

Article

Digital and Operational Modernization and the Sustainability and Performance of the Intermodal Transport Chain: A Pre–Post Analysis of Nine Serbian Firms

Aleksandar Jovanović¹, Đorđe Vranješ², Branka Bursać Vranješ², Violeta Lukić Vujadinović³, Goran Tričković⁴, Filip Dobrić⁵ , Lazar Veljković⁶, Nebojša Čurčić²  and Aleksandar Gošić^{7,*}

¹ Pro Star Safety Team Niš, 18000 Niš, Serbia; jovaanovic@gmail.com

² Department Zemun, Belgrade Academy of Applied Studies Politehnika, 11000 Belgrade, Serbia; djvranjes@politehnika.edu.rs (Đ.V.); bbvranjes@politehnika.edu.rs (B.B.V.); ncurcic@politehnika.edu.rs (N.Č.)

³ Faculty for Economics and Engineering Management, Business Academy Novi Sad, 21000 Novi Sad, Serbia; violeta.lukic.vujadinovic@fimek.edu.rs

⁴ Department for Railroad Traffic, Railway College of Vocational Studies Belgrade, Zdravka Čelara 14, 11000 Belgrade, Serbia; goran.trickovic@vzs.edu.rs

⁵ Faculty of Technical Sciences, University of Novi Sad, 21000 Novi Sad, Serbia; filipdobric@yahoo.com

⁶ Millenium Osiguranje d.o.o., 11070 Belgrade, Serbia; toza18@gmail.com

⁷ Department for Railroad Traffic, Academy of Technical and Art Professional Studies, 11060 Belgrade, Serbia

* Correspondence: gosic.aleksandar@gmail.com

Abstract

Intermodal freight transport is an integral, strategic foundation of the European Union's vision to decarbonize Europe, but in non-EU countries such as Republic of Serbia, the split in modalities remains heavily focused on road haul, while terminal infrastructure remains poorly interconnected and digital maturity remains low. This research study investigates the adoption of new digital and operational technologies along the intermodal transport chain. It is measured in the context of enhancing ecological and operational performance in the Serbian environment. Research data was collected from a sample of nine medium and large Serbian intermodal logistics companies, who operate along Pan-European Corridor X and the Rhine–Danube Corridor. Three ecological and three operational key performance indicators (KPIs) were defined to measure the level on enhancements reached through sustainability efforts. The study is an uncontrolled, firm-level pre–post comparison: three directional hypotheses were evaluated using paired-sample *t*-tests, exact Wilcoxon signed-rank tests, and bootstrap confidence intervals on pre- and post-modernization firm-level aggregates. In the post-modernization period, mean CO₂ intensity per TEU (twenty-foot equivalent unit) was 17.4% lower, terminal energy intensity (kWh/TEU) 14.3% lower, and terminal dwell time 22.5% lower than in the pre-modernization period (exact $p \leq 0.001$; 95% bootstrap confidence intervals excluding zero). Implications were discussed for EU Green Deal alignment, Trans-European Transport Network (TEN-T) extension to the Western Balkans, and future research has been initially defined. Given the pre/post design without a control group, the reported effects are associations rather than causal estimates and should be read as preliminary, exploratory evidence.

Keywords: enhancement; intermodal transport; sustainability; performance



Received: 15 June 2026

Revised: 7 July 2026

Accepted: 9 July 2026

Published: 14 July 2026

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1. Introduction

Freight transportation is holding over a third of transport-related carbon emissions in the EU, and the European Commission's Freight Transport Package envisioned that

decarbonization measures within EU freight transport will grow by a quarter by 2030 and by half through 2050 [1–3].

Since the change in modality from road to rail and inland water transport is the main policy handle: the Sustainable and Smart Mobility Strategy aims to increase by half the share of rail transport by 2030, also to double it by 2050 [1,4]. The revised TEN-T Regulation aggregates these milestones by mandating exceptionally long train capabilities, expansion of trans-shipment terminals, and emissions through door-to-door connection [3,5].

Serbia, located in the center of crossroad of Pan-European Corridor X towards Greece, as well as Corridor VII, or the Rhine–Danube Corridor, involves a structurally key position in this European setup [6–8].

Yet the country's performance of intermodal transport and combination of water, road and railroad is practically non-existent: since World Bank's in report of World performance of the year 2023 estimates Serbia with score of 2.8—recording a drop from the 2.84, that was estimated in 2018—meaning Serbia has practically been stagnating, while similar economies have progressed [9,10]. Majority of transport in Serbia is moving by road, with transport trends for 2025. report that road freight transport has increased by a third during the period of ten years. This comes as a direct consequence of new motorways being available from 2014 to 2025. Railroad and waterway transport has remained stagnant [11–13].

Since rail freight performance in EU fell by little as 1% percent in 2024, according to Eurostat, Serbia recorded an increase of 7.8 percent increase in weight transported through Serbian railroads [14]. Installed capacity for intermodal transport is still very limited: capacities are around 10,000 TEU (twenty-foot equivalent units) per year at the main railway Belgrade terminal, 12,000 TEU/year at the Port of Belgrade, and approximately 3000–5000 TEU/year at Pančevo port terminal [11,15,16].

The newly operational Batajnica Intermodal Terminal—co-financed by the EU and the Republic of Serbia—adds 1530 TEU of container-storage capacity with three rail tracks and 108 plug-ins for trucks [17,18].

Following this topic, digital and automation technologies are increasingly deployed in freight terminals across the globe, and they are applied to forecast estimated time of arrival, to optimize scheduling of container placement, and to automate gate operations and customs operations through demand forecasting [19–29].

Existing studies consistently report about productivity gains and lower emission up to a quarter at top tier terminals [30–32]. However, examples from Balkans regions and Serbia specifically are nonexistent.

To the best of our knowledge, this is the first peer-reviewed study to quantify empirically the ecological and operational impact of digital and operational modernization along the Serbian intermodal chain.

Research questions were defined as the following:

RQ1. “Is the deployment of digital and operational modernization measures along the Serbian intermodal transport chain associated with measurably lower CO₂ intensity per TEU and energy intensity per container managed?”

RQ2. “Are digitally modernized terminal operations associated with lower terminal energy intensity and lower terminal dwell time?”

Asset utilization (O3), on-time performance (O2), and the share of the electrified rail leg (E3) are examined as secondary, descriptive outcomes only.

Practical contributions of this paper are the following: first, the authors provide a pilot empirical based, KPI-driven assessment of the recorded impact of digital and operational modernization being applied in Serbian intermodal logistics.

Second, in this research is proposed an operational KPI framework that can be streamlined directly onto the EU Green Deal, the Sustainable and Smart Mobility Strategy, and Serbia's National Smart Specialization Strategy [33].

Next part of this research, Section 2, further widens the literature review, defines research hypotheses, explains the research sample, and how the overall KPI methodology was defined. Section 3 displays descriptive statistics and hypothesis testing outcome. Section 4 discusses implications of research results. Section 5 presents the conclusions and directions for future research.

2. Materials and Methods

2.1. Literature Review

In the classical sense, intermodal transport includes the transport of products into a single, loaded unit, which can be constructed as a container or trailer, using at least two modes of transport, organizing and handling treatment of goods at the modal location [34].

Sustainability of these locations is thought through in detail, therefore across observed sites in Europe, Kirschstein and Meisel found that “intermodal rail/road routing to be more eco-efficient than road-only routing for more than 90 percent of simulated shipments” [35].

Since the EEA (European Environment Agency) found out that emissions of CO₂ at level of approximately 75–80 g CO₂e/tkm for diesel HGVs, as well as up to a quarter gram of CO₂e/tkm for electric rail freight, and just below 30 g CO₂e/tkm for inland waterway transport [36,37].

Other report from International Council about clean transportation efforts throughout the world indicates the EU heavy duty fleet caused high CO₂ emissions even under a regulated reporting framework [38].

Shifting about 10% of freight from road to cargo trains in Czechia has caused reduction of energy consumed for the same cargo weight to an 85% decrease and emissions to drop for about 75%, saving annually 212 million kWh and 59,000 tons of CO₂ [39].

Since the digitalization and modernization effort, throughout the intermodal chain has worldwide application, for the purpose of understanding, operational KPIs have been organized into five groups:

- (i) Estimated time of arrival (ETA);
- (ii) terminal slot allocation and intermodal equipment organization;
- (iii) transport module organization and intermodal location;
- (iv) advanced analytics for maintenance of stock and terminal equipment;
- (v) intelligent management of documentation and inspection at gates and customs.

Balster analyzed estimated time of arrival analytical model for intermodal freight networks that recorded quality of prediction improvements by a fifth, over base travelling times, for sampled shorter trips [20].

El Mekkaoui showed through data driven maritime vessel model for estimated time of arrival, significantly shows improvement rather than analyzing general port data [21].

For inland waterways, Xie and Liu investigated traffic-flow methods based on available data and statistics methods [40], while most recent papers extend the proposed model with more advanced architecture [22,41].

Through port terminal activities, there are available methods to optimize and enhance performance that display a predominant shift towards dynamic management of cranes and other equipment. There are numerous applications of digital tools where activities of yard crane operators were automated, and the result was significant reduction of waiting time for trucks [42]. Le Ngoc investigated frameworks for optimization through different heuristics that would lead to crane automated scheduling [23].

Through last couple of years, there have been many applications of introducing advanced digitalization into real time crane scheduling, that outputs in decrease of compute time and improvements in overall productivity [43,44].

Architectures that enable container optimization have outperformed old mathematical models by more than 50% for intermediate problems and around 80% for large problems [45].

Enabling digital twins as replicas of existing terminal systems, and feeding twins with real time streaming data, emerges as a new way of integrating digital technologies in maritime ports and intermodal terminals across the world [25,26,46].

Following that path, research by Kim reported that digital twins at Pusan international terminal reduced CO₂ emissions by around 80% when compared to previous scheduling plans [47]. Also, through an international survey including 107 intermodal rail terminal professionals, it has been discovered that 44% defined sustainability tech as a top priority for investments into technology.

Intelligence that comes through streaming from sensor data in railway systems, has achieved accuracy above 99% on fault prediction, which was confirmed in metro system of Porto in Portugal [48,49].

When it comes to automated damage detection in intermodal terminals including containers and trailers, Cimili et al. [19] found out that this technology can reduce manual inspection time at checkpoint gates, and in some cases gate systems can be automated by up to two thirds, which reduces truck idling time and emissions measured through sustainability reports. In the Moroccan port of Casablanca, Bouyahia et al. [28] found out that it was possible to reduce incredibly significant amounts of CO₂ by shifting at least 8% of trucks arriving at peak hours [28,50].

In a detailed review of digital applications that help optimize logistics activities in a sustainability effort, data driven and technology enabled routing, forecasting of demand, scheduling of equipment has reduced energy consumption significantly, as well as emissions [51]. Sustainability enhancement has been achieved through a technology driven approach that includes automating container operations, as Tsolakis has investigated this in detail [52].

Next, digitally integrated supply chains focus sustainability in the first plan, converging on several of its mechanisms—better matching of capacity towards actual demand, idle time decrease as well as accounting on gas emissions [53–56].

Through approach of digital and robotized technology, reduction of supply chain carbon emission is driven, as this is the most common situation happening in almost 60% of cases [57].

When it comes to the specific situation and position of Serbia, Tadić, Zečević, Krstić and colleagues researched Serbian intermodal terminals in great depth, technology selection and dry-port concepts [58–70]. Is it worth mentioning that Vidović modelled a Serbian intermodal terminal with hub modelling zones [71].

Some Serbian authors evaluated financially intermodal terminals in Belgrade [66] and assessed service quality in river transportation [72], while others introduced new methods for last mile delivery [73]. A new, hybrid model for ranking industry 4.0 technologies in last mile logistics has been introduced [74], with Kalem supporting these findings through his evaluated railway infrastructure through a fuzzy MCDM model [75].

None of these research papers have empirically quantified pre-modernization versus post modernization indicators of performance and sustainability.

Synthesizing the reviewed studies, four recurring mechanisms link digital and operational modernization to the KPIs examined in this paper. First, information-side technologies (terminal operating system (TOS) upgrades, ETA forecasting, slot and equip-

ment planning) act primarily by reducing idle running, waiting, and empty repositioning, which lowers fuel use and CO₂ intensity per TEU·km [20–23,40–44]. Second, documentation and gate technologies (electronic data interchange (EDI), the electronic consignment note (e-CMR), automated inspection and gate processing) shorten administrative lead times and truck queues, which is reflected in terminal dwell time and on-time performance [19,28]. Third, terminal automation, digital twins, and predictive maintenance compress equipment downtime and improve scheduling, supporting asset utilization and terminal productivity [25,26,42–49]. Fourth, energy-side measures (electrified handling equipment, fleet renewal, and modal shift towards electrified rail) act directly on terminal energy intensity and the share of electrified traction [36–39,51,52]. These four mechanisms structure the conceptual framework presented in Figure 1 (Section 2.2) and motivate the hypotheses evaluated below. Policy documents, industry surveys, and other grey-literature sources are used for infrastructure and policy context only; empirical claims about performance effects rely on peer-reviewed studies.

2.2. Research Methodology

Since intermodal transport chain has been modelled as a sequential flow of steps, including first mile road, rail or river barge main haul, and finally a last mile road trip. It has been connected throughout with terminal nodes, where transfer is made, documentation is exchanged and storage is managed. Modernization efforts can be targeted towards any step or part of the flow. This research hypothesis that combines effect of multi-effort modernization can be evaluated through the following sustainability outcomes:

1. CO₂ intensity per TEU shipped (chain-level);
2. Terminal-node performance.

Three research hypotheses have been defined:

H1. *Modernization of intermodal transport activities are associated with lower CO₂ emissions per TEU.*

In more detail, this hypothesis requires a paired-sample benchmarking of CO₂ per TEU per KM, measured prior and after the change, since the first measurable digital and operational modernization on the same transport way.

H2a. *Modernized terminal operations are associated with lower terminal energy intensity (measured in kWh/TEU).*

In more detail, there will be conducted a comparison of energy intensity used and terminal dwell time per container, prior and post modernization efforts.

H2b. *Modernized terminal operations are associated with lower terminal dwell time (measured in hours).*

Energy intensity and dwell time are analyzed as separate outcomes (H2a and H2b), each with its own paired comparison.

The conceptual framework of this research—linking modernization measures, their mechanisms of action, and the resulting KPI outcomes—is presented in Figure 1 below. In the framework, the modernization measures are the exposures and the KPIs are the outcomes; infrastructure quality, data quality, digital maturity, firm size, terminal ownership, and transport configuration are treated as contextual conditions and potential moderators. The framework is an organizing device rather than a tested causal model.

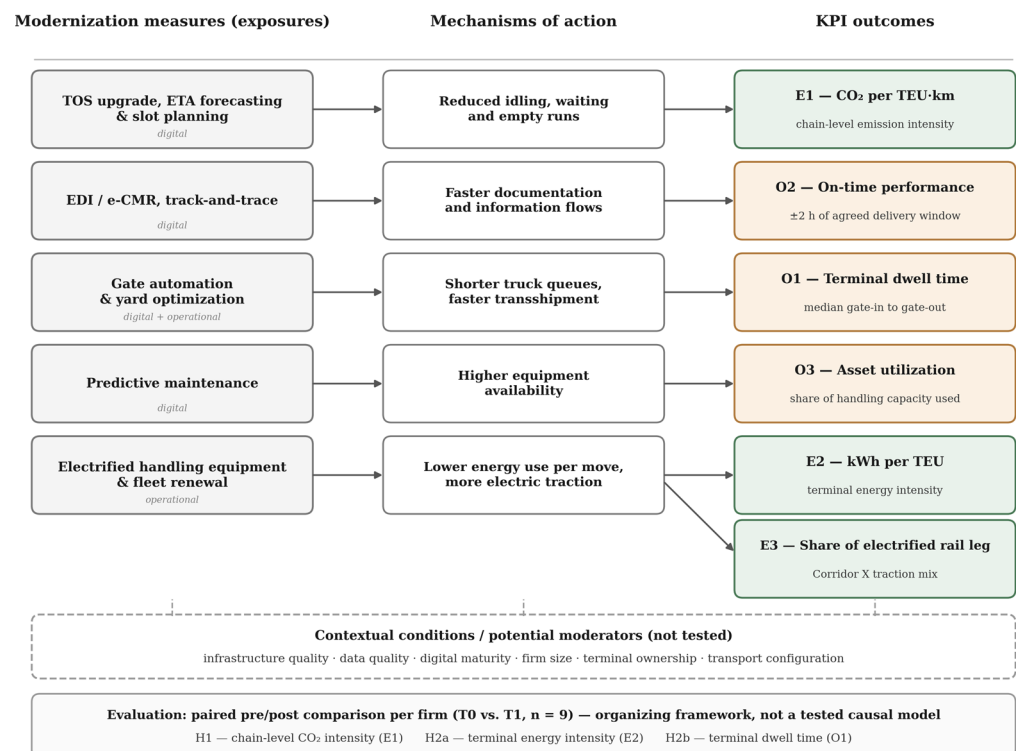


Figure 1. Conceptual framework of the study: modernization measures, mechanisms of action, and KPI outcomes.

This research combines a narrative literature review of 86 sources (predominantly published between 2018 and 2025, complemented by older methodological references), a survey of nine medium sized and large sized intermodal logistics firms from Serbia, and 24 months of data including observations from firm supplied operational data records, where modernization period is in the middle of that long period of time.

The unit of analysis is the firm. From the 24 months of records, two 12-month firm-level aggregates were computed for each firm (T0 and T1), yielding 18 firm-period observations; monthly-resolution values could not be shared in a homogeneous form across all firms for confidentiality reasons. Intensity indicators were computed as ratios of 12-month totals, and dwell time as the median of container-level values within each firm-period, so annual values are implicitly weighted by activity. This aggregation entails a loss of the monthly structure; interrupted time-series and panel specifications on monthly data, as well as difference-in-differences designs with non-modernized comparison firms, are identified as future work (Section Limitations).

The sampling frame comprised the population of organizations with documented intermodal activity in Serbia: twelve terminal facilities operated by seven intermodal service providers, together with integrated road–rail forwarders active on Corridor X. Fourteen candidate firms were identified from national registers and industry directories and approached directly; five were excluded (three declined to participate and two lacked terminal handling activity owing to limited infrastructure), yielding nine participants. A minimum annual revenue of EUR 10 million was applied as an eligibility criterion because smaller operators could not supply 24 months of consistent operational records; this criterion limits generalizability to larger operators, and the sample is purposive rather than representative of the Serbian intermodal market. Results were reported after anonymization, with throughput values rounded and firm descriptors generalized to reduce re-identification risk; all participating firms approved publication of the reported profiles. Operational data were validated against published industry benchmarks. Outlier filtering

(Winsorization at the 5th and 95th percentiles) was applied only to container-level records within each firm-period when computing the firm-level aggregates, affecting fewer than 2% of records; the nine firm-level aggregates themselves remained unchanged, and the direction and statistical significance of all reported results are unchanged when unfiltered records are used.

2.3. Sample and Data Collection

When observing intermodal logistics companies in Serbia, it is mandatory to have in mind that the potential is extremely big, but number of existing companies in that domain and activity is limited. There were identified twelve terminals in Serbia and in total seven intermodal service providers. The largest one is the Port of Belgrade, with Pančevo port including a Dry Port terminal [15].

EU-definition of SMEs is cited: “medium companies have 50–250 employees and revenue 10–50 million EUR; large companies have above 250 employees or above 50 million EUR”.

Anonymized sample of nine firms (four medium, five large) in this sample has been defined to reflect to this market complexity. Company-level characteristics are summarized in Table A1 (Appendix A).

The specific digital and operational modernization measures implemented by each participating firm, together with the year of implementation, are summarized in Table 1; the corresponding observation windows T0 and T1 are defined in Section 2.4.

Table 1. Digital and operational modernization measures implemented by the surveyed firms ($n = 9$).

Firm	Digital Measures Implemented (Year)	Operational Measures Implemented (Year)	T0 Window	T1 Window
Company A	TOS upgrade with AI-based slot optimization (2023); EDI/e-CMR (2023); predictive maintenance (2023); digital-twin pilot of yard operations (2024)	Gate automation with OCR (2024); two electrified handling units (2024)	2022	July 2024–June 2025
Company B	TOS upgrade (2023); EDI/e-CMR (2024); data-driven ETA forecasting (2024)	Automated gate pre-announcement (2024)	2022	July 2024–June 2025
Company C	Track-and-trace (2023); predictive maintenance of handling equipment (2024)	Electrified reach stacker (2024)	2022	July 2024–June 2025
Company D	EDI/e-CMR (2023); data-driven arrival forecasting (2024)	Yard slot-planning module in TOS (2024)	2022	July 2024–June 2025
Company E	Digitized gate and yard records (2023); static slot planning in TOS (2024)	—	2022	July 2024–June 2025
Company F	EDI/e-CMR (2023); track-and-trace across carriers (2024); data-driven ETA forecasting (2024)	—	2022	July 2024–June 2025
Company G	EDI/e-CMR (2024); predictive maintenance of own truck fleet (2023)	Partial fleet renewal, Euro VI (2024)	2022	July 2024–June 2025
Company H	Digitized transport documentation (2024)	Static route planning (2024)	2023	July 2024–June 2025
Company I	Digitized order and dispatch records (2023)	—	2022	July 2024–June 2025

TOS = terminal operating system; EDI = electronic data interchange; e-CMR = electronic consignment note; ETA = estimated time of arrival; OCR = optical character recognition.

All measures listed in Table 1 were fully implemented before the start of the corresponding T1 window; measures dated 2024 were completed in the first half of 2024, and no implementation continued into the post-modernization period. Because the firms adopted heterogeneous combinations of measures, each firm is assigned to one of two modernization categories—digital-only (Companies E, F, I) or combined digital

and operational (Companies A–D, G, H)—and an exploratory, descriptive comparison by category is reported in Section 3.4.

2.4. Definition of Sustainability and Performance KPIs

2.4.1. Sustainability KPIs

E1—CO₂ emissions per TEU·km throughout the intermodal chain (CO₂ per TEU per km), allocated across the road, rail, and barge legs using an activity-based approach consistent with ISO 14083 [76] and the GLEC Framework [36,37,77]. The system boundary is door-to-door: the first-mile road leg, the main rail or barge leg, the last-mile road leg, and terminal handling; empty repositioning is excluded. Emission factors are the EEA well-to-wheel factors for road, rail, and inland-waterway transport [36,37], with the Serbian national grid-average factor applied to electricity consumption.

E2—Terminal energy intensity (kWh per TEU) decomposed by equipment class [78–81]. For firms without own terminal capacity, E2 and O1 were measured at the firm's primary partner terminal and attributed to the firm's container flows.

E3—Share of electrified rail leg along Corridor X [7,82].

2.4.2. Operational KPIs

O1—Terminal dwell time (hours)—median time a container spends in the terminal from arrival to departure. The firm-level value is the median of container-level dwell times within each 12-month period; sample statistics in Section 3 are therefore means and standard deviations of nine firm-level medians.

O2—On-time performance (share of deliveries completed within ± 2 h of the contractually agreed delivery time window).

O3—Asset utilization rate (share of handling capacity used).

Table 2 summarizes, for each KPI, the calculation formula, unit of measurement, primary data source, and allocation methodology, so that the computation of every indicator can be replicated.

Table 2. Definition of the KPIs: calculation formulas, units, data sources, and allocation methodology.

KPI	Calculation Formula	Unit	Data Source	Allocation/Notes
E1	$\Sigma \text{ over legs (fuel or energy per leg} \times \text{mode-specific emission factor)}/\Sigma \text{ TEU} \cdot \text{km}$	g CO ₂ e/TEU·km	Firm fuel and traction-energy records; leg distances from transport documents	Activity-based allocation per mode (road, rail, barge) consistent with ISO 14083/GLEC, aggregated along the chain
E2	Metered terminal electricity (plus diesel converted to kWh equivalent)/TEU managed	kWh/TEU	Terminal electricity meters; equipment fuel logs	Decomposed of equipment class (cranes, reach stackers, gates, other)
E3	Electrified train-km/total train-km on Corridor X legs	%	Traction and route records of rail operators	Weighted by TEU·km per shipment
O1	Median (gate-out – gate-in) per container	hours	TOS gate-in/gate-out timestamps	Median per firm and period; outliers filtered at the 5th/95th percentile
O2	On-time deliveries/total deliveries	%	CMR/e-CMR delivery confirmations vs. agreed delivery windows	On time = within ± 2 h of the contractually agreed delivery time window (not the scheduled arrival time)
O3	TEU managed/nominal annual handling capacity	%	TOS throughput records; nominal equipment capacity	Annual basis, per firm

TOS = terminal operating system; CMR/e-CMR = (electronic) consignment note; GLEC = Global Logistics Emissions Council.

Each sustainability and operational KPI has been measured through two 12-month periods, where:

- T0 = the year prior to the first significant digital and operational modernization in the firm's operations;
- T1 = the most recent 12 months.

Dimension of transformation maturity towards digitalization has been identified on three levels, as basic, intermediate and advanced. The three levels are operationally defined through an explicit indicator checklist: Basic—digitized operational records and static (hard-coded) planning only; Intermediate—at least two of the following capabilities in productive use: data-driven forecasting, predictive maintenance, or EDI/e-CMR document flows; Advanced—AI-based automation and/or digital-twin integration in daily operations [51,52]. The rating of each firm reported in Table A1 was re-verified against these criteria, based on the measures listed in Table 1. The classification was assigned by researchers based on the documented systems in Table 1 and structured interviews with the firm's operations managers; two authors rated all nine firms independently, agreeing on eight of nine, and the remaining case was resolved by consensus. Because only one firm is rated Advanced, maturity is used descriptively and maturity is interpreted descriptively only, outside the hypothesis-testing framework.

3. Results

3.1. Descriptive Statistics of the Sample

Table 3 (Section 3.2) reports the per-firm values of the primary KPIs, and Table A1 summarizes the company-level profiles. Since average annual TEU managed was 6840, this reflected small capacity size of intermodal transport in Serbia, for medium firm size it was up to 5000 TEU annually and for large firms up to 12,000 TEU, with majority of capacity managed at three terminals in Belgrade and Pančevo cities. Three out of nine firms are doing business only along the Corridor X route, two firms are operating on a trimodal basis, and the remaining four companies are road to rail forwarders, without any terminal capacity that they own. After analysis, 3 firms were rated with basic digital maturity, 5 firms with intermediate and only one with advanced digital maturity. This is in line with global research for 2025, where it was stated that only one in seven intermodal transport companies use digital tools to collect and process available data.

It should be noted that the combined firm-level volume of the sample (around 62,000 TEU per year) is a sum across firms occupying distinct roles along the intermodal chain (five terminal-owning operators and four road–rail forwarders). Because the same physical container is typically handled by more than one participating firm as it moves along the chain, firm-level volumes overlap; the sample total therefore measures a different quantity from the installed capacity of individual terminals cited in the Introduction and the two are interpreted separately (approximately 25,000–27,000 TEU per year in total across the Belgrade railway terminal, the Port of Belgrade, and Pančevo).

3.2. Results of Testing Research Hypotheses

Table 3 reports the verified per-firm values of the three primary KPIs, and Figure 2 displays each firm's paired pre- and post-modernization observations. Ninety-five percent confidence intervals for mean paired differences were obtained by percentile bootstrap resampling of firms (10,000 resamples, random seed 42); exact *p*-values are reported, with Holm adjustment across the three primary outcomes.

H1 (CO₂ per TEU·km). Mean pre-modernization CO₂ intensity across the nine firms was 62.8 g CO₂e/TEU·km (SD 8.0); post-modernization it was 51.9 g CO₂e/TEU·km (SD 10.2). The mean paired difference is 10.9 g CO₂e/TEU·km (95% bootstrap CI [8.1, 13.6]),

a 17.4% lower value. The distribution of paired differences is consistent with a normal distribution (Shapiro–Wilk $p = 0.64$); the paired-sample t -test yields $t(8) = 7.4$, exact $p = 7.6 \times 10^{-5}$ (Holm-adjusted $p = 2.3 \times 10^{-4}$), Cohen’s $d_z = 2.47$. The exact Wilcoxon signed-rank test gives $W = 0$, $p = 0.0039$: all nine firms recorded a lower post-modernization value (Table 3, Figure 2). H1 is supported; details are given in Table A2.

Table 3. Per-firm pre- and post-modernization values and relative changes for the primary KPIs ($n = 9$).

Firm	Category	TEU/yr	E1: Pre → Post ($\Delta\%$)	E2: Pre → Post ($\Delta\%$)	O1: Pre → Post ($\Delta\%$)
Company A	B	11,900	50.2 → 38.6 (−23.1%)	9.8 → 8.1 (−17.3%)	28.5 → 23.3 (−18.2%)
Company B	B	11,000	53.6 → 40.6 (−24.3%)	9.2 → 7.7 (−16.3%)	33.0 → 26.3 (−20.3%)
Company C	B	9500	57.8 → 42.9 (−25.8%)	10.4 → 8.2 (−21.2%)	41.2 → 32.6 (−20.9%)
Company D	B	8000	60.9 → 51.1 (−16.1%)	8.1 → 7.2 (−11.1%)	36.8 → 29.4 (−20.1%)
Company E	D	7000	65.3 → 61.1 (−6.4%)	7.4 → 6.9 (−6.8%)	52.4 → 36.6 (−30.2%)
Company F	D	4800	67.0 → 61.0 (−9.0%)	6.6 → 6.0 (−9.1%)	30.6 → 22.4 (−26.8%)
Company G	B	3900	64.1 → 47.3 (−26.2%)	9.9 → 8.1 (−18.2%)	44.9 → 35.1 (−21.8%)
Company H	B	3000	72.4 → 57.6 (−20.4%)	8.9 → 7.7 (−13.5%)	59.8 → 47.6 (−20.4%)
Company I	D	2460	73.9 → 66.9 (−9.5%)	5.3 → 4.9 (−7.5%)	20.2 → 15.8 (−21.8%)

E1 in g CO₂e/TEU·km; E2 in kWh/TEU; O1 = firm-level median dwell time in hours. Negative percentages denote lower post-modernization values. Category: D = digital-only, B = combined digital and operational (see Table 1).

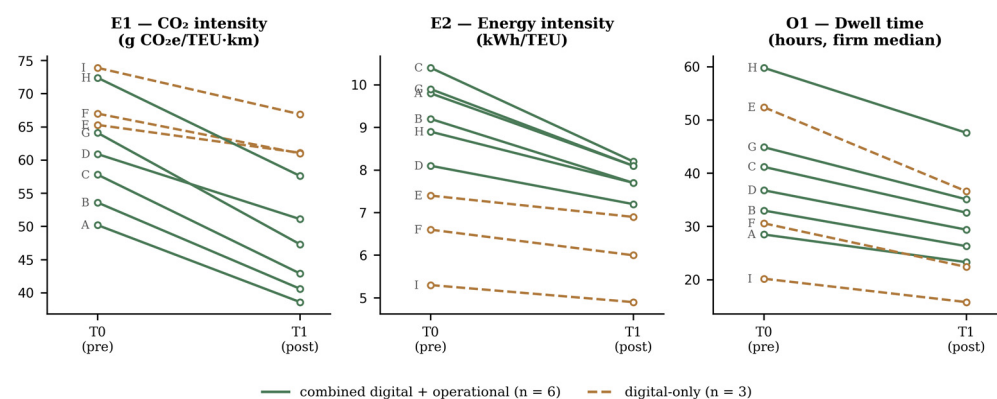


Figure 2. Per-firm pre- and post-modernization values for the primary KPIs (paired observations, $n = 9$). Solid lines: firms with combined digital and operational measures; dashed lines: digital-only firms.

H2a (terminal energy intensity). Mean kWh/TEU declined from 8.4 (SD 1.7) to 7.2 (SD 1.1); the mean paired difference is 1.2 kWh/TEU (95% bootstrap CI [0.8, 1.6]), a 14.3% lower value. Shapiro–Wilk $p = 0.59$; $t(8) = 5.62$, exact $p = 5.0 \times 10^{-4}$ (Holm-adjusted $p = 5.0 \times 10^{-4}$); Cohen’s $d_z = 1.87$; Wilcoxon $W = 0$, exact $p = 0.0039$. H2a is supported.

H2b (terminal dwell time). The mean of firm-level median dwell times declined from 38.6 h (SD 12.4) to 29.9 h (SD 9.4); the mean paired difference is 8.7 h (95% bootstrap CI [6.7, 11.0]), a 22.5% lower value. Shapiro–Wilk $p = 0.56$; $t(8) = 7.36$, exact $p = 7.9 \times 10^{-5}$ (Holm-adjusted $p = 1.6 \times 10^{-4}$); Cohen’s $d_z = 2.45$; Wilcoxon $W = 0$, exact $p = 0.0039$. H2b is supported. Details for H2a and H2b are given in Table A3.

Because the firms differ in annual volume, throughput-weighted estimates are reported alongside the unweighted firm-level estimates: weighting by annual TEU yields relative changes of −18.8% (E1), −15.2% (E2), and −22.2% (O1), close to the unweighted values. The unweighted estimates describe the average firm-level change; the weighted estimates approximate the change across the freight volume represented by the sample.

The secondary outcomes, reported descriptively, moved in the same direction: on-time performance (O2) from 78.6% to 84.9%, asset utilization (O3) from 61.4% to 67.2%, and the share of the electrified rail leg (E3) from 54.0% to 56.5% (sample means). Given the small

sample and the absence of pre-specified hypotheses for these indicators, formal testing was restricted to the three primary outcomes.

3.3. Sustainability Impact Analysis

Taken together, the improvements associated with modernization analyzed through this research correspond to an estimated decrease of 2200 tons of CO₂ emissions per year across the nine participating firms, with combined firm-level volumes of around 62,000 TEU per year (Section 3.1). This figure was obtained by multiplying each firm's observed change in E1 by its annual TEU·km volume and summing across firms; it describes the participating firms only and is indicative rather than inferential. A national, sector-wide extrapolation is left for future research: firm-level volumes in the sample overlap along the chain and measure a different quantity from installed terminal capacity, and a linear projection from nine purposively selected firms would require a larger, representative sample together with consistent, non-overlapping capacity data.

3.4. Exploratory Comparison by Modernization Category

As the interventions were heterogeneous (Table 1), an exploratory, descriptive comparison was made between the three firms that implemented digital measures only (Companies E, F, I) and the six firms that combined digital and operational measures. Firms with combined measures recorded larger mean relative reductions in CO₂ intensity (−22.6% vs. −8.3%) and terminal energy intensity (−16.3% vs. −7.8%), whereas digital-only firms recorded a larger mean reduction in dwell time (−26.2% vs. −20.3%). These contrasts are consistent with the mechanisms in Figure 1, but with three and six firms per group they are reported descriptively only.

4. Discussion

The findings of this research identified 17.4 percent CO₂/TEU and 22.6 percent dwell-time decrease through a quarter, that exist in researched reports within port digitalization pilots [47,52] and much lower than experimented high boundaries, reported in a set of digitalization studies (around 78% of CO₂ reduction examined by Pusan Newport [47]; just over a quarter of decrease through optimization of container stacking process [45]; up to 83 percent reduced queue length of truck in the Casablanca analysis [28]). Simulation results and single-port engineering scenarios address a different unit of analysis than firm-level pre-post observations; the comparison is made only to situate the order of magnitude of the present estimates.

The identified pattern of results serves directly as empirical evidence of the distribution of digital maturity in the Serbian sample: only one surveyed company operates at elevated level; most are medium maturity (data-driven forecasting with some sense of predictive maintenance) where gains are practical but incremental [83].

The observed pattern is descriptively consistent with the digital-readiness thesis, which states “the value of digital technologies scales non-linearly with prior digitalization. Firms that already operate modern TOS, EDI/e-CMR document flows, and granular sensor data extract more value from a given digital investment than firms layering new tools on top of legacy systems.”

Beyond the measured indicators, three contextual factors condition intermodal operations in Serbia. These factors remained outside the empirical design and are discussed here as external context and boundary conditions rather than as findings.

Firstly, it is a matter of infrastructure, where during the process of audit in technical sense (2024), it was noted that near half of Pančevo quay walls are old with constructions older than 45 years, with limited draught limitations of around 3.5 m, with restricted vessel access during low water periods, and also having in mind the limited approach for electric

powered trains and vehicles. It will be needed to wait until 2027 for an intermodal terminal in Pančevo, that will increase capacity of road haulage in container operations [16,84–86]. All of this cannot be substituted through digitalization; physical infrastructure is necessary.

Next, having in mind significant siloed data approach, where almost half of intermodal terminals lack real time visibility of data and still face data accuracy challenges; the Serbian case follows the same pattern; therefore, all ETA models are retrained on missing, bad or incomplete data.

Correlating human capital as the last dimension, but maybe the most significant one, it is reported that around 900 people (technical specialists) emigrated annually, majority workers in transport operations have passed 50 years of age, and experienced logistics directors pool in Serbia is very low [16].

Limitations

This study rests on several fundamental constraints. First, the observational pre/post design cannot isolate the effect of modernization from concurrent influences on the same indicators. Second, the sample comprises nine purposively selected medium and large operators, so the findings describe those firms only; Serbia hosts a small population of intermodal operators, which restricted external replication from the outset. Third, the implemented interventions are heterogeneous (Table 1), which rules out attribution of the observed changes to individual measures. Fourth, firm-level volumes overlap along the intermodal chain, which restricts aggregation and comparison with installed terminal capacity.

Benchmarking against published global values proved unreliable for several reasons, chiefly because recent years in Europe offered an unstable reference period for a study of this kind, given the succession of disruptions within a short interval (wars, pandemics, economic crises, trade tensions). In addition, the KPI definitions follow international convention but still vary across Serbian intermodal transport operators. The introduction of standardized reporting under the CountEmissions EU methodology would strengthen future replication [3].

In line with the pre/post design without a control group, the results reported in Section 3 should therefore be interpreted as associations rather than causal effects. Several confounding factors contributed to the observed changes, most notably fuel and energy price fluctuations, macroeconomic conditions during the observation window, infrastructure improvements along Corridor X, and fleet renewal unrelated to digitalization. For this reason, findings are positioned as preliminary, exploratory evidence intended to motivate a larger, controlled study—ideally a difference-in-differences design, as outlined in Section 5.

Each of these limitations defines a task for future research: a controlled design (difference-in-differences or synthetic control) with comparison operators from neighboring markets; representative sampling that includes smaller firms; standardized reporting under CountEmissions EU to harmonize KPI definitions; decomposition of heterogeneous intervention bundles into individual measures; and corridor-level, sensor-based emissions measurement to complement firm-level records.

5. Conclusions

The findings of this research indicate that targeted digital and operational modernization through the intermodal transport chain is associated with simultaneous improvements in ecological and operational performance, even in the demanding Serbian context. Across the samples of medium and large firms examined, the deployment of digital and operational tools was associated with a 17.4 percent decrease in carbon emissions per TEU and a 14.3 percent decrease in terminal energy intensity. These associations are subject to the limitations set out in Section Limitations: the absence of a control group, heteroge-

neous interventions, a small purposive sample, and firm-level aggregation prevent causal attribution and national generalization.

The findings suggest that digitalization remains a potentially underused lever for decarbonization efforts in a country with many burdens, such as Serbia, having extremely limited intermodal systems.

For Serbia in particular, policy proposals informed by these findings—as motivating evidence rather than statistical proof—include accelerating the modernization of terminals along the priority corridors, enabling mandatory document interoperability, and fostering targeted digital-modernization grants under different funds, available for medium-sized operators with limited in-house data and analytics resources.

Digitally driven intermodal organization should be seen as a priority domain in the Smart Specialization Strategy.

Future research should extend the analysis to other Western Balkan markets, implement the controlled design outlined in Section Limitations, combine firm-level records with real-time, sensor-based corridor-level emissions measurement, and develop a national extrapolation based on representative sampling and non-overlapping capacity data.

Author Contributions: Conceptualization, A.J. and G.T.; methodology, A.J., Đ.V. and G.T.; literature review, B.B.V., V.L.V. and N.Ć.; data curation, F.D. and L.V.; formal analysis, A.J. and Đ.V.; writing—original draft, A.J., G.T. and N.Ć.; writing—review and editing, all authors; visualization, A.G.; supervision, G.T.; project administration, G.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Anonymized firm-level KPI data (excluding firm identifiers) are available from the corresponding author upon reasonable request for verification purposes, subject to a standard non-disclosure agreement to protect commercial confidentiality. An aggregated, de-identified dataset and the analysis code supporting the reported statistics can be shared under the same conditions.

Conflicts of Interest: Author Aleksandar Jovanović was employed by the company Pro Star Safety Team Niš. Author Lazar Veljković was employed by the company Millenium Osiguranje d.o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Consolidated per-firm profile: size classification, scale, operational configuration, annual throughput, modernization category, and digital maturity ($n = 9$).

Firm	Size Class ¹	Empl.	Rev. (€ M)	Operational Model	Corridor X Node ²	TEU/yr	Modern. Category ³	Digital Maturity
Company A	Large	420	78	Tri-modal (Danube + X)	Belgrade (X/Danube)	11,900	Both	Advanced
Company B	Large	310	54	Tri-modal (Danube + X)	Pančevo (X/Danube)	11,000	Both	Intermediate
Company C	Large	290	52	Corridor X terminal	Belgrade ŽIT (X)	9500	Both	Intermediate
Company D	Large	265	48	Corridor X terminal	Novi Sad (Xb)	8000	Both	Intermediate
Company E	Large	255	40	Corridor X terminal	Šimanovci–Stara Pazova (X)	7000	Digital-only	Basic

Table A1. Cont.

Firm	Size Class ¹	Empl.	Rev. (€ M)	Operational Model	Corridor X Node ²	TEU/yr	Modern. Category ³	Digital Maturity
Company F	Medium	95	21	Road–rail forwarder	Subotica (Xb)	4800	Digital-only	Intermediate
Company G	Medium	80	17	Road–rail forwarder	Niš (Xc)	3900	Both	Intermediate
Company H	Medium	70	14	Road–rail forwarder	Šid (X)	3000	Both	Basic
Company I	Medium	60	11	Road–rail forwarder	Belgrade (X)	2460	Digital-only	Basic

¹ Size class per European Commission Recommendation 2003/361/EC (Large: ≥ 250 employees or $>€50$ M turnover; Medium: otherwise). Employee and revenue figures are rounded 2024 values. Empl. = number of employees; Rev. = annual revenue (EUR million). ² Pan-European Corridor X and its branches (Xb: Budapest–Novi Sad–Belgrade; Xc: Niš–Sofia); “Danube” denotes Rhine–Danube waterway (Corridor VII) access supporting the barge leg. ³ Modernization category, derived from Table 1—Digital-only: TOS, e-documentation, track-and-trace, or forecasting measures only (Companies E, F, I); Both: digital measures combined with equipment electrification/renewal or process redesign. Firms are anonymized (Company A–I). Of the 14 firms approached, 5 were excluded (3 declined to participate, 2 lacked terminal handling activity), yielding 9 participants (Section 2.2). Throughput values are rounded and firm descriptors generalized to reduce re-identification risk; all firms approved publication of the reported profiles. The throughput values reported here are identical to those in Table 3 (main text). Sample profile: nine participating firms (5 large, 4 medium); annual revenue €11–78 M; combined firm-level volume $\approx 61,600$ TEU/yr (volumes partly overlap along the chain, Section 3.1); modernization category: 3 digital-only, 6 combined.

Table A2. Hypothesis H1—paired pre-/post-modernization comparison of chain-level CO₂ intensity (E1, g CO₂e/TEU·km; $n = 9$).

	CO ₂ Intensity (E1)
Pre-modernization, mean (SD)	62.8 (8.0)
Post-modernization, mean (SD)	51.9 (10.2)
Mean paired difference (95% bootstrap CI)	10.9 [8.1, 13.6]
Relative change (throughput-weighted)	−17.4% (−18.8%)
Shapiro–Wilk p (paired differences)	0.64
Paired-sample t -test	$t(8) = 7.40$
Exact p , two-tailed (Holm-adjusted)	7.6×10^{-5} (2.3×10^{-4})
Cohen’s d_z	2.47 (large)
Wilcoxon signed rank (exact)	$W = 0, p = 0.0039$
Decision	H1 supported

Table A3. Hypotheses H2a and H2b—paired pre-/post-modernization comparisons of terminal energy intensity (E2) and terminal dwell time (O1) ($n = 9$).

Statistic	Energy Intensity (E2, kWh/TEU)	Dwell Time (O1, h)
Pre-modernization, mean (SD)	8.4 (1.7)	38.6 (12.4)
Post-modernization, mean (SD)	7.2 (1.1)	29.9 (9.4)
Mean paired difference (95% CI)	1.2 [0.8, 1.6]	8.7 [6.7, 11.0]
Relative change (weighted)	−14.3% (−15.2%)	−22.5% (−22.2%)
Shapiro–Wilk p (differences)	0.59	0.56
Paired-sample t -test	$t(8) = 5.62$	$t(8) = 7.36$
Exact p (Holm-adjusted)	5.0×10^{-4} (5.0×10^{-4})	7.9×10^{-5} (1.6×10^{-4})
Cohen’s d_z	1.87 (large)	2.45 (large)
Wilcoxon signed-rank (exact)	$W = 0, p = 0.0039$	$W = 0, p = 0.0039$
Decision	H2a supported	H2b supported

Confidence intervals: percentile bootstrap over firms (10,000 resamples, random seed 42). Dwell time is the mean of firm-level median container dwell times. Exact two-tailed p -values from the paired t distribution; Holm adjustment across the three primary outcomes (E1, E2, O1). Cohen’s d_z = mean paired difference/SD of paired differences. The per-firm values underlying all statistics are given in Table 3 (main text). The summary statistics reported here are identical to those in Section 3.2.

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