PPP MODELS AND DIGITAL RISK MITIGATION IN THE RECOVERY OF UKRAINIAN PORT INFRASTRUCTURE

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Abstract

The 2022 invasion of Ukraine disrupted Eastern European logistics, shifting maritime traffic from blockaded Southern deep-water ports to the Danube River network ("Danube Cluster"). For post-war recovery, Ukraine must not only rebuild but modernize its maritime economy. Facing a multibillion-dollar financing gap due to defense spending, the state must rely on private capital. However, investors remain deterred by war-related and historical governance risks. This study investigates how technological innovation and economic theory can optimize Public-Private Partnerships (PPPs) for port reconstruction. The paper proposes a modified PPP model utilizing the AK growth theory, demonstrating that integrating technology with infrastructure capital creates a multiplier effect for sustained long-term growth. Findings suggest that traditional PPPs must evolve into tiered finance structures backed by international "first-loss" guarantees. Furthermore, integrating "Smart Port" technologies like Artificial Intelligence (AI) is essential. These technologies provide the radical operational transparency required to make high-risk investments feasible, enforce institutional integrity, and mitigate corruption risks.

Keywords: Public-Private Partnerships, Ukraine; Smart Ports, Post-War Recovery, Logistics Clusters, AK Growth Model

JEL Classification: H54, L32, O33, R42

1. Introduction

The 2022 invasion of Ukraine forced a critical shift in maritime logistics from Southern deep-water ports to the Danube River cluster, underscoring infrastructure as a matter of national sovereignty. As Ukraine plans for post-war recovery, the estimated billions required to reconstruct and modernize these ports cannot be met by its state budget. This paper addresses this financing gap by investigating how economic theory and digital innovation can transform Public-Private Partnerships (PPPs) to attract private capital. First, how can PPPs be structured to transform Ukrainian ports into drivers of regional economic recovery? Second, what role could technology play in this economic development to mitigate investment risk and enhance operational efficiency? Specifically, this study argues that integrating the AK Growth Model with "Smart Port" technologies can de-risk investments by ensuring operational transparency and sustaining long-term growth. To achieve this, the paper first reviews the literature on Ukrainian ports. Next, the methodology section

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outlines a qualitative synthesis of policy and technical data. The analysis then explores structural PPP reforms and the role of technology in mitigating corruption and financial risks. Finally, the discussion and conclusion offer policy recommendations for implementing a tech-enabled PPP framework to drive regional economic stabilization.

2. Literature Review

To understand the feasibility of a technology-driven PPP model for Ukraine, one must first analyze the existing academic and regulatory landscape. This covers the legal evolution of PPPs, the shifting geo-economic status of Ukrainian port infrastructure, and global technological benchmarks.

2.1 Public-Private Partnerships in Ukraine: Persistent Barriers

Early analyses of Ukraine's PPP framework highlighted structural weaknesses that continue to hamper port concessions. Soloviov (2016) examined the legal environment before the 2015–2016 reforms, noting excessive regulatory uncertainty, unpredictable price setting by the state, and the absence of independent arbitration.

Karpa et al. (2022) confirmed that many of these problems persisted into the early 2020s: weak risk allocation, lack of transparent tendering, and insufficient guarantees against non-commercial risks. The war has only vastly increased reconstruction needs while shrinking public resources.

Le Ber et al. (2025) cite Ukraine's Rapid Damage and Needs Assessment 4th Phase (RDNA4) showing US$36.7 billion in direct transport-sector damage and US$46.8 billion in losses as of end-2024.

Becker et al. (2025) offer the most comprehensive post-war policy synthesis to date. Although their review covers the entire economy, they explicitly identify transport infrastructure, notably ports, as a sector where well-designed PPPs with strong risk-sharing and credit-enhancement mechanisms could accelerate recovery.

2.2 Economic Models for Port Development

Several studies propose modeling approaches suitable for Ukrainian port PPPs under high uncertainty. Liashenko et al. (2021) develop a conceptual transport-logistics cluster framework for the Prydniprovsky economic region, arguing that integrating river and sea ports into regional innovative infrastructure can produce substantial GDP and employment multipliers. While their work predates the full-scale invasion, the cluster logic remains relevant for post-war recovery strategies built around PPP concessions.

Horoshkova et al. (2024) focus specifically on Danube ports during and after the war. They stress the need for adaptive development models that account for continuing security risks and shifting trade flows. Table no. 1 discussing the status of Ukrainian port clusters further elaborates on this. Similarly, Afanasieva and Pokora (2020) examine innovation policy for

Ukrainian seaports and propose strategic planning frameworks that incorporate PPPs.

Table no. 1: Comparative status of Ukrainian port clusters

Feature	**Greater Odesa Cluster (Pre-War Dominance)**	**Danube Cluster (War-Time Pivot)**
Primary Ports	Odesa, Chornomorsk, Pivdennyi	Reni, Izmail, Ust-Danube
Status	Blockaded / Damaged	Active "Lifeline" / Exponential Growth
Depth/Capacity	Deep-water (High Capacity)	Shallow draft (Limited Capacity); dredged to 6.5m
Challenges	Security risks; Naval blockade	"Technologically obsolete"; Congestion; Rail bottlenecks
Future Role	Primary export gateway (Restoration required)	Alternative route; Green logistics hub

Source: This table synthesizes the shift in logistics as described by Horoshkova et al. (2024).

2.3 The Role of Technology in De-Risking

A second theme in the literature is the transformative potential of digital technologies. HPC Hamburg Port Consulting (2024) provides evidence from global implementations showing that AI-driven predictive maintenance and digital twin platforms have delivered improvements in crane productivity and vessel turnaround times. The authors argue that such technologies are no longer optional add-ons but core enablers of certain port projects.

Waseem Al Rousan (2024) reinforces this message in the context of "smart ports," documenting how AI, automation, and real-time analytics optimize container handling and improve safety. This directly increases the revenue potential of a concession. Furthermore, Manget and Alsina (2025) highlight big data, IoT, and AI applications in modern maritime operations, showing that predictive analytics can provide "all actors in the logistics chain" with transparent, real-time performance data.

2.4 Synthesis

The sources, despite their differences, converge on these key points:

- Traditional Ukrainian PPP frameworks have suffered from regulatory opacity and poor risk allocation. [Karpa et al., (2022); Soloviov, (2016)]
- The war has made private capital indispensable yet more risk averse. [Becker et al., (2025); Le Ber et al., (2025)]
- Regional economic recovery can be accelerated by clustering ports with logistics and industrial zones, using models that capture multiplier effects. [Horoshkova et al., (2024); Liashenko et al., (2021)]
- Advanced technologies (AI, "digital twins", automation, and real-time data platforms) offer dual benefits: substantial operational efficiency gains and

reduced information asymmetry, both of which lower the risk premium demanded by investors. [HPC Hamburg Port Consulting GmbH, (2024); Al Rousan, (2024); Manget and Alsina, (2025)]

Thus, the literature strongly suggests that the next generation of Ukrainian port concessions must integrate three elements from the outset: (i) contractual structures that allocate risks transparently and include performance-linked payments, (ii) economic models (cluster-based, resilience-oriented) that demonstrate regional impact under uncertainty, and (iii) adoption of smart-port technologies that enhance both efficiency and investor confidence.

2.5 Remaining Gaps

Even within these sources, gaps persist:

- No study yet combines actual post-2022 Ukrainian port data with real-options or Monte-Carlo simulations tailored to these PPP structures.
- The precise magnitude of risk-premium reduction achievable through mandatory digital transparency in a wartime context remains unquantified for Ukraine.
- Empirical links between specific smart-port technologies and successful PPP bidding outcomes in comparable high-risk jurisdictions are still illustrative rather than Ukraine-specific.

3. Research Methodology

This research from the literature employs a qualitative methodology, utilizing a synthesis of legal analysis, economic case studies, and technical industry reports. The approach aligns with the method described by Becker et al. (2025), which focuses on aggregating policy proposals to determine optimal reconstruction strategies.

3.1 Data Collection

The study draws on primary legislative reviews [Soloviov, (2016)], recent empirical studies on Ukrainian logistics flows [Horoshkova et al., (2024)], and expert insights on maritime technology. [HPC Hamburg Port Consulting GmbH, (2024); Manget and Alsina, (2025)]

3.2 Analytical Framework

The analysis is structured around the two research questions. For the first research question, the paper employs a comparative legal and economic analysis, harmonizing Soloviov's concession frameworks with the cluster theories of Liashenko et al. For the second research question, the paper utilizes a techno-economic assessment, mapping the capabilities of AI applications (as defined by Al Rousan (2024)) directly to the risk factors identified by Karpa et al. (2022).

3.3 Scope

The study focuses on the Prydniprovsky Economic Region and the Danube Port Cluster as primary case studies for the proposed models.

4. Results (Analysis)

While the prevailing literature comprehensively identifies the critical structural and financing gaps facing Ukraine's reconstruction (specifically the need for infrastructure capital and the necessity of institutional anchors for EU accession), it does not explain the mechanism by which these inputs will generate sustained recovery. Existing studies treat reconstruction as a static accounting exercise of replacing lost assets, failing to sufficiently operationalize the dynamic economic growth mechanisms required to leapfrog a post-conflict stagnation trap. This theoretical gap justifies the introduction of an explicit economic growth lens as an interpretive framework. Consequently, this paper adopts the AK Growth Model (Y=AK) to demonstrate that reconstruction cannot rely solely on capital accumulation (K); rather, it must prioritize the technology multiplier (A), embedded through PPPs, to generate the non-diminishing returns essential for Ukraine's rapid economic modernization.

The results of the analysis are presented in two parts, corresponding to the research questions regarding the financial structure (PPP) and the technological enablers (AI).

4.1 Analysis of Research Question 1: Structuring the PPP for Recovery

To transform Ukrainian ports into drivers of regional recovery, the traditional concession model must evolve. Historically, PPPs in Ukraine have faced "legislative and regulatory issues" and "communication problems between partners." [Soloviov, (2016)] A post-war framework must address these by adopting a different financial model for PPPs. A "one-size-fits-all" PPP model is no longer viable. The deep-water ports, while offering high capacity, face war risks that deter private capital. To address this, the findings propose a PPP Model that segments risk into tiered capital structures.

4.1.1 PPP Model: Operationalizing the "First-Loss" Guarantee

The core of this model is the segmentation of risk. Building on the reconstruction principles outlined by Becker et al. (2025), who advocate for grant-based funding to avoid debt traps, a tiered capital structure should be:

- **Tier 1 (Public/Donor):** International Financial Institutions (IFIs) like the EIB or World Bank provide "first-loss" guarantees or political risk insurance. This covers risks such as residual war risk or regulatory changes. [Becker et al., (2025); Soloviov, (2016)]
- **Tier 2 (Private Concessionaire):** Global port operators fund the operational equipment and management expertise. Because the donor tranche absorbs the catastrophic risk, the private operator is insulated from "force majeure" events. [Becker et al., (2025); Soloviov, (2016)]
- **Tier 3 (State):** The Ukrainian government contributes the land and basic dredging, retaining ownership while granting long-term usage rights.

4.1.2 Legal Reforms: Harmonizing Soloviov's Framework

To make this model viable, Ukraine's legal framework requires evolution to harmonize with the European Union. This, as noted later, has been partially

accomplished through the 2025 Ukrainian PPP Law No. 4510-IX. Still, Soloviov (2016) noted that while Ukraine had established the concept of concessions, the mechanisms for risk allocation remained immature. Specific amendments should formally include:

- **"First-Loss" Guarantee Clause:** A new amendment must explicitly legalize state-backed guarantees underwritten by international donors. The 2025 Ukrainian PPP law only enables "Minimum Revenue Guarantees (MRG)" to be written into individual contracts. But the guarantees must be negotiated on a case-by-case basis. In cases where the losses are due to the war, the Export Credit Agency's war-risk program (Ukrainian Resolution No. 1541) provides compensation. This operationalizes Becker's call for "grant-based funding" and thus makes grants a legal insurance policy.
- **Governance Transparency:** Becker et al. (2025) emphasize that "institutional quality" is the primary constraint on recovery. The legal framework must mandate the creation of Special Purpose Vehicles (SPVs) for port projects that are governed by mixed boards (rather than just authorizing the use of SPVs (as allowed under the 2025 Ukrainian PPP law)), shielding the project from local political interference. [Karpa et al., (2022)]

4.1.3 The "Cluster" Economic Model

A standalone port is vulnerable. Liashenko et al. (2021) propose a "Transport and Logistics Cluster" approach, using the Prydniprovsky Economic Region as a case study. By legally structuring the PPP to include not just the quay wall but also the hinterland rail connections and nearby industrial zones, the state creates a "network effect." The economic model here shifts from simple transit fees to integrated logistics services, capturing more value within the Ukrainian economy.

4.1.4 Theoretical Framework: Application of the AK Growth Model

While not explicitly cited in the source texts, the findings of this research align with the AK model of endogenous growth (Y=AK). In standard neoclassical models (Solow), capital accumulation leads to diminishing returns. However, the AK model suggests that if technology (A) serves as a multiplier on capital (K), growth can be sustained indefinitely without diminishing returns.

Applying the literature to this equation:

- **K (Capital Accumulation):** Represented by the physical reconstruction of ports (quays, terminals) funded through the PPPs described by Becker et al., (2025) and Soloviov, (2016).
- **A (Technology/Efficiency):** Represented by the "Smart Port" innovations (AI, Digital Twins, JIT systems) described by HPC Hamburg Port Consulting GmbH, (2024) and Al Rousan, (2024).

In the context of Ukrainian recovery, simply rebuilding the old infrastructure (increasing K) would eventually lead to stagnation (diminishing returns). However, by mandating the "Smart Port" technologies (A) identified by Manget and Alsina (2025), the PPP ensures that the marginal product of capital remains high. The "Cluster Approach" proposed by Liashenko et al. (2021) acts as the transmission mechanism, ensuring that these efficiency gains (A) spill over into the regional economy, creating the permanent growth trajectory predicted by AK theory.

4.1.5 Real-World Data Verification (2021–2024)

Real-world data verified from recent logistics reports (2021–2024) for the Danube Cluster and Southern Ukraine/Greater Odessa Ports supports the application of the AK Growth Model. The data, as outlined in Table no. 2, reveals the stagnation of the pre-war period, the asymmetric shock of the invasion, and the divergent recovery paths of the deep-water versus riverine clusters.

Table no. 2: Cargo throughput by port (million tons)

Cluster / Port	**2021 (Pre-War)**	**2022 (Shock)**	**2023 (Pivot)**	**2024 (Recovery)**
Greater Odesa	~101.6	~20.0	~30.6	79.9
Pivdennyi (Yuzhny)	53.5	15.3	10.1	35.6
Chornomorsk	25.6	11.8	11.4	26.0
Odesa	22.6	7.7	8.4	18.3
Danube Cluster	5.4	16.5	32.1	17.3
Izmail	3.9	8.9	20.3	13.4
Reni	1.4	6.8	10.1	3.4
Ust-Dunaisk	0.06	0.8	1.7	0.5
TOTAL	**153.3**	**59.0**	**62.0**	**97.2**

Source: Ukrainian Sea Ports Authority Management Reports (2021, 2023, & 2024), GMK Center Report (2022), Ukrainian Shipping Magazine (2023), Interfax-Ukraine (2024), & Transport Strategies (CFTS) (2025).

4.1.6 Analysis by Port

Greater Odesa Ports

- **Pivdennyi (Yuzhny):** Historically, Ukraine's largest port by volume, specializing in ore and chemicals. It suffered the sharpest decline in 2023 (dropping to ~10M tons) because the Black Sea Grain Initiative excluded its primary cargo (iron ore). Its 2024 resurgence to 35.6M tons follows the opening of the independent Ukrainian Sea Corridor, which allowed ore exports to resume. [Center for Transport Strategies (CFTS), (2025)]
- **Chornomorsk:** The most resilient deep-water port during the crisis. It maintained steady grain flows even during the restrictive "Grain Deal" phase (2022-2023), handling 11.4M tons in 2023. In 2024, it nearly recovered to pre-war levels (26M tons), effectively reclaiming its role as a key agricultural hub.

- **Odesa:** The oldest major port faced significant security constraints due to its proximity to the city center and passenger terminals. While it recovered to 18.3M tons in 2024, it remains below its pre-war levels, indicating lingering capacity constraints or prioritization of the more industrial Pivdennyi/Chornomorsk terminals.

The Danube Cluster

- **Izmail:** The clear winner of the AK Model's "Efficiency (A)" multiplier. With negligible physical expansion (K), it more than quintupled its output from 3.9M (2021) to 20.3M (2023). However, the drop to 13.4M in 2024 signals that as deep-water routes reopened, shippers abandoned the more expensive river logistics, reverting to the mean.
- **Reni:** This port serves as the volatility index for Ukrainian logistics. It jumped in 2023 to 10.1M tons only to rapidly decline in 2024 (down to 3.4M tons). This extreme fluctuation proves that Reni functions purely as an "overflow valve" and remains economically uncompetitive during peace without the "Smart Port" technologies to lower costs.
- **Ust-Dunaisk:** The smallest player saw the most dramatic relative rise (28x growth in 2023, .06M tons to 1.7M tons), driven by the desperate need for any available berth. Its rapid decline in 2024 suggests it is the first to be abandoned when normal trade routes resume. (It should be noted that the "Kiliia Port Point" is structurally part of the Ust-Dunaisk Commercial Sea Port, serving as the "upstream" collection point and that the Kiliia Shipbuilding-Ship Repair Yard (KSRZ) is a separate private legal entity.)

Another notable port in this region is Bilhorod-Dnistrovskyi. [GMK Center, (2022)] Just like the Danube Cluster ports, its use increased in the pivot from the Black Sea ports in 2022. Since it is a shallow-water port with fixed physical capital (K), it shifted its operational model to a "Dry Port" logistics hub. This resulted in about an 83x increase in cargo (from approximately 2.4 thousand tons to over 200 thousand tons) during the war (and was not caused by building new berths (K did not change). [Ukraine Business News, (2024); GMK Center, (2023)] It was caused entirely by the change in operational strategy (A). This was a pure efficiency gain (A), and the asset generated exponential output growth (Y). The 2025 privatization of this port confirms that for smaller assets, transferring ownership to the private sector is the most effective way to unlock this efficiency multiplier. [Ukrinform, (2025)] Hence this port demonstrated the AK model on a smaller scale. Furthermore, the successful privatization price (~UAH 90 million) reflects the market's belief that a private operator can maintain this high A permanently.

There are other ports in Southern Ukraine. But due to the war, many remain closed and have not been considered in this analysis.

Some further observations regarding the Danube Cluster:

A standard model would predict that pouring 32M tons of cargo into "technologically obsolete" ports would cause immediate congestion and a flat-lining of growth. That did not happen. Growth remained linear/exponential. There were physical investments (K) such as (1) dredging: deepening the Bystre Estuary draft from ~3.9m to 6.5m in February 2023; and (2) infrastructure: the opening of 23 new cargo terminals in the Danube region in 2023 alone. Also, there was a shift to 24/7 operations, new barge-to-ship transshipment schemes, and the strategic prioritization of grain corridors. This factor (A) multiplied the effectiveness of the shallow 6.5m draft, allowing it to handle volumes usually reserved for deep-water ports.

The Danube cluster provides empirical proof of the AK model: A capital investment (K) that merely deepened the draft to 6.5 meters should not have yielded about a sixfold increase or almost 500% increase in output (Y). The difference is accounted for by the radical shift in technological and operational efficiency (A), which allowed the Danube ports to handle 32+ million tons in 2023, a volume previously thought impossible for this infrastructure. But it is important to note that these ports require constant investment.

4.1.7 Implications for PPPs

The data confirms that while the deep-water ports are irreplaceable for volume, the Danube ports proved that efficiency is the critical variable for resilience.

- **For Investors:** The 2023 peak proves that "obsolete" infrastructure can generate massive returns if managed efficiently. PPPs in 2025 should target the Danube not for volume, but for high-value, low-draft cargo (e.g., fuel, container feeders) using the "Digital Twin" technology to maintain the efficiency gains won during the war. Investors should target Pivdennyi/Chornomorsk for high-volume bulk/ore concessions (high K) and Izmail for niche, high-tech logistics services (high A) that can remain profitable even with lower volumes.
- **For the Ukrainian State:** As Danube volumes recede from their emergency peak, technology must be the driver of efficiency to keep these ports competitive.

4.2 Analysis of Research Question 2: Technology as a De-Risking Tool

The second research question investigates the role of technology. While the operational benefits of "Smart Ports" are well documented, their role in financial risk mitigation as outlined in Table no. 3 is critical for Ukraine.

Table no. 3: Technology-enabled risk mitigation matrix

Identified Risk / Barrier	Technological Solution	Mechanism of Action
Information Asymmetry	Digital Twin (IoT + Big Data)	Provides "radical transparency" allowing remote auditing of physical assets by investors in safe locations.
Corruption / Admin Resistance	Blockchain Procurement	Removes "human factor" discretion from routine processing; creates audit trails.
High Insurance / Demurrage	AI-Driven JIT Arrival	Predicts precise arrival times to minimize dwell time and waiting fees, offsetting high insurance premiums.
Supply Chain Fragility	Predictive Maintenance	Uses sensors to predict failure *before* it occurs, maximizing uptime in resource-constrained environments.

Source: Mapping technological solutions to specific administrative and financial risks identified by Karpa et al. (2022) and Soloviov (2016).

4.2.1 "Digital Twins"

Investing in a post-conflict zone is plagued by information asymmetry. Manget and Alsina (2025) describe the "Digital Twin" as a virtual replica of physical assets updated in real-time via IoT sensors. Described as the "single source of truth," a "Digital Twin" would allow an outside financier to audit the physical state of the port infrastructure without physical inspection. This level of transparency would lower the risk premium investors charge, directly making the project more financially viable. At the same time, this could increase investor confidence as use of this technology could mitigate "monitoring costs" for international backers.

4.2.2 AI-Driven Efficiency as a Competitiveness Buffer

Post-war Ukraine will likely face stiff competition from other international Black Sea ports. Afanasieva and Pokora (2020) note innovation policy is essential for seaports to remain competitive.

- **Just-in-Time (JIT) Arrival:** Al Rousan (2024) explains that AI-driven traffic management systems can predict arrival times with high precision and reduce "demurrage" (waiting fees).
- **Predictive Maintenance:** HPC Hamburg Port Consulting GmbH (2024) notes that AI can predict equipment failure before it happens. In a resource-constrained environment like post-war Ukraine, where spare parts may be difficult to import quickly, this is vital.

4.2.3 Institutional Integrity: The Anti-Corruption Ecosystem

Karpa et al. (2022) highlight "corruption risks" as a barrier to PPPs. Integrating blockchain-based procurement systems and automated customs processing removes human discretion from routine processes. When a port's operational data is immutable and transparent, the risk of revenue leakage decreases, increasing investor confidence.

While financial guarantees and "digital twins" mitigate commercial and operational risks, the "institutional risk" of corruption remains a primary deterrent for private capital. To address this, there is a need for a multi-layered anti-corruption ecosystem that supports the PPP framework by enforcing transparency through digital procurement and legislative reform.

4.2.4 Digital Procurement and "Smart Contracts"

The cornerstone of this ecosystem is the removal of the "human factor" from financial transactions. This is in line with the 2025 Ukrainian PPP law, mandating all competitive procedures to be conducted through an electronic trading system both aligned with EU standards and integrated into Ukraine's ProZorro platform (https://prozorro.gov.ua/en).

- **Mechanism:** Karpa et al. (2022) identify "administrative resistance" and "corruption risks" as primary barriers to PPP implementation. To counter this, the integration of digital procurement (as mandated by the 2025 Ukrainian PPP Law) ensures that tenders for construction materials or fuel are immutable and transparent.
- **Impact on PPPs:** By using "smart contracts," the selection of private partners and the management of funds are conducted through visible, automated protocols. This "institutional straitjacket" removes human discretion from routine processes, directly addressing the communication and transparency problems identified in public administration. [Karpa et al., (2022)]

4.2.5 Automated Customs and Logistics

Beyond procurement, operational corruption is mitigated through the "Smart Port" technologies described by Al Rousan (2024) and HPC Hamburg (2024) and as further discussed in Table no. 4.

- **Automated Processing:** Integrating AI into customs and logistics flows minimizes the "gatekeeper" role of officials. If an AI algorithm determines inspection queues based on risk profiling rather than human choice, the opportunity to solicit bribes to "speed things up" vanishes. [Al Rousan, (2024)]
- **Efficiency as Integrity:** This automation not only speeds up logistics but creates a digital audit trail that is harder to manipulate than paper records, increasing investor confidence in the security of their revenue streams. [HPC Hamburg Port Consulting GmbH, (2024)]

Table no. 4: The anti-corruption "stack" for port PPPs

Corruption Risk	Anti-Corruption Mechanism	Impact on Investor
Rigged Tenders	Blockchain-based Procurement	Creates immutable, transparent tender records, reducing "administrative resistance."
Bribery for Access	Automated Customs (AI)	Removes human discretion from routine processing; speeds up logistics.
Fund Misappropriation	Digital Twin Verification	Allows remote auditing of physical assets to verify capital expenditure.
Regulatory Capture	SPV Governance	Shields projects from local political interference through mixed-board governance structures.

Source: Karpa et al., (2022), Al Rousan, (2024), Manget and Alsina, (2025), & Becker et al., (2025).

5. Discussion

The findings of this study strongly support the working hypothesis that a "Tech-Enabled Hybrid PPP Model" is the optimal mechanism for post-war recovery, validating the theoretical application of the AK Growth Model (Y = AK) to infrastructure development.

The empirical data from the Danube Cluster's "pivot" (2022–2023) provides a real-world stress test of this theory. While physical capital (K) in the form of channel depth was limited to 6.5 meters, the output (Y) increased exponentially, from 5.5 million tons in 2021 to 32 million tons in 2023. [Horoshkova et al., (2024)] This nearly 500% growth can only be explained by a radical increase in the efficiency variable (A), driven by the operational shift to 24/7 logistics and the "dry port" innovation at Bilhorod-Dnistrovskyi. [GMK Center, (2023); Ukraine Business News, (2024)] This contradicts the standard Solow growth model, which would predict diminishing returns due to the physical obsolescence of the Danube ports.

Furthermore, the legislative analysis confirms that Ukraine is moving toward the financial structures for PPPs proposed by Becker et al. (2025). Ukrainian Law No. 4510-IX in 2025 does not merely update technical procedures; it serves as the primary legal vehicle for integrating Ukraine's infrastructure market with the European Union. First, the new law explicitly aligns Ukrainian PPP definitions and concession procedures with EU Directive 2014/23/EU. Second, to improve transparency in the bidding process and mitigate corruption risks, it mandates that by January 1, 2027, all competitive selection procedures for PPPs must be conducted through an electronic trading system integrated with the ProZorro platform. Third, the law legalizes different

types of PPPs by introducing the basis for "Minimum Revenue Guarantees" and allowing for donor grants to cover capital expenditures, directly addresses the war risks identified by Soloviov (2016) and Becker et al., (2025). The "first-loss" guarantee is no longer just a theoretical recommendation but a reality.

5.1 Broader Implications

In the broadest context, these findings suggest that the reconstruction of Ukrainian ports will serve as a global test case for "resilient logistics." The successful privatization of the Bilhorod-Dnistrovskyi port in 2024 and Ust-Dunaisk port in 2023 demonstrates that private capital is willing to enter high-risk environments if the asset is priced correctly and the operational model allows for agility. [Ukraine Business News, (2024)]

This approach, where small, non-strategic assets are fully privatized to maximize efficiency (A), while large, strategic deep-water ports (Chornomorsk, Pivdennyi) utilize PPPs to fund massive capital upgrades (K), creates a diversified risk profile for the state. As Ukraine aligns its digital customs and procurement systems (ProZorro) with EU standards, its ports are transitioning from Soviet-legacy into the eastern gateway of the Trans-European Transport Network (TEN-T).

By integrating AI and automation (A) into the reconstruction, Ukraine can sustain a linear growth trajectory. The "efficiency multiplier" provided by technologies like JIT arrival and predictive maintenance ensures that the marginal product of capital remains high, preventing the economic stagnation often seen in post-conflict zones.

5.2 Limitations of the Research

While the results are robust, several limitations must be acknowledged:

- **Data Volatility:** The analysis relies on operational data from a period of active conflict (2022–2025). As the deep-water ports reopen, the "efficiency" gains in the Danube may prove temporary without sustained investment.
- **Lack of Physical Verification:** Due to security restrictions, the study relies on mostly secondary data rather than onsite inspections.
- **Legislative Nascent Stage:** While Ukrainian Law No. 4510-IX has been adopted, its practical enforcement in a post-war environment remains untested. [Karpa et al., (2022)] The gap between *de jure* protections (legislative stability) and *de facto* enforcement remains a historical weakness in Ukraine.

5.3 Recommendations for Future Research

To address these unresolved questions, future research should focus on:

- **Quantitative Risk Modeling**: Researchers should apply Monte-Carlo simulations to the specific concession tenders in Ukraine. This would quantify the exact "first-loss" coverage required to achieve an internal rate of return (IRR) acceptable to international investors under different war-risk scenarios.

- **Digital Twin Efficacy**: Empirical studies are needed to measure the actual reduction in insurance premiums for ports that implement "Digital Twin" technologies. Does "radical transparency" translate into a measurable financial discount from war-risk insurers?
- **Comparative Post-Conflict Analysis**: Future studies should compare the Ukrainian PPP model with reconstruction efforts in other post-conflict zones (e.g., the Balkans or Iraq) to determine if the "Tech-Enabled" variable provides a statistically significant advantage in recovery speed.

6. Conclusion

The reviewed literature collectively indicates that Ukrainian ports can become engines of regional economic recovery only if future PPPs depart radically from past practice. Optimal frameworks must incorporate transparent risk-sharing mechanisms, regional cluster-oriented economic models, and deep integration of AI and digital technologies from the design stage. Technology is not merely an efficient tool; it has evolved into a critical instrument for de-risking private investment in an environment where traditional guarantees alone are insufficient.

The theoretical application of the AK Growth Model to these findings suggests that this approach offers more than just immediate recovery. Unlike standard reconstruction efforts where returns on capital (K) eventually diminish, the integration of "Smart Port" technologies (A) creates a multiplier effect. By embedding AI-driven efficiency and digital oversight into the concession structure, Ukraine can dismantle the "human factor" that drives corruption and sustain a linear growth trajectory, preventing the economic stagnation often seen in post-conflict zones.

6.1 Policy Recommendations

To operationalize this framework, Ukraine should implement two specific initiatives:

1. **Create a "Digital Port Sandbox" in the Danube Region:** The Ministry should designate the Danube cluster (Reni, Izmail) for Smart Port technologies. [Liashenko et al., (2021)] Using the "Cluster Approach" proposed by Liashenko et al. would allow for the expedited procurement of a unified "Danube Digital Twin" that integrates barge traffic and rail spurs. Success here provides the "proof of concept" needed to attract larger investors to the Black Sea ports.
2. **Amend PPP Laws to Mandate "Digital Twin" Deliverables:** An amendment to the Ukrainian Law on Public-Private Partnerships is needed to require the bidder to provide a "Digital Twin" strategy. This legal mandate would ensure that the private operator cannot value-engineer the technology out of the project, effectively codifying transparency into the contract. (It should be noted that in November 2025, the EU launched a "Digital Twin for the

Reconstruction of Ukraine" initiative, to track Ukrainian projects transparently and estimate costs.)

Looking beyond the immediate horizon of reconstruction, the integration of PPPs and AI positions Ukraine to redefine its role in the global supply chain. Unlike the established ports, which must retrofit legacy systems, Ukraine can build a "cloud-native" maritime sector from the ground up. As Ukraine moves toward European Union accession, its ports will transform into Green, Smart Logistics Hubs. The "Digital Twin" that today mitigates war risk will tomorrow serve as the platform for carbon tracking and environmental compliance, aligning Ukraine with the EU. [Manget and Alsina, (2025)] Lastly, the adoption of Law No. 4510-IX signals that Ukraine has moved beyond theoretical discussions of modernization. By legally embedding EU-standard transparency for its electronic trading system (ProZorro) and financial guarantees (MRGs) into the PPP framework, Ukraine has designed the standards necessary to attract European capital.

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