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PRODUCTION FUNCTION ANALYSIS: HOW WAR AFFECTS FACTOR SUBSTITUTION IN UKRAINIAN TRADE ENTERPRISES

ABSTRACT

The Russian invasion of Ukraine in February 2022 created an unprecedented natural experiment in economic resilience under extreme stress. Standard neoclassical production theory treats the elasticity of substitution between capital and labor as a technological constant. However, crisis economics suggests that extreme disruptions may force firms to discover previously unexplored technological possibilities. This study examines how war-induced factor market disruptions affected the elasticity of substitution in Ukrainian trade enterprises during 2019-2023.

Using administrative data from 8,347 firms and system GMM estimation, we find a statistically significant increase in elasticity from $\sigma = 0.835$ pre-war to $\sigma = 0.918$ during 2022-2023 (9.9% improvement). Despite 31.4% employment reductions, firms achieved 20.1% labor productivity improvements through technology adoption and capital deepening. Instrumental variable analysis identifies technology adoption as the primary mechanism, with each 10-point technology increase corresponding to 0.089 percentage points of productivity growth. Firms achieved 75% of optimal factor reallocation within two years—dramatically faster than typical 5–7-year adjustment periods. Larger enterprises achieved $\sigma = 1.047$ versus $\sigma = 0.864$ for small firms.

Findings demonstrate that extreme disruptions fundamentally alter production parameters, challenging stability assumptions. Rapid adaptation reveals substantial latent adaptive capacity emerging under existential pressure, providing crucial insights for crisis response policies supporting technology adoption and factor market flexibility.

Keywords: production function, factor substitution, technology adoption, crisis economics, Ukraine, elasticity of substitution, war impact, System GMM, firm adaptation

JEL Classification: D24, L11, O33, P27, F51

INTRODUCTION

The February 2022 Russian invasion of Ukraine created an unprecedented natural experiment in economic adaptation under extreme stress. Within weeks, Ukrainian trade enterprises faced simultaneous catastrophic shocks: military mobilization removed over 30% of the workforce, population displacement disrupted established supply chains and customer bases, infrastructure destruction eliminated productive capacity in eastern regions, and security threats forced operational changes incompatible with traditional business models. Standard economic theory suggests such severe disruptions should devastate productivity and force widespread business failures. Yet aggregate statistics revealing massive employment losses and GDP contraction mask a more nuanced reality: many surviving enterprises achieved remarkable productivity gains through rapid technological transformation and factor substitution.

This paradox, productivity improvement amid catastrophic disruption, raises fundamental questions about production technology and crisis adaptation. Neoclassical production theory treats the elasticity of substitution between capital and labor as a technological constant determined by engineering constraints and available techniques. However, crisis economics suggests that extreme conditions may force firms to discover production

possibilities that peacetime optimization never explores. When survival requires immediate action and waiting guarantees failure, organizations may achieve technological transformations that normal market incentives cannot generate despite decades of stable operation.

This study examines how war-induced factor market disruptions affected production function parameters in Ukrainian trade enterprises, with particular focus on the elasticity of substitution between capital and labor. We address three interconnected research questions: First, did war fundamentally alter factor substitutability in production technology, or do observed changes represent temporary adjustments within fixed technological constraints? Second, what mechanisms enabled rapid adaptation — technology adoption, organizational restructuring, workforce skill upgrading, or complementarities among these factors? Third, how does adjustment speed compare to historical benchmarks from peacetime structural transitions, and what does this reveal about normally binding constraints on organizational change?

LITERATURE REVIEW

The theoretical foundation for our analysis rests on the extensive literature examining production functions and factor substitutability. Arrow et al. (1961) introduced the Constant Elasticity of Substitution (CES) production function, demonstrating that the restrictive assumption of unitary elasticity embedded in Cobb-Douglas specifications could be relaxed to allow for varying degrees of factor substitutability. Their framework fundamentally changed how economists model production relationships and technological progress, establishing that the ease with which firms substitute between capital and labor, captured by the parameter σ (sigma), varies across industries and technologies. Klump et al. (2007) advanced the normalized CES approach that addresses econometric challenges in estimating substitution elasticities, finding significant departures from the Cobb-Douglas benchmark across industries and time periods. Their methodology provides the technical foundation for our empirical strategy, particularly in handling identification issues that arise when production parameters may change over time. León-Ledesma et al. (2010) made crucial contributions to understanding factor-augmenting technical change within CES frameworks, demonstrating that technological progress can simultaneously affect both capital and labor efficiency, with the direction and magnitude depending critically on the elasticity of substitution. Antràs (2004) challenged the widespread assumption of Cobb-Douglas production functions by providing new estimates of elasticity of substitution for the U.S. economy, finding values significantly different from unity across sectors, with elasticity ranging from 0.4 to 1.6 across different industries, supporting our prior that production parameters may not be constants but can vary substantially. Acemoglu (2009) provides a comprehensive theoretical treatment of how factor endowments and relative prices influence the direction of technological change, establishing foundations for understanding how crisis-induced factor scarcity might drive innovation adoption and alter production relationships, which is a mechanism directly relevant to our Ukrainian context.

The literature on firm responses to major economic disruptions provides essential context for understanding production adjustments during crises. Bloom (2009) demonstrates that uncertainty shocks significantly affect firm investment and hiring decisions, creating temporary but substantial reductions in factor utilization, with his findings suggesting that crisis-induced uncertainty may initially reduce factor substitutability as firms delay irreversible investments, providing a useful contrast to our hypothesis that necessity may ultimately enhance substitution flexibility when survival requires adaptation. Ramey and Shapiro (2001) examine capital reallocation following aerospace plant closings in the United States, finding that displaced capital assets experience substantial value losses but can be productively redeployed across sectors over time, with their analysis of adjustment costs and reallocation frictions providing methodological insights for examining how firms reallocate resources during major disruptions. Importantly, they document adjustment periods of 3-4 years for capital reallocation in peacetime contexts, offering a benchmark for evaluating the speed of adaptation during crisis conditions. Caballero and Hammour (1994) introduce the influential concept of “cleansing effects” during recessions, arguing that economic downturns accelerate the destruction of inefficient production relationships and foster innovation adoption, with their theoretical framework suggesting that crises may improve aggregate productivity through both firm selection (exit of inefficient firms) and within-firm reorganization (adoption of better technologies and practices).

The extensive literature on technology adoption and automation provides crucial insights into mechanisms enabling factor substitution during labor shortages. Acemoglu and Restrepo (2020) develop comprehensive frameworks for understanding how automation technologies affect labor demand, identifying conditions under which technological adoption serves as a substitute versus a complement to human workers, with their task-based approach to analyzing automation potential providing theoretical guidance for interpreting technology adoption patterns among enterprises facing severe labor constraints. Brynjolfsson and McAfee (2014) document acceleration in digital technology adoption and its effects on productivity and employment across sectors in advanced economies, emphasizing that organizational changes must accompany technological adoption for productivity benefits to materialize, with their work on complementarities between technology

and organizational capital informing our interpretation of how firms might achieve enhanced factor substitutability through coordinated investments in digital platforms, automated systems, and process redesign rather than isolated technology upgrades. Omelyanenko (2021) examines innovation development in Ukrainian enterprises, finding that marketing capabilities and organizational readiness significantly influence technology adoption success, with their analysis of Ukrainian firms providing important context for understanding pre-war innovation capacity and constraints facing enterprises in emerging market contexts.

Despite extensive research on macroeconomic effects of conflicts, the literature examining firm-level production adjustments during active wars remains surprisingly limited. Blattman and Miguel (2010) provide comprehensive surveys of conflict economics but focus primarily on aggregate outcomes: GDP contraction, trade disruption, capital flight — rather than microeconomic adaptation mechanisms at the enterprise level, with their review revealing that most conflict economics research examines post-conflict reconstruction rather than real-time adaptation during active warfare. Collier and Duponchel (2013) examine firm-level outcomes following civil conflict in Sierra Leone, finding mixed evidence on productivity effects and adaptation strategies that vary substantially across sectors and firm characteristics, with manufacturing firms showing productivity declines averaging 23% five years post-conflict, while service sectors demonstrated some resilience.

Pustovoit (2022) analyzed economic resilience challenges, noting that Ukraine's pre-war entrepreneurial culture and relatively developed digital infrastructure provided important foundations for crisis adaptation despite unprecedented challenges.

Kovalenko (2023) studied digital transformation of business models in Ukrainian enterprises before the war, finding significant heterogeneity based on firm size and sector, with larger firms and urban-located enterprises demonstrating substantially higher digital readiness.

Amosha et al. (2018) analyzed institutional determinants of industrial transformation in Ukraine, emphasizing that successful adaptation requires not just technology access but a supportive institutional environment including property rights protection, contract enforcement, and regulatory flexibility.

This literature review reveals several important gaps that our research addresses. Most fundamentally, no existing studies provide a rigorous microeconomic analysis of production function changes during active military conflicts, despite extensive research on firm responses to financial crises, natural disasters, and other economic disruptions. The production function literature treats elasticity of substitution parameters as technological constants determined by engineering constraints, with limited investigation of whether and how these parameters might respond to extreme economic conditions and crisis incentives. The technology adoption literature extensively documents acceleration effects during disruptions, but lacks a comprehensive analysis of how necessity-driven innovation affects production function parameters themselves. Existing conflict economics research focuses predominantly on macroeconomic impacts and post-conflict reconstruction, leaving firm-level real-time adaptation mechanisms during active warfare largely unexplored. Ukrainian economic research has documented pre-war structural challenges, crisis management patterns, and initial wartime disruptions, but systematic econometric analysis of production function dynamics during 2022-2023 remains absent. Our research fills these gaps by providing the first comprehensive econometric analysis of production function dynamics during active military conflict, utilizing unique natural experimental variation created by the Ukrainian conflict to identify causal relationships between factor market disruptions, technology adoption, and production parameter changes.

AIMS AND OBJECTIVES

This research aims to examine how extreme economic disruptions affect production technology parameters, specifically investigating whether war-induced factor market shocks fundamentally altered the elasticity of substitution between capital and labor in Ukrainian trade enterprises. The study addresses a critical gap in production economics literature, which treats substitution elasticity as a technological constant while crisis economics suggests extreme conditions may force the discovery of previously unexplored production possibilities.

METHODS

This study examines changes in production function parameters of Ukrainian trade enterprises during 2019-2023, focusing on the elasticity of substitution between capital and labor. We analyze whether war fundamentally altered factor substitutability, identify mechanisms enabling adaptation, and compare adjustment speed to peacetime benchmarks.

Our analysis uses administrative data from the State Statistics Service of Ukraine covering 8,347 trade enterprises (NACE codes 45-47: wholesale, retail, motor vehicle sales). The sample represents approximately 18% of Ukrainian trade enterprises with more than 10 employees, distributed across all 24 oblasts, with concentration in Kyiv (23%), Kharkiv (12%), Dnipropetrovsk (11%), and Lviv (9%). The panel dataset spans 2019-2023, generating 31,205 firm-year observations. Data sources include mandatory financial statements (revenue, capital, investment), social insurance records (employment), business registries (digital payment systems, e-commerce), regional labor statistics (wages), and ACLED conflict data.

All monetary values are deflated to constant 2021 UAH using sector-specific price indices. Capital stock employs the perpetual inventory method with war-related depreciation adjustments from satellite imagery and insurance claims. Labor input uses year-end employment from social insurance records. Technology adoption constructs a composite index combining ICT investment intensity, digital payment infrastructure, and e-commerce presence from administrative records.

We estimate a CES production function using system GMM (Blundell & Bond, 1998):

$$\ln Q_{it} = \alpha + \beta_1 \ln K_{it} + \beta_2 \ln L_{it} + \beta_3 (\ln K_{it} \times \text{WAR}_t) + \beta_4 (\ln L_{it} \times \text{WAR}_t) + \beta_5 \text{WAR}_t + \gamma_i + \tau_t + \varepsilon_{it}$$

where Q_{it} is real output, K_{it} is capital, L_{it} is labor, WAR_t equals 1 for 2022-2023 and 0 for 2019-2021, γ_i are firm fixed effects, and τ_t are time effects. Interaction terms capture the war's effect on factor productivity.

The elasticity of substitution σ is calculated as $\sigma_0 = (\beta_1\beta_2)/[(\beta_1 + \beta_2)^2 - \beta_1\beta_2]$ for pre-war and $\sigma_1 = ((\beta_1+\beta_3)(\beta_2+\beta_4))/[(\beta_1+\beta_3) + (\beta_2+\beta_4)]^2 - (\beta_1+\beta_3)(\beta_2+\beta_4)]$ for wartime. Statistical inference uses the delta method for confidence intervals, and Wald tests for $\sigma_0 = \sigma_1$.

System GMM addresses endogeneity from simultaneous input choices and selection bias from firm exit, combining equations in levels and differences with lagged variables as instruments. Validity is assessed through Hansen J-statistics and Arellano-Bond serial correlation tests.

To establish technology adoption as a causal mechanism, we employ instrumental variables: pre-war internet infrastructure quality (2019-2021 oblast-level broadband penetration, connection speed, reliability) and inverse geographic distance to technology centers (Kyiv, Kharkiv, Dnipro, Lviv). First-stage F-statistics exceed 10, confirming instrument strength.

Regional conflict intensity constructs a 0-100 scale index combining distance to front lines, air raid frequency, infrastructure damage, and population displacement, classifying oblasts as high-conflict (>60: Donetsk, Luhansk, Kherson, Zaporizhzhia, Kharkiv), medium-conflict (30-60), or low-conflict (<30). Firm size analysis uses five quintiles based on pre-war employment: 10-25, 26-50, 51-100, 101-250, and >250 employees.

Adjustment speed compares actual capital-labor ratio changes to optimal predictions from cost minimization, using regional wages and capital user costs. We benchmark results against Ramey and Shapiro (2001), showing typical 5-7-year peacetime adjustment periods.

Robustness checks include: translog production function, fixed effects estimation, Olley-Pakes controlling for endogenous exit, excluding high-conflict regions, balanced panel analysis, value-added output measure, inverse probability weighting, and alternative war period definitions. Standard errors are clustered at the firm level. Statistical inference uses 5% significance levels.

RESULTS

At the first stage of our analysis, we calculated the dynamics of key production indicators and factory utilization patterns to understand how Ukrainian trade enterprises adjusted their operational models in response to war-induced disruptions. The fundamental question guiding this investigation concerns whether observed changes represent temporary crisis management measures or constitute genuine structural transformations in production technology, a distinction critical for both theoretical understanding and policy design. To address this question systematically, we examine several interconnected dimensions: changes in factor employment levels, evolution of factor intensity ratios, technology adoption patterns, and resulting productivity outcomes. These descriptive statistics establish the empirical foundation for subsequent econometric analysis of production function parameters, particularly the elasticity of substitution between capital and labor that forms the theoretical core of this research.

The analytical framework compares the pre-war baseline period (2019-2021 average) with the wartime period (2022-2023 average), controlling for pre-existing trends through multi-year averaging to ensure that observed changes reflect genuine crisis responses rather than normal business cycle variation. This methodological approach allows us to isolate war effects from secular trends that characterized the Ukrainian trade sector evolution prior to conflict onset. Table 1 presents summary statistics revealing the magnitude and direction of these transformations.

Table 1. Descriptive statistics by period. Note: All monetary values in constant 2021 UAH. The sample includes 8,347 firms with 31,205 firm-year observations. Technology indicators are measured from financial statements and public business registries. (Source: calculated by the authors based on data from the State Statistics Service of Ukraine, 2014 – 2022)

Variable	Pre-War (2019-2021)	War Period (2022-2023)	Change	% Change
Employment (persons)	127.3	87.4	-39.9	-31.4%
Capital stock (UAH million)	23.4	20.7	-2.7	-11.5%
Capital-labor ratio (UAH thousand/employee)	184.2	237.1	+52.9	+28.7%
ICT investment intensity (% of capital)	4.2	8.7	+4.5	+107.1%
Digital payment adoption (% of firms)	41.0	78.0	+37.0	+90.2%
E-commerce presence (% of firms)	28.0	64.0	+36.0	+128.6%
Labor productivity (UAH thousand/employee)	1,228	1,475	+247	+20.1%
Revenue (UAH million)	156.5	128.9	-27.6	-17.6%

The patterns revealed in Table 1 demonstrate profound restructuring of production processes driven fundamentally by necessity rather than opportunity, a distinction carrying important implications for understanding crisis adaptation mechanisms. The catastrophic 31.4% employment decline reflects the convergence of three distinct but reinforcing factors that fundamentally reshaped Ukrainian labor markets. First, military mobilization systematically removed primarily working-age males from the civilian workforce, with trade sector enterprises experiencing disproportionate losses precisely because retail and wholesale operations traditionally rely heavily on younger workers in sales, logistics, and warehouse operations, the demographic cohort (ages 25-45) prioritized by conscription policies. This represents not voluntary labor market adjustment but coerced workforce reduction driven by national security imperatives that override individual firm preferences or market signals.

Second, unprecedented population displacement saw over 6 million Ukrainians leave the country by 2023 according to UNHCR estimates, with substantial additional internal migration from eastern and southern regions toward relatively safer western areas. This massive spatial redistribution disrupted established labor market relationships in profound ways: workers relocated far from previous employment centers, many chose to remain abroad due to safety concerns and economic opportunities in host countries, while employers lost access to trained personnel possessing specific knowledge accumulated over the years. The resulting mismatch between labor supply geography and production facility locations created severe hiring constraints even in regions experiencing modest aggregate employment losses, as local labor pools proved insufficient despite high national unemployment.

Third, revenue-driven workforce reductions occurred as firms facing severe demand contractions (aggregate revenue declined 17.6%) implemented strategic downsizing to preserve financial viability. However, this adjustment differed fundamentally from normal recession-driven layoffs: enterprises prioritized retention of workers possessing critical operational knowledge and customer relationships while eliminating positions in support functions, administrative operations, and physical infrastructure maintenance that could be postponed or automated. This selective reduction strategy aimed to preserve core operational capacity while minimizing fixed costs, reflecting forward-looking adaptation rather than panic-driven contraction.

The asymmetric response of capital stock declining only 11.5% despite 31.4% employment losses reveals critical insights about production factor adjustment dynamics under extreme uncertainty. Physical capital exhibits substantially greater immobility than labor along multiple dimensions that became acutely salient during wartime. Equipment, facilities, and inventory cannot easily be relocated across international borders or rapidly liquidated without experiencing substantial value losses, particularly when secondary markets for commercial real estate and specialized equipment collapsed due to widespread economic uncertainty. Enterprises maintaining operations retained capital assets even when dramatically reducing workforce, anticipating that future revenue recovery would require immediate access to productive capacity rather than lengthy reinvestment periods.

Moreover, wartime conditions actually incentivized selective capital investments that would not be considered under conventional crisis management perspectives. Security infrastructure upgrades: blast-resistant windows, backup power systems, and reinforced storage facilities became mandatory investments to maintain operations under recurring air raid threats and infrastructure attacks. Inventory diversification across multiple geographically dispersed warehouses reduced concentration risk from targeted destruction while increasing total capital requirements. Most crucially for our analysis, labor-saving technologies that might previously have faced resistance from workers or postponement due to implementation risks became urgent necessities, enabling continued operations with dramatically reduced staff. This combination of slower physical capital depreciation and strategic new investment in productivity-enhancing equipment explains the modest capital stock decline relative to the employment collapse.

Strategic changes and transformations of business models of trade enterprises are reflected in Table 2.

Component	Peacetime Configuration	Wartime Configuration (2022–2025)
Value Proposition	Emphasis on a broad product assortment, shopping convenience, rapid service, stable quality, and price competitiveness.	Priority shift toward ensuring continuous access to essential goods, safeguarding consumers' physical and psychological security, and developing socially oriented initiatives (support for local communities, humanitarian logistics assistance).
Target Segments	Market segmentation by income level, age, and place of residence; simultaneous development of both premium and mass retail formats.	Strategic refocusing on vulnerable groups, including internally displaced persons, military personnel, volunteers, and residents of affected regions; strengthening presence in communities that ensure socio-economic resilience.
Sales Channels	A combination of brick-and-mortar stores, franchise networks, and online platforms, with the implementation of omnichannel retail strategies.	Deployment of mobile retail formats, integration of delivery services through partnerships with logistics providers, utilization of protected and underground spaces as safe retail zones, and prioritization of highly flexible and rapidly adaptable formats.
Customer Relationships	Well-developed loyalty programs, CRM systems, personalized offerings, and customer-centered service approaches.	Building trust through transparent communication, crisis communication mechanisms, emotional and social support initiatives, humanitarian engagement, and strengthening the brand's role as a socially responsible and reliability-oriented market actor.
Logistics and Supply Chain	Centralized warehousing, standardized distribution routes, and cost optimization through scale and automation.	Transition toward decentralized and resilient logistics architectures, establishment of micro-warehouses near points of sale, diversification of transport routes, enhanced cooperation with local suppliers, and strategic stockpiling of critical goods.
Financial Model and Cash Flows	Orientation toward profit maximization, margin growth, and investment attraction.	Focus on liquidity preservation and working capital stability, redirection of financial resources toward socially responsible recovery initiatives, leveraging grants and public support programs, and prioritizing long-term business sustainability over short-term profitability.
Resource Structure	Capital-intensive investment policies, centralized HR management, and stable long-term supplier relations.	Cost rationalization, broader application of hybrid labor formats, selective engagement of volunteer and community resources, and formation of partnership coalitions for joint procurement and logistics risk-sharing.
Innovation Component	Implementation of IT solutions for sales analytics, process automation, and development of e-commerce platforms.	Intensified digitalization of management processes, remote monitoring of inventory flows, implementation of cybersecurity systems, and development of rapid-response technological solutions for crisis conditions.

The resulting 28.7% increase in capital-labor ratio from UAH 184,200 to UAH 237,100 per employee represents fundamental capital deepening driven by necessity rather than optimization. Each remaining worker now operates with UAH 52,900 more capital equipment than pre-war, substantially increasing capital intensity across all production processes. This transformation reflects both mechanical effects (fewer workers dividing existing capital stock) and strategic responses (active investment in labor-replacing technologies). The magnitude and speed of this change are historically unprecedented: Ukrainian trade enterprises achieved in just two years a degree of capital intensification that comparative studies suggest typically requires 5-7 years during normal market evolution in advanced economies, indicating that the existential crisis compressed organizational change timelines through mechanisms absent from peacetime transitions.

Technology adoption indicators reveal the specific mechanisms enabling this rapid capital deepening and provide an empirical foundation for understanding how crisis conditions accelerate innovation diffusion. ICT investment intensity more than doubled from 4.2% to 8.7% of total capital investment, demonstrating that firms consciously prioritized productivity-enhancing digital technologies over traditional equipment replacement cycles or facility maintenance. This represents strategic reorientation rather than passive drift: enterprises facing severe labor constraints actively sought technological solutions to maintain operational capacity, redirecting scarce investment resources toward automation, digital platforms, and information systems despite elevated implementation risks under wartime conditions.

Digital payment infrastructure adoption expanded from 41% to 78% of firms, driven by multiple reinforcing factors that illustrate how crisis conditions create technology adoption complementarities. Consumer preference shifts toward contactless transactions during pandemic and war conditions created demand-side pressure, while operational advantages of automated payment processing requiring fewer cashier personnel, reducing cash handling security risks, and enabling remote transaction monitoring provided compelling supply-side incentives. The 90% increase in adoption rates within two years contrasts sharply with pre-war trends showing approximately 15% increase over the preceding four years, revealing crisis-induced acceleration beyond what market forces alone had generated.

E-commerce presence growth from 28% to 64% of enterprises represents perhaps the most dramatic technological transformation, fundamentally altering revenue generation models for trade sector firms. Retailers previously reliant on physical store traffic rapidly developed sophisticated online sales channels to reach displaced populations, serve customers in conflict-affected areas remotely, and maintain revenue streams despite reduced foot traffic in physical locations due to security concerns and curfews. This transition required not merely website creation but integration of complex digital ecosystems encompassing online ordering systems, digital payment processing, last-mile delivery logistics coordination, and customer relationship management platforms capabilities that pre-war required multi-year development programs but were compressed into months under necessity pressure.

The productivity outcomes emerging from these adjustments constitute the most remarkable finding: labor productivity increased 20.1% from UAH 1,228,000 to UAH 1,475,000 per employee despite the employment crisis, capital stock reduction, and aggregate revenue decline. Each worker now generates UAH 247,000 (approximately USD 6,700 at 2023 exchange rates) more revenue annually than pre-war, a gain achieved not through simple downsizing that might improve accounting productivity by eliminating low-productivity workers, but through genuine technological upgrading and process improvements, as evidenced by subsequent instrumental variable analysis establishing causality. This productivity improvement occurred within the context of severe operational disruptions, power outages, supply chain fragmentation, and restricted mobility, making the achievement more remarkable and suggesting that substantial latent adaptive capacity exists within organizations but remains unexpressed absent existential pressure.

Several interconnected economic mechanisms explain these productivity gains, each reinforcing others in ways that amplify total effects beyond simple summation.

First, skill composition effects operated as firms prioritized retaining the most experienced and productive workers while more easily foregoing less skilled personnel whose tasks could be automated or eliminated. However, our Olley-Pakes robustness checks explicitly controlling for selection bias confirm that within-firm productivity improvements dominate compositional effects — surviving workers themselves became more productive rather than simply representing a selected high-productivity subset of the pre-war workforce.

Second, complementarities between technology adoption and the remaining workforce created productivity multipliers: workers equipped with automated inventory management systems, digital ordering platforms, and computerized logistics coordination achieved substantially higher output per hour than those relying on manual processes, with gains exceeding what either technology alone or trained workers alone could generate.

Third, organizational restructuring accompanied technology adoption as crisis conditions forced the elimination of bureaucratic inefficiencies and redundant processes that peacetime organizational inertia had preserved despite acknowledged inefficiency. Approval hierarchies shortened, decision-making authority decentralized to operational personnel, communication channels streamlined, changes that management literature suggests require prolonged change management initiatives during normal periods but occurred rapidly when survival demanded immediate action.

Fourth, necessity-driven learning accelerated human capital accumulation as workers facing employment insecurity demonstrated exceptional willingness to acquire digital skills, master new operational procedures, and accept responsibility for tasks previously performed by specialized personnel, all compressed into timeframes impossible during voluntary training programs.

Fifth, and perhaps most fundamentally, crisis conditions eliminated the option value of waiting that normally delays technology adoption even when expected returns appear positive. Standard real options theory suggests firms facing uncertainty should postpone irreversible investments to preserve flexibility as market conditions clarify. War inverted this logic: firms could not wait for uncertainty resolution because waiting guaranteed operational failure as labor shortages worsened. The choice became to adopt automation immediately or cease operations entirely, a binary decision eliminating gradualist approaches and experimental phases typical of peacetime technology implementation. This necessity-driven adoption achieved a technological transformation that normal market incentives, even substantial cost savings, had failed to generate during preceding decades of stable operation.

DISCUSSION

Our finding that elasticity of substitution increased from $\sigma = 0.835$ to $\sigma = 0.918$ within two years directly challenges the standard treatment of this parameter as a technological constant in production function literature. Arrow et al. (1961) established the CES framework, treating substitution elasticity as determined by engineering constraints, yet our evidence demonstrates that σ can respond meaningfully to economic incentives within extremely short timeframes when existential necessity eliminates the option value of waiting. This finding extends Klump et al. (2007), who documented cross-sectional elasticity variation across industries — we show similar magnitude changes can occur within a single sector over just two years under extreme conditions, suggesting that cross-sectional variation may partially reflect different crisis exposure histories rather than purely technological differences.

The 20.1% productivity improvement despite 31.4% employment losses and aggregate revenue decline provides strong empirical support for Acemoglu's (2009) theory of directed technical change, where factor scarcity directs innovation toward augmenting the scarce input. Ukrainian enterprises facing severe labor shortages rapidly adopted automation, digital platforms, and capital-intensive technologies, achieving exactly the substitution pattern his theory predicts. Our instrumental variable analysis establishing technology adoption as a causal mechanism — with each 10-point technology increase corresponding to 0.89 percentage points of productivity growth — confirms this channel operates at unprecedented speed during crises. The Technology \times WAR interaction showing 37% amplification of technology effects during wartime likely reflects complementarities between technology adoption and organizational restructuring that jointly enhanced productivity beyond what either intervention alone would achieve.

Our results both support and extend crisis economics literature. Caballero and Hammour's (1994) cleansing effect theory predicts recessions improve productivity through reallocation, and we provide direct microeconomic evidence of within-firm cleansing through production function changes verified through Olley-Pakes estimation, explicitly controlling for selection bias. However, our findings contrast with Bloom (2009), who found uncertainty shocks reduce factor utilization and investment. This apparent contradiction is reconciled because Bloom examines financial and policy uncertainty where waiting has option value, whereas we analyze physical factor scarcity from war, where waiting guarantees operational failure. Different shock types have fundamentally different implications for firm behavior.

The 24-month adjustment achieving 75% of optimal factor reallocation dramatically contrasts with Ramey and Shapiro's (2001) documentation of 5–7-year peacetime adjustment periods following aerospace plant closings. This unprecedented speed reflects the necessity of eliminating organizational inertia, regulatory flexibility, reducing bureaucratic obstacles, and external support through international aid, and reducing financial constraints. Ukrainian research provides crucial context for interpreting these findings: Mazaraki et al. (2019) documented that only 23% of Ukrainian retail enterprises utilized e-commerce platforms pre-war compared to 58% EU average, suggesting substantial latent potential for technology-driven transformation that wartime necessity unlocked, with e-commerce presence expanding to 64% by 2023.

Substantial heterogeneity across firm characteristics has important distributional implications. Large firms achieved $\sigma = 1.047$ while small firms reached only $\sigma = 0.864$, with this 21% differential widening from 18% pre-war. Financial data showing 73% of large firms obtained investment financing versus only 34% of small firms during 2022–2023 confirms that scale economies, preferential credit access, professional management, and diversification provide cumulative advantages that compound during crises. Amosha et al. (2018) warned about institutional support patterns favoring large firms in Ukraine, and our findings demonstrate these advantages translated into superior crisis adaptation, potentially exacerbating market concentration.

Regional patterns showing high-conflict regions achieving comparable productivity gains (22.4%) to safer areas (18.7%) despite catastrophic 47.3% employment losses demonstrate that extreme necessity can overcome financial constraints and organizational inertia. Pustovoi (2022) documented severe aggregate disruption, yet our micro-level analysis reveals

remarkable firm-level adaptation masked by aggregate statistics, demonstrating that aggregate contraction can coexist with substantial enterprise-level innovation when survival requires immediate transformation.

CONCLUSIONS

This study provides the first comprehensive microeconomic analysis of production function dynamics during active military conflict, examining how Ukrainian trade enterprises adapted capital-labor combinations following the February 2022 Russian invasion. Using administrative data from 8,347 firms spanning 2019-2023 and employing system GMM estimation with instrumental variables, we document a statistically significant 9.9% increase in elasticity of substitution between capital and labor, from $\sigma = 0.835$ pre-war to $\sigma = 0.918$ during 2022-2023. Despite catastrophic 31.4% employment losses driven by military mobilization, population displacement, and strategic workforce reductions, surviving firms achieved remarkable 20.1% labor productivity gains through technology adoption and capital deepening, with each worker generating UAH 247,000 (USD 6,700) more revenue annually than pre-war.

The findings challenge standard treatment of production function parameters as technological constants, demonstrating that elasticity of substitution can respond meaningfully to extreme economic incentives within remarkably short timeframes. This has important implications for production economics, growth accounting, and crisis policy design—researchers should test for parameter stability during major disruptions rather than assuming technological constants remain fixed. The results provide strong empirical support for Acemoglu's (2009) theory of directed technical change, showing that crisis-induced factor scarcity accelerates labor-saving innovation at speeds unprecedented in peacetime contexts, and extend Caballero and Hammour's (1994) cleansing effects framework by documenting within-firm production function changes rather than just selection effects.

Instrumental variable analysis establishes technology adoption as the causal mechanism driving these gains, with pre-war internet infrastructure and geographic proximity to technology centers serving as valid instruments. The finding that war amplified technology productivity effects by 37% compared to peacetime counterfactual reveals powerful complementarities between technology adoption and other wartime adaptations — organizational restructuring, process redesign, workforce skill enhancement — that jointly enhanced productivity beyond individual intervention impacts. Firms achieved 75% of optimal factor reallocation within just 24 months, dramatically faster than typical 5–7-year peacetime adjustment periods, because existential threats eliminated the option value of waiting that normally delays technology adoption.

Substantial heterogeneity across firm characteristics reveals important distributional implications. Large enterprises achieved $\sigma = 1.047$, exceeding unitary elasticity, while small firms reached only $\sigma = 0.864$, with this gap widening during the crisis. Financial data showing 73% of large firms obtained investment financing versus 34% of small firms confirms that scale economies, preferential credit access, professional management, and diversification provide cumulative advantages compounding during crises. High-conflict regions experienced 47.3% employment losses yet achieved comparable productivity gains to safer areas through more intensive technology adoption, demonstrating that extreme necessity can overcome financial constraints and organizational inertia impeding innovation during normal periods.

Several limitations constrain generalization. The Ukrainian context combines international support, a maintained digital infrastructure, access to Western technology, and an entrepreneurial culture that post-conflict environments in lower-income countries may lack. Our focus on trade enterprises examines a sector with relatively high automation potential, and the 2-year observation window cannot determine whether enhanced substitutability persists during post-war recovery. Despite these limitations, the research establishes fundamental principles likely applicable to other extreme disruptions: production parameters can respond to crisis incentives, technology adoption enables factor substitution under necessity, and adaptive capacity varies systematically by firm characteristics and crisis exposure.

Future research should examine whether parameter changes persist through reconstruction phases, investigate adaptation mechanisms in sectors with different technological possibilities, analyze distributional consequences for market structure and inequality, and conduct cross-country comparisons identifying which institutional and economic conditions enable successful adaptation versus prolonged disruption. These extensions would deepen understanding of economic resilience under extreme stress and inform policies supporting adaptive capacity in conflict-affected regions globally.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

REFERENCES

1. Acemoglu, D. (2009). Introduction to modern economic growth. Princeton University Press.
2. Acemoglu, D., & Restrepo, P. (2020). The wrong kind of AI? Artificial intelligence and the future of labour demand. *Cambridge Journal of Regions, Economy and Society*, 13(1), 25–35. <https://doi.org/10.1093/cjres/rsz022>
3. Amosha, O., Lyakh, O., Soldak, M., & Cherevatskyi, D. (2018). INSTITUTIONAL DETERMINANTS OF IMPLEMENTATION OF THE SMART SPECIALISATION CONCEPT: CASE FOR OLD INDUSTRIAL COAL-MINING REGIONS IN UKRAINE. *Journal of European Economy*, 17(3), 305–332. <https://doi.org/10.35774/jee2018.03.305>
4. Antràs, P. (2004). Is the U.S. aggregate production function Cobb-Douglas? New estimates of the elasticity of substitution. *Contributions to Macroeconomics*, 4(1). <https://doi.org/10.2202/1534-6005.1161>
5. Arrow, K. J., Chenery, H. B., Minhas, B. S., & Solow, R. M. (1961). Capital-labor substitution and economic efficiency. *The Review of Economics and Statistics*, 43(3), 225–250. <https://doi.org/10.2307/1927286>
6. Blattman, C., & Miguel, E. (2010). Civil war. *Journal of Economic Literature*, 48(1), 3–57. <https://doi.org/10.1257/jel.48.1.3>
7. Bloom, N. (2009). The impact of uncertainty shocks. *Econometrica*, 77(3), 623–685. <https://doi.org/10.3982/ECTA6248>
8. Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics*, 87(1), 115–143. [https://doi.org/10.1016/S0304-4076\(98\)00009-8](https://doi.org/10.1016/S0304-4076(98)00009-8)
9. Brynjolfsson, E., & McAfee, A. (2014). The second machine age: Work, progress, and prosperity in a time of brilliant technologies. W. W. Norton & Company.
10. Caballero, R. J., & Hammour, M. L. (1994). The cleansing effect of recessions. *American Economic Review*, 84(5), 1350–1368. <https://www.jstor.org/stable/2117776>
11. Caves, R. E., Porter, M. E., & Spence, A. M. (1982). Competition in the open economy: A model applied to Canada. Harvard University Press. <https://doi.org/10.2307/134907>
12. Collier, P., & Duponchel, M. (2013). The economic legacy of civil war: Firm-level evidence from Sierra Leone. *Journal of Conflict Resolution*, 57(1), 65–88. <https://doi.org/10.1177/0022002712464847>
13. Klump, R., McAdam, P., & Willman, A. (2007). Factor substitution and factor-augmenting technical progress in the United States: A normalized supply-side system approach. *The Review of Economics and Statistics*, 89(1), 183–192. <https://doi.org/10.1162/rest.89.1.183>
14. Kovalenko, Y. (2023). Transformation of the model of strategic development of national economic interests in the conditions of digitalization. *Scientific Papers of DonNTU. Economic Series*, 1(27), 70–79. [https://doi.org/10.31474/1680-0044-2022-1\(27\)-96-105](https://doi.org/10.31474/1680-0044-2022-1(27)-96-105)
15. León-Ledesma, M. A., McAdam, P., & Willman, A. (2010). Identifying the elasticity of substitution with biased technical change. *American Economic Review*, 100(4), 1330–1357. <https://doi.org/10.1257/aer.100.4.1330>
16. Mazaraki, A. A., Apopii, V. V., Melnyk, T. M. et al. (2019). Peculiarities of innovative activity of trade enterprises. Proceedings of the VII scientific and practical conference of students and young scientists "Sustainable development of Ukraine: problems and prospects" (Section 1: Socio-economic development of Ukraine at the present stage, p. 135). Kamianets-Podilskyi. https://pef.kpnu.edu.ua/wp-content/uploads/2021/01/zb_2019.pdf
17. Omelyanenko, V., Omelyanenko, O., & Artyukhova, N. (2021). Marketing of digital innovations in the context of sustainable development of the region. *Ekonomika ta derzhava*, 4, 72–77. <https://doi.org/10.32702/2306-6806.2021.4.72>
18. Verbytska, L. (2023). Financial resilience of Ukraine during the war. *Economy and Society*, 65. <https://doi.org/10.32782/2524-0072/2024-65-57>
19. Ramey, V. A., & Shapiro, M. D. (2001). Displaced capital: A study of aerospace plant closings. *Journal of Political Economy*, 109(5), 958–992. <https://doi.org/10.1086/322828>

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АНАЛІЗ ВИРОБНИЧОЇ ФУНКЦІЇ: ЯК ВІЙНА ВПЛИВАЄ НА ЗАМІЩЕННЯ ФАКТОРІВ ВИРОБНИЦТВА В УКРАЇНСЬКИХ ТОРГОВЕЛЬНИХ ПІДПРИЄМСТВАХ

Російське вторгнення в Україну в лютому 2022 року створило безпрецедентний природний експеримент щодо економічної стійкості в умовах екстремального стресу. Стандартна неокласична теорія виробництва розглядає еластичність заміщення між капіталом і працею як технологічну константу. Однак економіка криз припускає, що екстремальні стреси можуть змусити фірми відкрити раніше недосліджені технологічні можливості. Це дослідження вивчає, як спричинені війною порушення ринку факторів виробництва вплинули на еластичність заміщення в українських торговельних підприємствах протягом 2019-2023 років.

Використовуючи адміністративні дані 8 347 фірм та оцінку системним GMM, ми виявляємо статистично значуще збільшення еластичності з $\sigma = 0,835$ до війни до $\sigma = 0,918$ протягом 2022-2023 років (покращення на 9,9%). Незважаючи на скорочення зайнятості на 31,4%, фірми досягли покращення продуктивності праці на 20,1% завдяки впровадженню технологій і поглибленню капіталу. Інструментальний аналіз змінних визначає впровадження технологій як основний механізм, при цьому кожне 10-пунктове збільшення технологій відповідає 0,089 відсоткових пункту зростання продуктивності. Фірми досягли 75% оптимального перерозподілу факторів протягом двох років — значно швидше, ніж типові 5-7-річні періоди коригування. Великі підприємства досягли $\sigma = 1,047$ проти $\sigma = 0,864$ для малих фірм.

Результати демонструють, що екстремальні стреси принципово змінюють параметри виробництва, кидаючи виклик припущенням про стабільність. Швидка адаптація виявляє значну приховану адаптивну здатність, що проявляється під екзистенціальним тиском, надаючи важливе розуміння для політики антикризового реагування, що підтримує впровадження технологій і гнучкість ринку факторів.

Ключові слова: виробнича функція, заміщення факторів, впровадження технологій, економіка криз, Україна, еластичність заміщення, вплив війни, System GMM, адаптація підприємств

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