 Scopus 国际科学引文数据库的 41 篇文献。综述结果表明，关于 TMT 概念的研究明显以量化方法为主，且主要聚焦于经济发达国家。与此同时，诸如实施长期战略的组织中高层管理团队的转型、团队内部的认知与行为过程，以及该概念在动态发展中国家企业中的具体表现等方面，仍有待深入研究。所发现的研究空白表明，有必要进一步开展实证研究和质性研究，以深化对高层管理团队形成与转型机制及其对组织战略韧性影响的理解。

关键词： 高阶理论，战略管理，组织韧性与竞争力因素

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Introduction

In the twenty-first century, uncertainty has become an inherent characteristic of the external business environment. This poses a significant challenge for both scholars and practitioners of strategic management: identifying the factors that ensure the sustainability and competitiveness of organizations implementing long-term strategic plans. In the long run, the strategic success of an organization is determined not only by ambitious development strategies but also by the presence of an effective top management team (TMT) capable of translating these plans into practice.

Over the years, a scholarly consensus has emerged that the composition and characteristics of the top management team directly influence strategic decision-making, which is ultimately reflected in organizational performance outcomes [Hambrick, Mason, 1984; Carpenter et al., 2004]. According to Upper Echelons Theory, the values and experiences of top executives shape specific perceptual filters through which the external environment is interpreted and determine the selection of strategic alternatives pursued by the organization [Hambrick, Mason, 1984; Hambrick, 2007; Kamolov, 2025]. In the context of long-term planning, these aspects of the management system become particularly important, as they directly affect the organization's ability to remain resilient under conditions of high uncertainty.

At the same time, contemporary research on top management teams predominantly focuses on short- and medium-term planning horizons. In contrast, the transformation of TMTs composition, competencies, and role structures during the implementation of long-term strategic initiatives remains underexplored and calls for specialized analytical approaches [Neely et al., 2020].

In this context, the present review pursues two primary objectives:

1) to systematize existing theoretical and empirical research on top management teams within the field of strategic management;

2) to identify and justify key research directions related to top management teams that require further empirical investigation.

Research on top management teams is grounded in several fundamental theoretical perspectives, each explaining the relationship between TMTs characteristics and organizational strategic outcomes. The most prominent framework is Upper Echelons Theory [Hambrick, Mason, 1984], according to which strategic decisions reflect the values, experiences, and cognitive frameworks of TMTs members. This theoretical perspective has been further developed in studies examining how executives' socio-demographic characteristics, professional experience, cultural background, and personal attributes influence strategic decision-making processes [Carpenter et al., 2004; Kamolov, Podolsky, 2013; Kamolov, Markov, 2024].

Another important theoretical perspective is the Resource-Based View (RBV) of the firm, within which TMTs is regarded as a unique strategic resource that provides organizations with competitive advantage through a specific combination of knowledge, skills, and social capital [Barney, 1991]. This approach emphasizes that the long-term effectiveness of an organization largely depends on the ability of the TMTs to accumulate and develop managerial competencies.

Strategic Leadership Theory, in turn, focuses on the role of leaders in shaping organizational vision, creating adaptive structures, and implementing change—processes that are particularly critical in the context of long-term strategic planning [Boal, Hooijberg, 2001].

Despite the extensive empirical evidence on top management teams accumulated over recent decades, the majority of existing studies concentrate on short- and medium-term effects. At the same time, the transformation of TMTs composition, competencies, and roles during the implementation of long-horizon strategies, as well as the integration of long-term strategic thinking into executive decision-making, remain comparatively underdeveloped areas of research.

1. Research Design

This study conducts a systematic literature review of research on top management teams. The sample includes 41 publications published in leading academic journals between 1980 and 2025. The literature search was conducted using the Web of Science and Scopus databases. Publications were selected according to the following criteria:

First, only articles published in Q1 journals according to the Scimago/Scopus ranking with an impact factor of at least 3.0 were included. This criterion follows widely accepted practices for assessing publication quality and ensures that the analysis focuses on highly cited and influential studies.

Second, the review included English-language articles whose titles, abstracts, or keywords contained the terms *"top management team," "TMT,"* or *"upper echelons."* This approach, commonly used in literature review studies, allows the sample to be narrowed to publications directly related to research on top management teams [Krause et al., 2022].

Third, the sampling period covers 1980–2025, which allows the analysis to trace the evolution of TMTs research from the emergence of Upper Echelons Theory to more recent studies examining micro-level processes as well as cognitive and emotional aspects of top management teams.

Fourth, the sample includes empirical, theoretical, and review articles, with priority given to studies that propose new conceptual models, methodological approaches, or analytical findings demonstrating the importance of TMTs for strategic management in organizations.

The article selection process consisted of several stages. In the first stage, an initial search was conducted using combinations of keywords together with filters for publication year, and the ranking of the journals in which the articles were published was also taken into account. The preliminary search in Web of Science and Scopus identified more than 100 publications. In the second stage, the abstracts of the identified studies were screened to assess their relevance to the research topic. Publications in which top management teams were mentioned only indirectly or played a secondary role in the study were excluded. After full-text screening for relevance to the research focus, the final sample consisted of 41 articles.

Subsequently, a bibliometric analysis was conducted, including an examination of publication growth over time, identification of the leading journals in which relevant studies were published, determination of key authors in the field, and identification of the main thematic research areas. The bibliometric analysis allowed us to assess the distribution of publications across journals and years, thereby facilitating the systematization and categorization of the literature.

At the final stage, each article was analyzed with regard to its primary research theme, research question, methodological approach, and key findings. As a result, the publications were classified into five main categories:

1) Upper Echelons Theory;
2) TMTs composition and diversity;
3) team dynamics and behavioral processes;
4) the impact of TMTs on organizational performance;
5) review and meta-analytic studies.

Each publication was also classified according to the type of research design, including quantitative methods (e.g., regression analysis and quasi-experimental designs) and qualitative methods (e.g., case studies and interviews). This approach helped identify the dominant methodological approaches in the literature and to determine existing research gaps.

Based on the results of the bibliometric and content analyses, two key research questions were formulated:

1) What are the main bibliometric characteristics of the TMTs literature over the period 1980–2025, including publication growth, leading journals, key authors, and thematic categories?

2) How are research methods distributed across studies on top management teams?

Thus, the analysis allowed the construction of a structured overview of the development of TMT research, reflecting publication dynamics, journal distribution, methodological approaches, and key thematic areas (Table 1).

2. Literature Analysis

The analysis of the 41 articles indicates that research on top management teams has developed through several stages. During the 1980s and 1990s, the foundations of Upper Echelons Theory were established, with research focusing on the relationship between the characteristics of top managers and organizational decisions and outcomes. A seminal contribution in this stream is the article by D.C. Hambrick and P.A. Mason, which conceptualizes the organization as a reflection of the key characteristics of its top managers [Hambrick, Mason, 1984]. During the same period, studies were published examining the influence of decision-making styles on organizational behavior [Henderson, Nutt, 1980], as well as research addressing the socio-demographic characteristics of top management teams and their influence on strategic change within organizations [Wiersema, Bantel, 1992].

Between 1990 and 2000, the number of studies examining demographic, functional, and cognitive diversity in top management teams increased significantly. For example, Bantel and Jackson analyzed the influence of team composition on innovation in the banking sector [Bantel, Jackson, 1989]. In the study [Kilduff et al., 2000], the authors investigated the effects of cognitive diversity on team performance. At the same time, scholars began to argue that under adverse environmental conditions and intense competition, top managers tend to select managers who are similar to themselves, while the most dissimilar members are more likely to leave the organization, thereby reinforcing team homogeneity [Boone et al., 2004]. During this period, research also emerged examining the influence of top management teams on international expansion and corporate ideology [Goll et al., 2001; Barkema, Shvyrkov, 2007].

Table 1
Selected Publications

№	Publication	Journal (Q1)	Study type	Data source	Research category
1	[Attah-Boakye et al., 2021]	European Journal of Finance	Quantitative study	Panel data	4
2	[Bantel, Jackson, 1989]	Strategic Management Journal	Quantitative study	Panel data	2
3	[Barkema, Shvyrkov, 2007]	Strategic Management Journal	Quantitative study	Panel data	2
4	[Barney, 1991]	Journal of Management	Conceptual paper	Theoretical	1
5	[Beckman, Burton, 2008]	Organization Science	Quantitative study	Panel data	2
6	[Boal, Hooijberg, 2001]	Leadership Quarterly	Conceptual paper	Literature	1
7	[Boone et al., 2004]	Academy of Management Journal	Quantitative study	Panel data	2
8	[Boone, Hendriks, 2009]	Management Science	Quantitative study	Panel data	4
9	[Carpenter, Fredrickson, 2001]	Academy of Management Journal	Quantitative study	Panel data	4
10	[Carpenter et al., 2004]	Journal of Management	Literature review	Literature	5
11	[Eriksson et al., 2020]	Journal of Strategic Marketing	Quantitative study	Case studies	4
12	[Finkelstein, 1992]	Academy of Management Journal	Quantitative study	Archival data	1
13	[Goll et al., 2001]	Management International Review	Quantitative study	Panel data	4
14	[Hambrick, 2007	Academy of Management Review	Literature review	Literature	1
15	[Hambrick, D'Aveni, 1992]	Management Science	Quantitative study	Panel data	4
16	[Hambrick, Mason, 1984]	Academy of Management Review	Conceptual paper	Theoretical	1
17	[Henderson, Nutt, 1980]	Management Science	Quantitative study	Experimental data	3
18	[Huang et al., 2020]	Emerging Markets Finance and Trade	Quantitative study	Panel data	4
19	[Keck, 1997]	Organization Science	Quantitative study	Panel data	2
20	[Kilduff et al., 2000]	Organization Science	Quantitative study	Experimental data	2

Table 1 – ending

№	Publication	Journal (Q1)	Study type	Data source	Research category
21	[Kisfalvi et al., 2016]	Long Range Planning,	Qualitative study	Case studies, interviews	3
22	[Knight et al., 1999]	Strategic Management Journal	Quantitative study	Panel data	3
23	[Krause et al., 2022]	Journal of Management	Literature review	Literature	5
24	[Liu et al.,2021]	Leadership Quarterly	Qualitative study	Case studies, interviews	3
25	[Ma et al.,2022a]	Sustainability	Quantitative study	Panel data	4
26	[Ma et al.,2022b]	Strategic Management Journal	Quantitative study	Theoretical	2
27	[Marcel, 2009]	Strategic Management Journal	Quantitative study	Panel data	4
28	[Meng et al., 2013]	Journal of Business Ethics	Quantitative study	Panel data	4
29	[Neely et al., 2020]	Journal of Management	Literature review	Literature	5
30	[Ormiston et al., 2022	Leadership Quarterly	Quantitative study	Panel data	3
31	[Ou et al., 2017]	Academy of Management Journal	Quantitative study	Panel data	3
32	[Pelled et al., 1999]	Administrative Science Quarterly	Quantitative study	Panel data	3
33	[Peterson et al., 2003]	Journal of Applied Psychology	Quantitative study	Interviews + panel data	3
34	[Pitcher, Smith, 2001]	Organization Science	Qualitative study	Case studies, interviews	2
35	[Saeed et al., 2022]	Journal of Business Research	Quantitative study	Panel data	2
36	[Saeed et al., 2025]	Journal of Product Innovation Management	Quantitative study	Literature	5
37	[Simons et al., 1999]	Academy of Management Journal	Quantitative study	Panel data	3
38	[Tushman, Virany, 1986]	Journal of Business Venturing	Qualitative study	Case studies	4
39	[Wiersema, Bantel, 1992]	Academy of Management Journal	Quantitative study	Panel data	2
40	[Wu et al., 2023]	SAGE Open	Quantitative study	Panel data	2
41	[Priem et al., 1999]	Journal of Management	Conceptual paper	Literature	1

Source: compiled by the author.

From the 2010s to 2025, research on TMTs increasingly shifted toward micro-level processes within organizations, including daily interactions, communication patterns, and collaborative activities among team members that shape group behavior and influence strategic decision-making [Kisfalvi et al., 2016]. Studies during this period began to examine emotional aspects of top management teams, as well as the role of sustainability and innovation [Liu et al., 2021]. For instance, researchers explored the micro-dynamics of team integration, analyzed relationships among team members and their influence on strategic decision-making, and examined the role of CEO emotional stability and team diversity in shaping the emotional climate of TMTs [Ormiston et al., 2022]. At the same time, research on corporate social responsibility and sustainability expanded. Studies examined the relationship between TMTs stability and the sustainability of corporate social responsibility initiatives [Huang et al., 2020], as well as the impact of changes in top management composition on corporate environmental responsibility [Meng et al., 2013].

In early studies of top management teams, researchers frequently employed an approach in which team heterogeneity was measured using the demographic characteristics of team members (such as age, gender, education, or tenure). However, it was later recognized that this approach has significant limitations. Although demographic indicators provide relatively reliable measures for empirical analysis, they do not allow researchers to fully capture the actual processes occurring within top management teams [Priem et al., 1999]. Consequently, subsequent research adopted a broader perspective on TMTs composition, incorporating role diversity, functional experience, and other organizational characteristics. Scholars have also noted that the literature contains a wide range of definitions of top management teams, and that studies often rely on convenience samples, which complicates comparisons across empirical findings [Carpenter et al., 2004]. A meta-analysis of 27 studies confirmed that both team size and team diversity influence strategic decision-making and firms' financial performance; however, the results depend strongly on how these characteristics are operationalized in empirical studies. This finding highlights the importance of carefully selecting appropriate measurement approaches when examining the relationship between TMTs characteristics and organizational performance [Certo et al., 2006].

The leading journals publishing the studies included in the sample are *Academy of Management Journal, Strategic Management Journal, Organization Science*, and *Journal of Management* (Table 2).

The sample is dominated by studies employing quantitative research methods. For example, several studies apply panel regression analysis to examine the effect of functional diversity on firm performance [Boone, Hendriks, 2009], while other research uses empirical analysis of samples of Chinese listed companies to investigate the influence of experiential heterogeneity on the quality of innovation [Ma et al., 2022a].

Qualitative methods appear less frequently but provide valuable insights into the internal processes and behavioral dynamics of top management teams. For instance, some studies analyze the micro-dynamics of top management teams through the concept of behavioral integration [Kisfalvi et al., 2016].

A number of studies also employ social network approaches and analyses of intra-team processes, examining the influence of power and personality heterogeneity within teams and identifying structural characteristics of top management teams [Pitcher, Smith, 2001]. Other research investigates the role of team diversity and internal debate in enhancing the comprehensiveness of team decision-making [Simons et al., 1999].

A separate stream of research consists of meta-analyses and review articles, which synthesize empirical findings and propose conceptual frameworks for future research. For example, R. Krause and co-authors develop research maps of the TMTs literature and propose pathways for its conceptual development [Krause et al., 2022]. Other studies synthesize results from numerous

Table 2
Leading Journals

Journal	SJR Quartile	Impact Factor	H-index
Academy of Management Journal	Q1	10.5	396
Strategic Management Journal	Q1	7.2	351
Organization Science	Q1	5.4	294
Journal of Management	Q1	15.7	296

Source: compiled by the author based on data from the SCImago Journal Rank database.

empirical investigations to evaluate how TMTs characteristics—such as experience, education, diversity, and team composition—influence organizations' ability to initiate new projects and pursue new strategic directions [Saeed et al., 2025].

Overall, the analysis shows that quantitative methods dominate research on the relationship between TMTs composition and organizational outcomes, whereas qualitative and mixed methods are primarily used to investigate micro-level processes, behavioral dynamics, and emotional aspects of executive team functioning.

3. Research gaps

Despite the large body of research on top management teams, the existing literature reveals several significant gaps, particularly in the context of long-term strategic planning and the transformation of executive leadership structures.

Most studies focus on strategic horizons of three to five years [Carpenter et al., 2004; Hambrick, 2007], while research examining TMTs in the context of long-term planning horizons (exceeding 12 years) remains extremely limited. Similarly, insufficient attention has been paid to evolutionary processes in the formation of top management teams and to intra-team processes during the implementation of long-term strategies. The absence of such research restricts the ability to identify relationships between changes in executive leadership structures and the successful implementation of long-term strategic objectives.

Existing research tends to emphasize demographic characteristics of executives, whereas managerial styles, behavioral patterns, and capabilities related to knowledge management and organizational learning are rarely examined as key explanatory variables [Peterson et al., 2003]. This gap limits our understanding of the mechanisms through which top management teams shape long-term strategic decisions.

Another limitation concerns the geographical concentration of empirical research. Most studies focus on U.S. and Western European firms. Although several recent publications have examined Chinese markets, revealing the importance of local institutional contexts for the composition, experience, and performance of top management teams, systematic comparative studies across different institutional environments remain scarce [Ma et al., 2022a].

The literature on TMTs is also characterized by the dominance of quantitative studies based on secondary data, regression models, and analyses of financial statements [Hambrick, D'Aveni, 1992; Boone, Hendriks, 2009; Attah-Boakye et al., 2021]. In contrast, case studies, interviews, and observational research, which make it possible to reconstruct internal decision-making processes, team transformations, and the emotional dynamics of top management teams, remain relatively rare [Kisfalvi et al., 2016; Liu et al., 2021; Ormiston et al., 2022].

Finally, the number of meta-analyses and systematic review studies that synthesize empirical findings and propose conceptual frameworks for future research on TMTs remains limited.

Conclusion

Based on the analysis of existing publications, several key research gaps in the study of top management teams can be identified. These include:

- insufficient attention to the transformation of TMTs in companies implementing long-term strategies;
- limited empirical evidence from emerging markets;
- the predominance of quantitative research methods and the limited use of qualitative studies that could reveal the internal processes of TMTs functioning;
- the insufficient number of systematic reviews synthesizing the results of empirical studies.

Addressing these gaps creates opportunities for a deeper understanding of the mechanisms underlying the formation and transformation of top management teams, as well as their influence on the implementation of strategic decisions. In the future, research may focus on:

- examining the evolution and transformation of TMTs over very long planning horizons;
- analyzing the cognitive, behavioral, and emotional aspects of top management teams;
- developing methodological approaches capable of capturing intra-team processes.

This research provide a basis for developing more comprehensive theoretical models that explain how top management teams shape organizational competitiveness under conditions of increasing environmental uncertainty.

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About the Author

Victoria K. Taysaeva
Postgraduate Student, Department of Asset Management Moscow State Institute of International Relations (MGIMO University) (Moscow, Russia); Referent, Ministry of Economic Development of the Russian Federation (Moscow, Russia).
Research interests: strategic management, corporate governance, digital transformation, knowledge management.
taisaevav@mail.ru

作者简介

Victoria K. Taysaeva
俄罗斯外交部莫斯科国立国际关系学院资产管理系博士研究生（莫斯科，俄罗斯）；俄罗斯联邦经济发展部专员（莫斯科，俄罗斯）。
研究领域：战略管理、公司治理、数字化转型、知识管理。
taisaevav@mail.ru

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Uncertainty and Risk Management in E&P: A Practical Approach

I.A. Volnov[1]
E.A. Mamedov[2]
[1] LUKOIL Overseas Iraq Exploration B.V. (Moscow, Russia)
[2] LUKOIL-Engineering LLC (Moscow, Russia)

Abstract

This article presents a practical approach to uncertainty and risk management in oil and gas production, drawing on LUKOIL's project experience. It describes, in detail, the step-by-step procedures used to identify, assess, and manage uncertainties and risks through Uncertainty Management Plans and Risk Management Plans (hereinafter referred to as UMPs/RMPs). In this context, UMPs/RMPs are not merely formal documents, but a working culture and discipline embedded in the day-to-day activities of project teams. Their application makes it possible to avoid catastrophic errors through explicit consideration of pessimistic scenarios, maximize asset value by selecting more realistic and flexible solutions, facilitate effective discussion of uncertainties and risks between technical specialists and project or asset managers, and shift the focus from searching for a single correct answer to managing a portfolio of opportunities. The use of UMPs/RMPs enables project teams to move from the illusion of full control to a more realistic and effective mode of operation. By adopting this systematic approach, oil and gas companies are able to make balanced decisions in one of the world's most uncertain industries.

Keywords: oil and gas project management, capital project, subsurface uncertaintyies, project decisions, decision-making process

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油气开采中不确定性与风险管理的实践经验

I.A. Volnov[1]
E.A. Mamedov[2]
[1] LUKOIL Overseas Iraq Exploration B.V.（莫斯科，俄罗斯）
[2] 卢克石油工程有限责任公司（莫斯科，俄罗斯）

摘要

本文介绍了卢克石油公司某油气开采项目中不确定性与风险管理的实践经验。文章详细阐述了根据经批准的内部规范性文件 —《地质与开发领域不确定性与风险管理规划方法》（PUN/PUR）— 在处理不确定性与风险时所采用的一系列程序。该方法不仅仅是一份文件，更是一种已融入项目团队日常工作的管理文化与工作纪律。其在项目中的应用能够：通过明确考虑悲观情景来避免灾难性错误；通过选择更为现实且更具灵活性的方案来实现资产价值最大化；促进技术专家与项目或资产管理者之间就不确定性与风险开展有效讨论；将关注重点从寻找唯一正确答案转向对机会组合的管理。PUN 方法论的应用使项目团队能够从"完全控制"的幻觉转向更加现实且有效的工作方式。借助 PUN 方法论及系统性方法，油气公司得以在全球最具不确定性的行业之一中作出审慎决策。

关键词： 油气项目管理，资本项目，地质不确定性，项目决策，决策过程

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Introduction

The process of planning uncertainty and risk management in geology and field development (hereinafter referred to as UMPs/RMPs) is a core component of decision-making within an integrated project management system and applies to all aspects of field development management [Voevodkin et al., 2019; Mamedov, Mardanov, 2025]. Project leaders and managers should have several decision-making tools at their disposal; otherwise, project management in many cases becomes overly dependent on chance.

Through regular UMP workshops and related work processes conducted for projects and assets, project teams develop a fundamental understanding of the degree of uncertainty and risk present at each phase of project implementation. The outcomes of uncertainty and risk management are then incorporated into the broader reservoir management process as documented expectations.

The uncertainty management planning process should be used proactively to identify and address uncertainties throughout the entire life cycle of a project or asset. Similarly, the risk management planning process should be applied to identify and mitigate risks through appropriate mitigation measures and contingency actions.

Well-developed uncertainty and risk management plans enable project teams to increase the value of information needed for a reliable assessment of reservoir productive potential. UMP and RMP documents should be integrated into the project or asset development work plan and regularly updated and reviewed. To ensure consistency, they should also be aligned with other field development management documents.

It is essential that the cross-functional team involved in UMP and RMP workshops and in preparing the relevant documents include drilling and completion specialists, facilities engineers, operations personnel, geologists, reservoir engineers, and commercial specialists. To remain relevant, UMP and RMP documents should be updated annually or whenever significant new information becomes available [Voevodkin et al., 2019; Mamedov, Mardanov, 2025].

1. Conceptual Framework for Uncertainty and Risk Management

Today, most oil and gas companies use structured, sequential procedures for uncertainty and risk analysis when evaluating exploration and production projects. These procedures involve identifying, classifying, and incorporating uncertainties and risks into project work plans (Figure 1).

Uncertainty and risk management makes it possible to:

- make informed decisions in complex situations characterized by multiple objectives and a high degree of uncertainty;
- address difficult trade-offs and stakeholder preferences in exploration and production decision-making;
- take all relevant factors into account in a comprehensive and systematic manner when making exploration and production decisions.

Within LUKOIL's project management system for major capital projects, five project phases are distinguished (Figure 1). To support uncertainty and risk management planning, UMP workshops are held during four phases of project implementation, from Phase 1, Definition, through Phase 3, Execution. This approach improves both decision-making quality and the overall effectiveness of project development. During Phases 1 and 2, UMP workshops focus on reservoir characteristics and on developing a plan to resolve or reduce uncertainties; during Phases 3 through 5, the focus shifts to preparing a risk management plan.

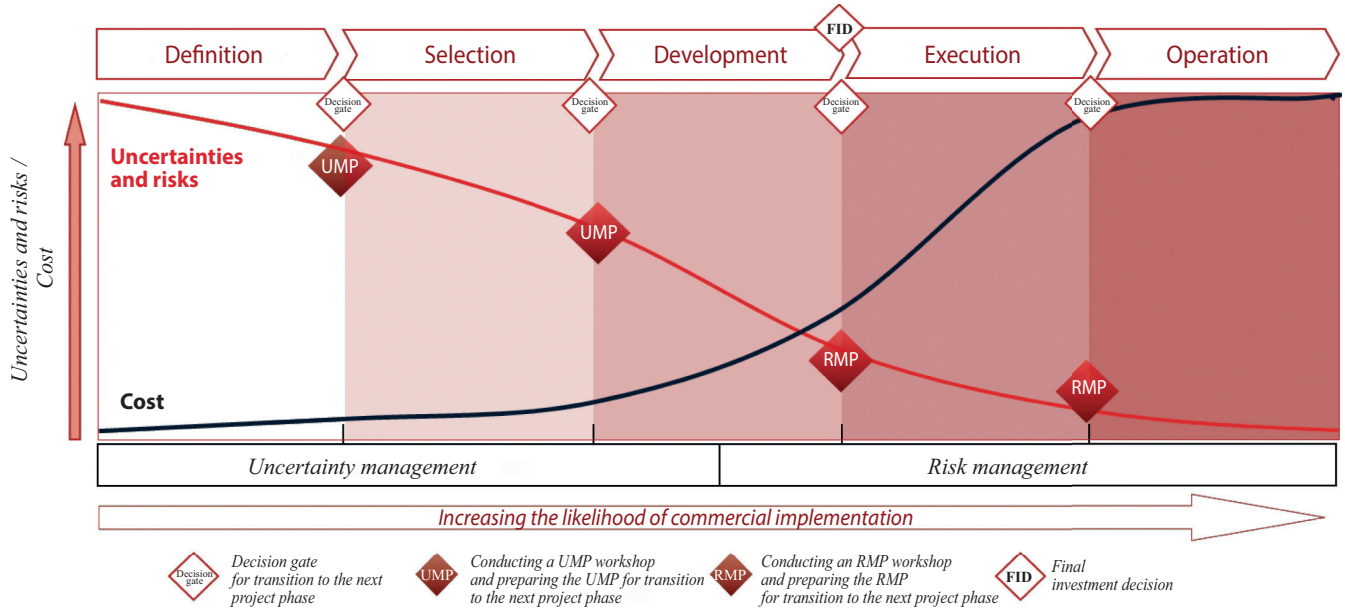
UMP workshops focused on uncertainties may be held at the end of Phase 1 or the beginning of Phase 2, in the middle of Phase 2, and at the end of Phase 2 or the beginning of Phase 3.

During Phases 1 through 3, uncertainties are identified, categorized, and incorporated into work plans, and the value of information is assessed in order to prepare a strategic uncertainty management plan, that is, the UMP document. The results of the UMP workshop are used to define the scope of work for subsequent phases and should be reflected in the project budget.

RMP workshops focused on risks are held in the middle of Phase 3, at the end of Phase 3 or the beginning of Phase 4, at the end of Phase 4 or the beginning of Phase 5, and at the end of Phase 5.

It is assumed that uncertainties decrease from phase to phase and should be reduced to a minimum, though not eliminated entirely, by Phase 4, Execution. This helps improve the quality of decisions aimed at reducing or, where possible, eliminating existing uncertainties. At the same time, it is important to understand that the main purpose of a UMP workshop is not to eliminate uncertainty altogether, but to support sound decision-making under conditions of uncertainty.

Although UMPs focus primarily on the subsurface aspects of a project, it is also important to assess uncertainties in other disciplines that may affect field development. Therefore, before conducting a UMP workshop, it is necessary to ensure that all required specialists and decision-makers are available to participate. These usually include reservoir engineers, geologists, petrophysicists,



Source: compiled by the authors.

Fig. 1. Uncertainty and Risk Management Process Across the Life Cycle of Major Capital Projects

drilling and completion specialists, capital construction and technical operations personnel, production specialists, health, safety, and environmental specialists, economists, risk specialists, and others.

UMP workshops provide project teams with clear procedures for identifying, assessing, and developing plans to reduce or resolve key geological and field development uncertainties. The UMP document produced as a result of the workshop is linked to and aligned with research and pilot fieldwork plans, technical plans, appraisal and exploration programs, field development and redevelopment projects, technical and authorial supervision activities, and project investment passports.

2. Preparing for a UMP Workshop

As noted above, before conducting a UMP workshop, it is important to ensure that all required specialists are available to participate. It is also necessary to agree in advance on which disciplines and participants should be involved in the workshop and whether project partners should be invited.

The sources of uncertainty in a project or asset include information related to geology, field development, drilling and well completion, facilities, and other areas (Figure 2).

Before the workshop, the venue should be selected, the meeting room reserved, and all audio and video requirements confirmed. It should also be verified whether electronic spreadsheets can be projected on a large screen with all columns visible at once, and whether the room is adequately equipped with desks, chairs, extension cords, network connections, and other practical necessities in accordance with a pre-prepared checklist. These arrangements are important for ensuring an efficient workflow for all workshop participants.

Before organizing the next UMP workshop, the following points should be clarified:

- whether a previous UMP exists for the project or asset under consideration, and when it was last updated;
- whether implementation of the actions defined in the previous uncertainty management plan has been reviewed;
- whether the project or asset work plan is aligned with the previous UMP document;
- whether the results of the UMP workshop will affect activities planned for the project or asset during the year;
- whether the objectives and expected outcomes of the upcoming UMP workshop have been agreed with stakeholders;
- whether agreement has been reached on which disciplines and specialists should participate in the workshop and whether project partners are to be invited.

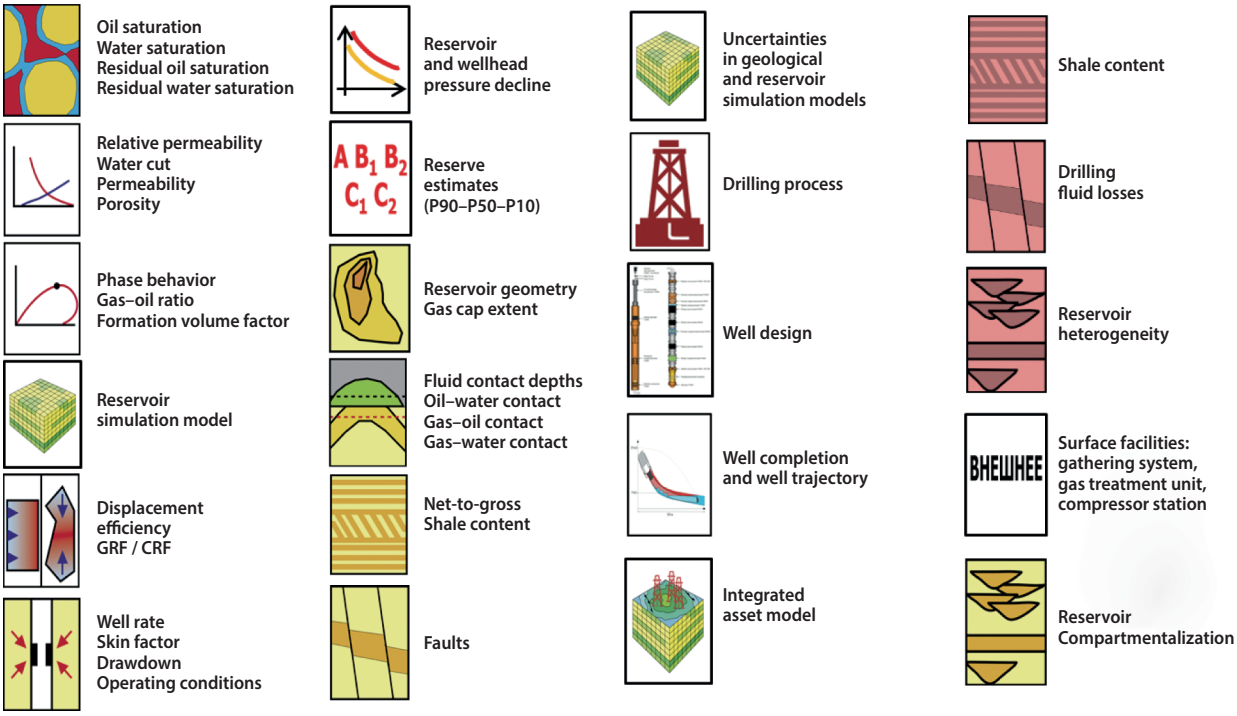
3. Conducting UMP Workshops

UMP workshops are conducted using structured facilitation techniques similar to those applied in uncertainty management sessions in geology and field development,

as well as idea-generation and discussion methods tailored to the specific purpose and objectives of the workshop. Workshop activities are supported by working spreadsheets. The workshop is carried out by a working group composed of specialists in geology and reservoir engineering, drilling and well completion, facilities design and operations, production, health, safety, and environment, economics, and other relevant disciplines. During the workshop, the group performs the following main tasks:

1) identifies, categorizes, and prioritizes uncertainties in geology, field development, drilling and well completion, surface facilities, and related areas using VUDOR categories;
2) describes uncertainty ranges, including measures, units, sources of information, and degree of uncertainty;
3) assesses the impact of each uncertainty on key project decisions using the Low, Middle, and High ranking scale and constructs a 3×3 matrix showing degree of uncertainty versus degree of impact on technical and economic indicators;
4) identifies the key decisions in the project decision hierarchy that should be included in the uncertainty management plan;
5) identifies key uncertainties and assesses their impact on key decisions, followed by construction of a 3×3 matrix of degree of uncertainty versus degree of impact on key project decisions;
6) assesses the degree to which key uncertainties can be resolved and develops possible response options, followed by construction of a 3×3 matrix of degree of resolvability versus degree of impact on key project decisions:
7) prepares a detailed strategic uncertainty management plan;
8) prepares a high-level plan for uncertainty reduction.

At the beginning of the UMP workshop, presentations are delivered in sequence by the project or asset leader or manager on the current status of the project or asset, including its objectives, scope, development concepts, and project boundaries. Geology specialists present information on the range of reservoir properties, including available 3D digital models and structural maps of productive formations, 3D seismic data, core and fluid sampling results, and related information. Reservoir engineers present the project decisions already adopted or the results of pilot development if field operations are already underway. Drilling and completion specialists describe key uncertainties and risks associated with well construction. Production specialists report on uncertainties and risks related to surface facilities, including the gathering, treatment, and transportation systems for hydrocarbons. Economists, risk specialists, and HSE specialists may also make presentations if their participation has been agreed in advance.



Source: compiled by the authors.

Fig. 2. Root Causes of Uncertainty

The results of the joint discussion of specialist presentations are entered into the VUDOR Register under the following categories:

- static uncertainties: uncertainties associated with objective natural properties, such as the exact volume of oil reserves in the reservoir or the physical properties of the rock. These factors must be measured, assessed, and incorporated into models, but they cannot be altered;
- dynamic uncertainties: uncertainties affecting recoverable reserves. Their relative importance depends on the reservoir development system. They may also be related to equipment performance, for example the causes of pump failure or measurement errors. These uncertainties can and should be reduced through the use of more reliable equipment, regular maintenance, and system redundancy;
- well-related uncertainties: a distinct category directly associated with drilling and well operation, such as wellbore instability or drilling complications. This highly specialized category helps engineers focus on specific risks;

Table
VUDOR Register

Category	Code	Term	Description
Issue Type	V	Value Driver	A factor that indicates the project's efficiency or value relative to other projects
	U	Uncertainty	A factor that matters, but whose value is uncertain and should therefore be described as a range of possible values.
	D	Decision	A choice that must be made.
	O	Other	Issues that do not fall within any of the other issue types
	R	Risk	A consequence of geological and field development uncertainties that may jeopardize the achievement of project objectives. Risk may be either technical or commercial
Decision Type	G	Given	Decisions that have already been made
	F	Focus	The most important decisions at the current project phase.
	T	Tactical	Decisions that may be important but are not required at the current phase of project execution
Uncertainty Category	S	Static	Uncertainties affecting hydrocarbons initially in place
	D	Dynamic	Uncertainties affecting recoverable reserves. Their relative importance depends on the reservoir development system.
	W	Well-related	Uncertainties affecting drilling, well completion, well productivity, and well integrity
	O	Operational	Uncertainties affecting facility performance and other factors, including product storage, offloading, and transportation
	P	Political	Uncertainties associated with changes in legislation, government regulation, and public response to the company's actions. They may arise from political instability, shifts in public governance, or sharp swings in public opinion
	C	Commercial	Uncertainties associated with market demand for the produced product and with price changes. They determine whether the project will be able to achieve its target revenue and profit indicators under changing market conditions.
Controllability	U	Uncontrollable	Uncertainties whose outcomes cannot be controlled. For example, the range of uncertainty associated with average effective porosity can be narrowed, but its actual value cannot be changed
	C	Controllable	Uncertainties that can be influenced through direct action. For example, the use of modern well completion methods may improve the resulting skin factor, although some uncertainty in execution still remains. In practice, some controllable uncertainties are effectively decisions.
Simple/Complex	S	Simple	Uncertainties driven by a single factor, such as horizontal permeability
	C	Complex	Uncertainties that are influenced by several simpler uncertainties; for example, oil reserves depend on porosity, area, reservoir thickness, water saturation, and other parameters
Risk Type	SSI	Subsurface Integrity	Defined for process safety purposes, for example equipment depressurization or loss of containment
	NORM	Conventional Risk	Risk not related to production process safety

Source: compiled by the authors.

- operational uncertainties: uncertainties arising from the company's internal processes, such as logistics disruptions, human factors, or planning errors. These are managed through business process optimization, personnel training, and the development of standards;
- market and commercial uncertainties: fluctuations in prices, demand, exchange rates, and competitor actions. These are typically managed through hedging, diversification, flexible pricing, and market analysis;
- political and country-level uncertainties: changes in legislation, sanctions, political upheaval, and tax policy. These are managed through political analysis, lobbying, geographic diversification of assets, and political risk insurance.

Classifying uncertainties by category gives the working group a clear understanding of how responsibilities are allocated. For example, technical uncertainties and risks are addressed by engineers, commercial uncertainties by marketing and finance specialists, and political uncertainties by legal and strategy teams.

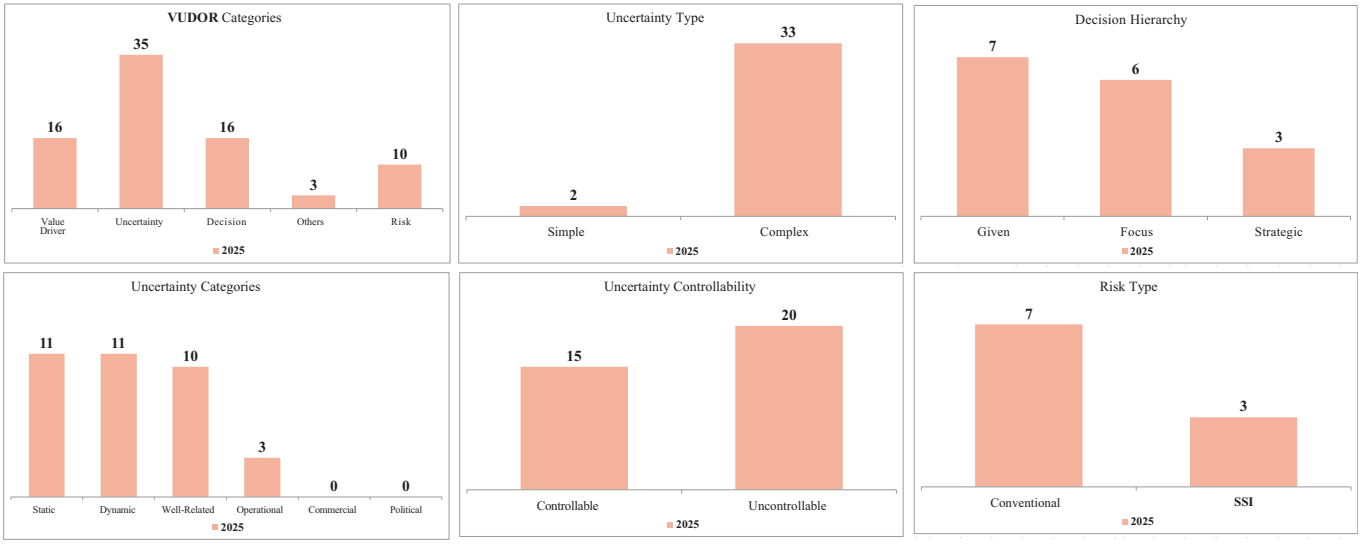
Classifying uncertainties by degree of complexity helps the team choose an appropriate analytical and decision-making approach and avoid strategic mistakes:

- simple uncertainties (where underlying patterns are clear): cause-and-effect relationships are evident, and past experience provides a reliable basis for anticipating future outcomes; for example, the known probability of failure of a particular type of valve. Such uncertainties can be addressed through statistical analysis, standard procedures, and established best practices;
- complex uncertainties (in a highly dynamic environment): cause-and-effect relationships are unclear, the system is constantly changing, and past experience is not always a reliable guide; for example, the market response to the launch of a fundamentally new product. Recognizing that the team is dealing with complex uncertainty calls for a different set of tools, such as experimentation, adaptive strategies, scenario planning, and pilot projects. The objective is not to predict every outcome in advance, but to build a system capable of responding quickly to change.

Classifying uncertainties by degree of controllability helps the team allocate time, money, and effort more effectively:

- controllable uncertainties: uncertainties that can be influenced through direct action, such as product quality, employee competence, or supply chain reliability. These should receive the greatest share of effort and resources, including the development of specific action plans to reduce or manage them;
- uncontrollable uncertainties: factors that cannot be directly influenced, such as global oil prices, weather conditions, a global economic crisis, or government decisions. The key task in such cases is not to try to change them, which is futile, but to adapt to them. This can be done through ongoing monitoring, contingency planning, the creation of financial buffers, and diversification to reduce dependence on any single uncontrollable factor.

The purpose of this classification is to describe all identified uncertainties as precisely as possible. For example, during a UMP workshop for one of LUKOIL's



Source: compiled by the authors.

Fig. 3. VUDOR Histogram

projects, the working group identified 35 uncertainties, of which 11 fell into the static category, 11 into the dynamic category, 10 into the well-related category, and 3 into the operational category. At the same time, 33 out of 35 uncertainties were recognized as complex, and 20 out of 35 as uncontrollable (Figure 3).

Project value drivers may include the following:

– the uniqueness of the field in terms of hydrocarbon reserves;
– high crude quality and favorable oil prices;
– large remaining oil reserves;
– low production costs;
– high production volumes;
– ongoing efforts to improve operating efficiency;
– deployment of advanced technologies, particularly in future expansion phases;
– experience in drilling deep wells;
– a high level of automation and control;
– full control over the value chain, with the operating company owning and managing the entire infrastructure;
– access to export routes;
– a diversified buyer base;
– high profitability;
– the project's significance for the country or republic in which it is located;
– reputational value for partners;
– concession expiry in 2030.

An understanding of a project's value drivers supports managerial decision-making. These drivers help managers prepare more accurate budgets and forecasts and make decisions more quickly and effectively. They also help shape business development strategy and make the company more flexible and better able to adapt to changing conditions.

Once the VUDOR Register has been completed, the working group jointly develops the project decision hierarchy. This hierarchy is a tool for structuring and prioritizing project decisions. It helps the team focus on the most important decisions while taking previously adopted decisions and assumptions into account (Figure 4). The hierarchy is developed collectively by the full working group, including representatives of both the project team and the asset.

The jointly developed and agreed decision hierarchy divides all project decisions into three categories:

1. Given decisions are decisions that have already been made and are not subject to change. Examples include:

– field development plan parameters;
– the inverted waterflooding system;
– the production rate through 20XX;
– water supply from Formation A;
– the water-cut profile;
– the pad startup sequence;
– drilling scheduled for 2028–2034;
– the artificial lift strategy for the well stock.

2. Strategic (focus or key) decisions are the most important decisions to be made at the current project phase. These may include:

– water injection and water treatment volumes;
– the effectiveness of acidizing, water shutoff operations, and remedial cementing;
– sustaining planned production levels;
– pilot EOR projects at the evaluation stage;
– infill drilling in Phase 1;

3. Tactical decisions may also be important, but they can only be made at subsequent project phases or milestones. These may include:

– infill drilling in Phase 2;
– extension of the production plateau;
– pilot EOR projects at the implementation stage.

Source: compiled by the authors.

Fig. 4. Hierarchy of Project and Asset Decisions

Based on the results of the active discussion and brainstorming, the key project decisions are identified.

Classifying all issues and topics raised during the workshop according to the VUDOR categories helps the project team move from a fragmented response to individual project problems toward a more systematic management approach. This provides several important benefits:

- prioritization: a clear understanding of what needs to be addressed first;
- more efficient resource allocation: time and money are directed toward controllable uncertainties and risks, as well as adaptation to uncontrollable ones, rather than being wasted on ad hoc responses to isolated problems;
- better decision-making with less stress: when uncertainty is structured, it is less likely to trigger re-

active or emotionally driven responses. Decisions are then based on analysis rather than intuition or fear;

- improved communication: a shared classification framework helps specialists from different disciplines, including geologists, engineers, and economists, communicate more effectively and develop a common understanding.

During the workshop, the working group, that is, the project team, jointly assesses the impact of uncertainties on the project's technical and economic indicators, which may include oil reserves, approved daily oil production rate, plateau duration, oil production per well, projected water-cut profile, and project NPV. The impact of each uncertainty on project decisions is ranked as Low (L, green, weight 1), Middle (M, yellow, weight 2), or High (H, red, weight 3). The same scale is used to assess the impact of uncertainties on focus decisions. If an uncertainty has no effect on project or focus decisions, it is assigned the rating NA (Not Applicable).

Figure 5 shows the working table used for weighted ranking of the impact of uncertainties on project decisions, which forms the core of the UMP document. This table is created in specialized software and includes the following mandatory columns:

1) Unique uncertainty identification number (ID):
   - used to track the category and type of uncertainty (static, dynamic, commercial, political, etc.);
   - used to describe the uncertainty in precise terms, for example, uncertainty in net effective oil-saturated thickness (NEST) in the southern part of the field;

2) Assessment and ranking of uncertainties as Low, Middle, or High:
   - quality of information: the degree of confidence in the available estimates (High indicates good-quality data, whereas Low indicates limited data);
   - impact on the project: a quantitative assessment of how changes in a given parameter affect key indicators such as NPV, production, and CAPEX, using a Low/Middle/High scale;
   - priority: determined using a 3×3 matrix based on degree of uncertainty and degree of impact. The highest priority is assigned to uncertainties with a Middle or High degree of uncertainty and a Middle or High degree of impact on project decisions.

ID #	Copy from VUDOR Неопределенности	Degree of uncertainty (H,M,L)	Weighted indicators	Degree of impact (H,M,L,0)	НГЗ	Поддержание полки добычи после 2030 г.	Утвержденный КИН	Накопленная добыча нефти до 2030 г.	CAPEX в период Концессии	Удельная себестоимость добычи нефти	NPV (LF)	Продление периода "плато" добычи на высоком уровне
17	Неоднозначный характер нефтенасыщения по площади и разрезу(объект x)	M	12,02	M	L	M	M	H	NA	NA	L	H
18	Неоднозначный характер нефтенасыщения по площади и разрезу(объект Y)	H	14,03	H	H	NA	H	H	NA	NA	M	H
19	Изменение проницаемости в процессе эксплуатации (причины, законы)	M	11,03	M	NA	M	M	M	NA	NA	M	H
20	Геомеханическая модель	H	12,02	M	NA	M	M	M	M	NA	M	M
21	Изменение продуктивности скважины во времени (PI)	M	15,02	H	NA	H	H	H	NA	L	M	H
22	Содержание CO2, H2S в продукции на объекте Y	L	7,04	M	NA	NA	NA	NA	M	M	M	L
23	Распределение давления по зонам (платформа, борт, склон)	H	8,03	M	NA	M	M	M	NA	NA	L	L
24	Неравномерная выработка запасов нефти по площади и разрезу	H	13,01	M	NA	L	L	L	M	H	H	M
25	Выбытие скважин (в том числе из-за обводнения)	H	14,01	M	NA	H	H	H	L	L	L	M
26	Межремонтный период скважин	L	8,01	L	NA	L	L	L	L	L	L	M
27	Выводы скважины на режим (длительность)	M	7,03	L	NA	M	L	L	NA	L	NA	M
28	Kv/Kh	M	10,01	M	NA	M	M	M	L	L	L	L
29	Зависимость ОФП, концевые точки)	H	7,04	M	NA	M	M	M	NA	NA	NA	L
30	Межколонное давление (быстрый набор давления, около 70 скважин)	L	10,01	M	NA	M	M	M	L	L	L	L
31	Изменение свойств пластовых флюидов резервуара	L	8,01	L	NA	L	M	L	L	L	L	L
32	Изменение обводненности продукции скважины	H	15,01	M	NA	M	M	L	H	H	M	M
33	Распространение зон трещиноватости	H	7,04	M	NA	L	H	L	NA	NA	NA	M
34	Малый объем ПГИ и керна на Объекте Y	H	7,05	H	H	NA	H	L	NA	NA	NA	NA
35	Высокая вариабельность по проницаемости на Объекте Y	H	3,06	M	NA	NA	M	NA	NA	NA	NA	L
36	Неясное распределение доломитизированных зон на Объекте Y	M	5,05	M	M	NA	M	NA	NA	NA	NA	L
37	Продуктивность Объекта Y	M	5,05	M	M	NA	M	NA	NA	NA	NA	L
38	Насыщенности по разрезу (зоны подвижной воды в объекте Y), водонасыщенные линзы	H	3,06	M	NA	NA	M	NA	NA	NA	NA	L
39	Причины высокой обводненности в скв. 2 и 3 (объекты X и Y)	H	1,07	NA	NA	NA	NA	NA	NA	NA	NA	L
40	Разница в пластовых давлениях объектов X и Y	H	3,06	M	NA	NA	M	NA	NA	NA	NA	L
41	Зависимость проницаемости матрицы от кавернозных/трещинных интервалов (объект Y)	M	12,02	H	M	M	H	M	NA	NA	M	L
42	Фациальная изменчивость склоновой зоны: Прогноз сети естественных трещин и их связь с матрицей	M	8,02	L	M	L	M	L	NA	NA	L	L
43	Качество матрицы (при стимуляции ПЗ скважин)	H	6,03	L	NA	L	M	L	NA	NA	L	L
44	Различие в ВНК объектов X и Y	H	10,02	M	H	M	M	L	NA	NA	L	L
45	Неподтверждение ВНК, что критично для бурения горизонтальных скважин	H	14,02	M	M	H	H	L	NA	NA	M	H
46	Завершение программы бурения	H	10,04	M	NA	H	H	L	NA	NA	NA	H
47	Результаты освоения скв. №1 влияющее на продолжение буровых работ и разработку объекта Y	H	6,05	M	NA	M	M	NA	NA	NA	NA	M
48	Эффективность ППД закачкой газа (прорыв газа в доб.скв.)	H	10,01	M	NA	M	M	M	L	L	L	L
49	Эффективность водоотдления	H	6,04	M	NA	NA	NA	NA	M	L	M	L
50	Водопроявление > 10%	H	5,03	L	NA	L	L	NA	NA	L	L	L
51	Эффективность ППД	H	7,02	L	NA	L	L	NA	L	L	L	M

Source: compiled by the authors.

Fig. 5. Assessment of the Degree of Uncertainty and its Impact on Technical Solutions and the High-Level Project Decisions

After the working group has jointly assessed the degree of uncertainty and the degree of impact on project decisions through brainstorming (Figure 5), 3×3 matrices are used to identify key uncertainties. Mapping uncertainties on a 3×3 matrix enables the project team to focus on those with a medium or high impact on project decisions. As an illustrative example, several 3×3 matrices are presented in Figures 6–8.

Using these 3×3 matrices, the working group identified 29 key uncertainties within the project or asset that had a medium or high impact on project decisions. At the final stage of the UMP workshop, the group discusses the further work required to address these key uncertainties. It then prepares a table entitled Strategic Uncertainty Management Plan, which constitutes the UMP document. This document sets out a detailed strategy for addressing key uncertainties. In doing so, project team members jointly determine which uncertainty-reduction measures are likely to provide the greatest benefit and select the preferred course of action. The UMP document includes the title and description of each activity, its cost, labor input, start and finish dates, and the responsible persons. The detailed uncertainty management plan is supplemented by a high-level work plan defining responsibilities, timelines, and the set of activities required to reduce uncertainty.

The Strategic Uncertainty Management Plan, or UMP document, is a key component of the decision-making system used in oil and gas project management. It is not merely a table, but a structured database that serves as a living management tool throughout the project life cycle. In essence, the UMP document is a centralized road map for managing project uncertainties. If uncertainties are viewed as hazards along a ship's route, the UMP document is not just a list of threats, but a navigational chart showing how

Степень неопределенности	Степень влияния на все проектные решения (средневзвешенное)		
	Low	Medium	High
High	Качество матрицы (при стимуляции ПЗ скважин)	Геомеханическая модель	Неоднозначный характер нефтенасыщения по площади и разрезу (объект X)
	Водопроявление > 10%	Распределение давления по зонам (платформа, борт, склон)	Малый объем ПГИ и керна на Объекте X
	Эффективность ППД	Неравномерная выработка запасов нефти по площади и разрезу	
		Выбытие скважин (в том числе из-за обводнения)	
		Зависимость ОФП, концевые точки)	
		Изменение обводненности продукции скважины	
		Распространение зон трещиноватости	
		Высокая вариабельность по проницаемости на Объекте X	
		Насыщенности по разрезу (зоны подвижной воды в объекте X), водонасыщенные линзы	
		Разница в пластовых давлениях объектов X и Y	
		Различие в ВНК объектов X и Y	
		Неподтверждение ВНК, что критично для бурения горизонтальных скважин	
		Завершение программы бурения	
		Результаты освоения скв. №1 влияющее на продолжение буровых работ и разработку объекта Y	
		Эффективность ППД закачкой газа (прорыв газа в доб.скв.)	
		Эффективность водоотдления	
Mid	Выводы скважины на режим (длительность)	Неоднозначный характер нефтенасыщения по площади и разрезу (объект X)	Изменение продуктивности скважины во времени (PI)
	Фациальная изменчивость склоновой зоны: Прогноз сети естественных трещин и их связь с матрицей	Изменение проницаемости в процессе эксплуатации (причины, законы)	Зависимость проницаемости матрицы от кавернозных/трещинных интервалов (объект Y)
		Kv/Kh	
		Неясное распределение доломитизированных зон на Объекте Y	
		Продуктивность Объекта Y	
Low	Межремонтный период скважин	Содержание CO2, H2S в продукции	
	Изменение свойств пластовых флюидов резервуара	Межколонное давление (быстрый набор давления в 30 скважинах)	

Source: compiled by the authors.

Fig. 6. 3×3 Matrix of Average Impact on All Project Decisions

Степень неопределенности	Влияние на поддержание полки добычи после 2030 г.		
	Low	Medium	High
High	Неравномерная выработка запасов нефти по площади и разрезу	Геомеханическая модель	Выбытие скважин (в том числе из-за обводнения)
	Распространение зон трещиноватости	Распределение давления по зонам (платформа, борт, склон)	Неподтверждение ВНК, что критично для бурения горизонтальных скважин
	Качество матрицы (при стимуляции ПЗ скважин)	Зависимость ОФП, концевые точки)	Завершение программы бурения
	Водопроявление > 10%	Изменение обводненности продукции скважины	
	Эффективность ППД	Различие в ВНК объектов X и Y	
		Результаты освоения скв.№1 влияющее на продолжение буровых работ и разработку объекта Y	
		Эффективность ППД закачкой газа (прорыв газа в доб.скв.)	
Mid	Фациальная изменчивость склоновой зоны: Прогноз сети естественных трещин и их связь с матрицей	Неоднозначный характер нефтенасыщения по площади и разрезу(объект X)	Изменение продуктивности скважины во времени (PI)
		Изменение проницаемости в процессе эксплуатации (причины, законы)	
		Выводы скважины на режим (длительность)	
		Kv/Kh	
		Зависимость проницаемости матрицы от кавернозных/трещинных интервалов (объект Y)	
Low	Межремонтный период скважин	Межколонное давление (быстрый набор давления, в 30 скважинах)	
	Изменение свойств пластовых флюидов резервуара		

Source: compiled by the authors.

Fig. 7. 3×3 Matrix of Impact on the Decision "Plateau Duration"

to avoid them, strengthen the project's resilience, and respond effectively when they materialize.

To improve the uncertainty management process, the strategic uncertainty management plan may be consolidated. As a result, the original set of 29 uncertainties can be grouped into 8 aggregated uncertainties (Figure 9).

Thus, the strategic uncertainty management plan enables project teams and asset management to carry out the following effectively:

- prioritization of investment in information gathering. The UMP document helps answer the question: which geological studies, pilot tests, or market assessments should be funded first? Resources are directed not simply to areas of

Степень неопределенности	Влияния на утвержденный КИН: Low	Medium	High
High	Неравномерная выработка запасов нефти по площади и разрезу	Геомеханическая модель	Неоднозначный характер нефтенасыщения по площади и разрезу(объект Y)
	Водопроявление > 10%	Распределение давления по зонам (платформа, борт, склон)	Выбытие скважин (в том числе из-за обводнения)
	Эффективность ППД	Зависимость ОФП, концевые точки)	Распространение зон трещиноватости
		Изменение обводненности продукции скважины	Малый объем ПГИ и керна на Объекте Y
		Высокая вариабельность по проницаемости на Объекте Y	Неподтверждение ВНК, что критично для бурения горизонтальных скважин
		Насыщенности по разрезу (зоны подвижной воды в объекте 2), водонасыщенные линзы	Завершение программы бурения
		Разница в пластовых давлениях объектов X и Y	
		Качество матрицы (при стимуляции ПЗ скважин)	
		Различие в ВНК объектов X и Y	
		Результаты освоения скв. №1 влияющее на продолжение буровых работ и разработку объекта Y	
		Эффективность ППД закачкой газа (прорыв газа в доб.скв.)	
Mid	Выводы скважины на режим (длительность)	Неоднозначный характер нефтенасыщения по площади и разрезу (объект X)	Изменение продуктивности скважины во времени (PI)
		Изменение проницаемости в процессе эксплуатации (причины, законы)	Зависимость проницаемости матрицы от кавернозных/трещинных интервалов (объект Y)
		Kv/Kh	
		Неясное распределение доломитизированных зон на Объекте Y	
		Продуктивность Объекта Y	
		Фациальная изменчивость склоновой зоны: Прогноз сети естественных трещин и их связь с матрицей	
Low	Межремонтный период скважин	Межколонное давление (быстрый набор давления, около 30 скважин)	
		Изменение свойств пластовых флюидов резервуара	

Source: compiled by the authors.

Fig. 8. 3×3 Matrix of Impact on the Decision "Projected Water-Cut Profile"

# ID	Название неопределенности	Степень неопредел енности	Степень влияния на решени	Название работы	Заказчик	Сроки начала работы	Срок окончания работы	Ответственное лицо	Влияние на проектные решения
32	Изменение обводненности продукции скважин	H	M	Анализ динамики обводнения действующего фонда скважин. Определение источников воды	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / CAPEX в период Концессии / Удельная себестоимость добычи нефти / NPV (LF) / Продление периода "плато" добычи на высоком уровне
21	Изменение продуктивности скважины во времени (PI)	M	H	Анализ фактических данных добычи по скважинам, анализ данных ГДИ.	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / Продление периода "плато" добычи на высоком уровне
25	Выбытие скважин (в том числе из-за обводнения)	H	H	Анализ динамики обводнения действующего фонда скважин. Определение источников воды	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
18	Неоднозначный характер нефтенасыщения по площади и разрезу(объект Y)	H	H	Анализ результатов бурения и опробования объекта Y в скв. №1	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / NPV (LF) / Продление периода "плато" добычи на высоком уровне
41	Зависимость проницаемости матрицы от кавернозных/трещинных интервалов (объект Y)	M	H	Анализ результатов бурения и опробования объекта Y в скв. №1	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / NPV (LF)
45	Неподтверждение ВНК, что критично для бурения горизонтальных скважин	H	H	Определение источников воды, изучение данных ГИС. Проведение новых ГИС в последующих скважинах	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Поддержание полки добычи после 2029 г. / Утвержденный КИН / NPV (LF) / Продление периода "плато" добычи на высоком уровне
20	Геомеханическая модель	H	M	Создание геомеханической модели	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / CAPEX в период Концессии / NPV (LF) / Продление периода "плато" добычи на высоком уровне
17	Неоднозначный характер нефтенасыщения по площади и разрезу(1-ый объект)	M	H	Уточнение геологической модели объекта X.	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / NPV (LF) / Продление периода "плато" добычи на высоком уровне
44	Различие в ВНК объектов X, Y	H	M	Уточнение положения ВНК для объектов и различных зон пласта-коллектора	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / NPV (LF) / Продление периода "плато" добычи на высоком уровне
28	Kv/Kh	M	M	SCAL-анализ	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
30	Межколонное давление (быстрый набор давления в 30 скважинах)	L	M	Анализ работающего фонда скважин с МКД. Анализ причин проявления МКД (тех.состояния колонны, проведения шумометрии)	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
48	Эффективность ППД закачкой газа (прорыв газа в доб.скв.)	H	M	Выполнение расчетов на ГДМ с последующей выработкой рекомендаций по изоляция зон газопроявления.	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
19	Изменение проницаемости в процессе эксплуатации (причины, законы)	M	M	SCAL-анализ	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / Продление периода "плато" добычи на высоком уровне
34	Малый объем ПГИ и керна на Объекте Y	H	H	Переобработка старых материалов, выполнение нового комплекса ПГИ, SCAL-анализ	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
46	Завершение программы бурения	H	H	Разработка стратегии развития месторождения в текущих планах Оператора после 2030 г.	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г. / CAPEX в период Концессии / Удельная себестоимость добычи нефти / NPV (LF) / Продление периода "плато" добычи на высоком уровне
23	Распределение давления по зонам (платформа, борт, склон)	H	M	Разработка программы ГДИ, построение карт изобар, актуализация ГДМ	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Продление периода "плато" добычи на высоком уровне
42	Фациальная изменчивость склоновой зоны: Прогноз сети естественных трещин и их связь с матрицей	M	M	Уточнение геологической модели объекта Y. для определения распространения зон трещиноватости в межскважинном пространстве».	ПАО	2025	2028	ЗГД по геологии и и разработке	НГЗ / Утвержденный КИН
31	Изменение свойств пластовых флюидов резервуара	L	M	Регулярный отбор проб и PVT-анализ	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
22	Содержание CO2, H2S в продукции на объекте Y	L	M	Анализ результатов опробования объекта Y в скв. №1 и с возможным повторным отбором PVT проб.	ПАО	2025	2028	ЗГД по геологии и и разработке	CAPEX в период Концессии / Удельная себестоимость добычи нефти / NPV (LF)
29	Зависимость ОФП, концевые точки)	H	M	SCAL-анализ	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Накопленная добыча нефти до 2033 г.
49	Эффективность водоотделения	H	M	Проработка вопроса запуска простаивающего обводненного фонда скважин	ПАО	2025	2028	ЗГД по геологии и и разработке	CAPEX в период Концессии / Удельная себестоимость добычи нефти / NPV (LF)
33	Распространение зон трещиноватости	H	H	Уточнение геологической модели объекта Y. для определения распространения зон трещиноватости в межскважинном пространстве».	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН / Продление периода "плато" добычи на высоком уровне
43	Качество матрицы (при стимуляции ПЗ скважин)	H	M	Подбор технологии и методов ПНП	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
36	Неясное распределение доломитизированных зон на Объекте Y	M	M	Построение детальной структурно-тектонической модели, структурно-парагенетический анализ, атрибутный анализ сейсмических данных, сопоставление сейсмического отклика с результатами скважинных исследований	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
37	Продуктивность Объекта Y	M	M	Анализ результатов бурения и опробования объекта Y в скв. №1	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
47	Результаты освоения скв. №1 влияющее на продолжение буровых работ и разработку объекта Y	H	M	Анализ результатов бурения и опробования объекта Y в скв. №1	ПАО	2025	2028	ЗГД по геологии и и разработке	Поддержание полки добычи после 2029 г. / Утвержденный КИН / Продление периода "плато" добычи на высоком уровне
35	Высокая вариабельность по проницаемости на Объекте Y	H	M		ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
38	Насыщенности по разрезу (зоны подвижной воды в объекте Y), водонасыщенные линзы	H	M	Переобработка старых материалов, выполнение нового комплекса ПГИ	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН
40	Разница в пластовых давлениях объектов X и Y	H	M	Рассмотрение возможности раздельной добычи	ПАО	2025	2028	ЗГД по геологии и и разработке	Утвержденный КИН

Source: compiled by the authors.

Figure 9. Strategic (Detailed) Uncertainty Management Plan

limited clarity, but to those where uncertainty has a material impact on project value and can realistically be reduced;
- support for key decisions. Before any major investment decision, including the Final Investment Decision (FID), management reviews the strategic uncertainty management plan, that is, the UMP document. If it still contains high-priority uncertainties for which no action plan has been developed, the decision is postponed until those uncertainties have been addressed;
- development of a flexible and robust project plan. The UMP document helps make the project more resilient under different scenarios. The field development plan is selected not for a single average case, but in a way that delivers acceptable results under a pessimistic scenario while preserving upside under an optimistic one;
- transparent communication and accountability. The UMP document serves as a single source of truth for geologists, engineers, economists, and senior managers. It ensures that all participants understand which uncertainties and risks are most important, who is responsible for them, and what is being done to manage them. This helps avoid situations in which everyone was aware of a risk, yet no one was accountable for addressing it.

Conclusion

The Uncertainty Management Plan (UMP) is an effective practical tool that transforms uncertainty management from an abstract concept into concrete, measurable, and actionable steps. It serves as the project's decision-support center, where economic indicators and the selected strategy are brought together to enable sound decision-making.

Experience gained from UMP workshops on both Russian and international projects shows that, despite the rigor of uncertainty and risk analysis, actual outcomes for many projects differ substantially from what was anticipated at the time of project approval [Bickel, Bratvold, 2007; Ward, Whitaker, 2016]. This once again confirms that, in major oil and gas projects, it is not enough simply to reduce uncertainty. Project teams must be able to make sound decisions under conditions of uncertainty. At the same time, a sound decision is not necessarily an ideal one, but one that is sufficiently well founded, timely, and adaptive. Such a decision means taking the best possible next step based on the information currently available. Rather than searching for a single correct answer, project teams prepare for several possible scenarios. When one of these scenarios materializes, the company already has either a ready response plan or at least a clear understanding of its first steps. As a result, it is not paralyzed by uncertainty and can respond quickly.

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About the Authors

Ignatiy A. Volnov
Deputy General Director for Geology and Development, LUKOIL Overseas Iraq Exploration B.V. (Moscow, Russia).
Research interests: risk and uncertainty management, reserves and resources classification standards, the energy transition and transformation in the oil and gas industry, field development management, strategic asset development planning.
Ignatiy.Volnov@yandex.ru

Emil A. Mamedov
Cand. sci. (Eng.), Chief Specialist at LUKOIL-Engineering LLC (Moscow, Russia).
Research interests: risk and uncertainty management in major capital projects, methodologies for resource assessment and ranking under high uncertainty, including deepwater offshore assets, strategic field development planning and optimization of project decision hierarchies, mathematical modeling of the impact of risks on the technical and economic performance of projects.
Emil.Mamedov@lukoil.com

作者简介

Ignatiy A. Volnov
地质与开发副总经理，LUKOIL Overseas Iraq Exploration B.V.（莫斯科，俄罗斯）。
研究方向：风险与不确定性管理，储量与资源分类标准，能源转型与油气行业职业转型，油气田开发管理，资产开发战略规划。
Ignatiy.Volnov@yandex.ru

Emil A. Mamedov
技术科学副博士，首席专家，LUKOIL-Engineering LLC（莫斯科，俄罗斯）。
研究方向：大型资本项目中的不确定性与风险管理，高不确定性条件下资源评估与排序方法论（包括深水海上资产），油气田开发战略规划与项目决策层级优化，风险对项目技术经济指标影响的数学建模。
Emil.Mamedov@lukoil.com

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