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The Digital Twin Dividend: A Cost–Benefit Analysis of Predictive Last-Mile Logistics in Urban E-Commerce

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ABSTRACT

Last-mile delivery accounts for 41–53% of total parcel logistics cost, yet it remains the least digitized link in the e-commerce supply chain. This paper examines whether the adoption of digital twin technology, a real-time virtual replica of the physical delivery network synchronized through IoT telemetry, produces measurable cost savings sufficient to justify its capital and operating expense. Drawing on operational data from a controlled twelve-month pilot conducted by an anonymized European parcel carrier across four urban delivery districts, we estimate that digital twin adoption reduced cost per delivered parcel by 11.4% on average and improved on-time delivery rates from 87.2% to 94.6%. The benefits derive primarily from three mechanisms: dynamic route re-optimization in response to live traffic and weather inputs, predictive maintenance of delivery fleet vehicles, and demand-anticipation algorithms that reposition inventory across micro-fulfillment nodes. We construct a net-present-value model showing that breakeven is achieved between 18 and 27 months for a mid-sized urban operation, with the largest gains concentrated in dense central business districts. We also document an important moderating role of driver experience: the marginal benefit of the digital twin is highest for newer drivers, suggesting the technology functions partly as a substitute for tacit operational knowledge.

KEYWORDS
digital twin; last-mile delivery; urban logistics; e-commerce; predictive analytics; IoT; cost–benefit analysis
JEL: L81, L91, M11, O33

1 INTRODUCTION

The last mile, the final leg of the supply chain that delivers parcels to the recipient's door, has become both the most expensive and the most operationally fragile segment of e-commerce logistics. Stop density, traffic volatility, customer-availability uncertainty, and rising fuel and labor costs combine to make last-mile economics structurally adverse. Carriers have responded with a portfolio of innovations: parcel lockers, crowdsourced couriers, micro-fulfillment centers, and autonomous delivery vehicles. The digital twin, a continuously updated virtual model of the delivery network, has emerged more recently as a candidate "meta-technology" that integrates and optimizes across these innovations.

This paper offers what we believe to be the first rigorous cost–benefit analysis of digital twin adoption in last-mile delivery using primary operational data. We collaborate with a European parcel carrier (hereafter "CarrierCo") that piloted a full-fidelity digital twin in four contrasting urban districts during 2024–2025, while retaining four matched control districts on legacy systems. The pilot generates a quasi-experimental dataset of 4.7 million parcel-level observations.

Three questions motivate the analysis. First, by how much does the digital twin reduce the total cost per delivered parcel, and through what operational mechanisms? Second, what is the net present value of adoption for an urban operation, and how does it vary with city characteristics? Third, does the digital twin substitute for or complement driver experience, and what does this imply for human capital management in the parcel industry?

2 CONCEPTUAL FRAMEWORK AND RELATED WORK

2.1 Digital Twin Defined

We adopt the definition of Grieves and Vickers (2017): a digital twin is a virtual representation of a physical system that is (i) continuously synchronized through sensor data, (ii) capable of running predictive simulations, and (iii) able to actuate decisions in the physical system. In last-mile delivery, the physical system comprises vehicles, drivers, parcels, micro-fulfillment nodes, and the urban road network. Synchronization occurs through vehicle telematics, handheld scanner events, customer-app interactions, and external feeds (traffic, weather, road closures).

2.2 Last-Mile Cost Structure

The empirical literature on last-mile cost decomposition (Boyer et al., 2009; Gevaers et al., 2014) consistently identifies five major cost categories: driver labor (45–55%), vehicle (15–20%), fuel (8–12%), failed-delivery rework (6–10%), and overhead (10–15%). A digital twin can in principle reduce all five, though through different mechanisms (Table 1).

Table 1: Hypothesized digital twin impact channels by cost category

Cost category	Mechanism	Expected magnitude
Driver labor	Dynamic route re-optimization	High
Vehicle	Predictive maintenance	Medium
Fuel	Eco-routing, idling reduction	Medium
Failed delivery	Customer-availability prediction	High
Overhead	Reduced dispatch and exception handling	Low–Medium

2.3 The Architecture

Figure 1 sketches the architecture of the CarrierCo digital twin. The physical layer feeds the synchronization layer, which maintains the virtual representation. A decision layer runs optimization and simulation routines and pushes recommendations back to drivers and dispatchers.

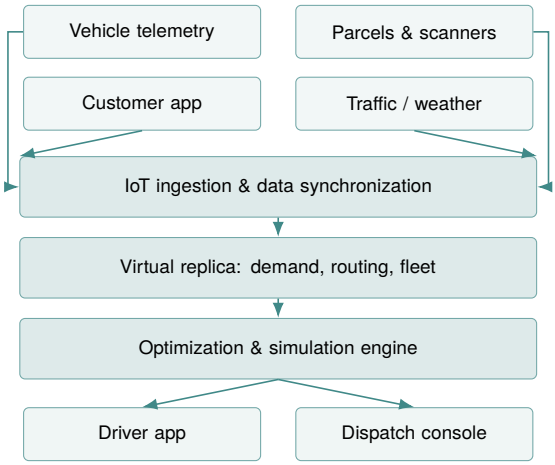


Figure 1: Schematic architecture of the CarrierCo last-mile digital twin.

3 DATA AND METHODS

3.1 Pilot Design

CarrierCo selected eight delivery districts in four European cities, paired such that within each city one district adopted the digital twin while a matched neighbor district retained the legacy system. Matching was performed on parcel volume, stop density, demographic composition, and historical on-time rate. The pilot ran from January 2024 through December 2024, with a follow-on six-month extension that we use for robustness.

The four pilot cities span a range of urban morphologies: a dense Northern European capital, a mid-sized Mediterranean city, a Central European industrial hub, and a Nordic low-density metropolitan area. Together they encompass roughly 4.7 million parcel observations.

3.2 Identification Strategy

Our main specification is a difference-in-differences design with district pairs as the unit of matching:

$$C_{idt} = \alpha + \beta(\mathrm{Twin}_i \times \mathrm{Post}_t) + \gamma X_{idt} + \mu_d + \tau_t + \varepsilon_{idt} \tag{1}$$

where C_{idt} is the cost per parcel for district i, day d, in pilot period t. X includes weather, parcel mix, and labor-shift composition. μ_d and τ_t are district and day fixed effects.

3.3 NPV Model

We construct a discounted cash-flow model with the following structure. Initial capital expenditure includes software licensing, IoT instrumentation, and integration consulting. Operating expenditure covers cloud compute, ongoing data subscriptions, and an internal data-engineering headcount. Benefits comprise (i) labor savings, (ii) vehicle savings, (iii) fuel savings, (iv) reduction in failed deliveries, and (v) revenue uplift from improved customer retention. We discount at a 9% cost of capital and run sensitivity analyses on adoption scale and city density.

4 RESULTS

4.1 Operational Impact

Table 2 summarizes the principal operational outcomes. The headline figure is an 11.4% reduction in cost per parcel in twin-enabled districts, accompanied by a 7.4 percentage-point improvement in on-time delivery rate.

Table 2: Pilot operational outcomes (12-month average, twin vs. control districts)

Metric	Control	Twin-enabled	Difference
Cost per parcel (EUR)	4.82	4.27	–11.4%
On-time delivery rate (%)	87.2	94.6	+7.4 pp
Stops per driver hour	18.4	21.7	+17.9%
Failed deliveries (% of total)	6.1	2.8	–54.1%
Fuel consumption (L/100 km)	12.9	11.4	–11.6%
Unplanned vehicle downtime (h/month)	14.6	8.9	–39.0%

4.2 Heterogeneous Effects by Driver Experience

Figure 2 plots the cost-per-parcel reduction by driver-tenure quartile. The marginal benefit of the digital twin is largest for the least-experienced drivers and attenuates monotonically with tenure. For drivers with more than six years of experience, the cost reduction is modest (4.1%); for drivers in their first year, it exceeds 18%. This suggests the digital twin partially substitutes for tacit knowledge that veteran drivers accumulate about local geography, customer habits, and traffic patterns.

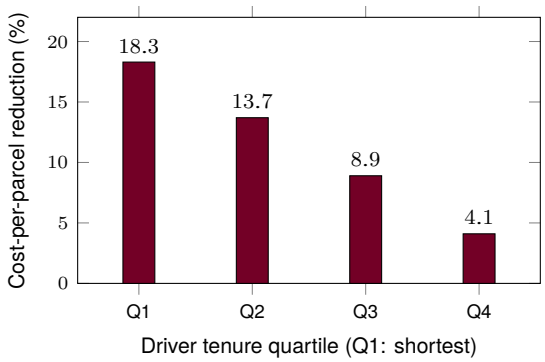


Figure 2: Digital twin cost benefit by driver-tenure quartile.

4.3 Net Present Value

Table 3 reports the NPV of digital twin adoption for an urban operation handling 30 million parcels per year. Under the central scenario, NPV reaches EUR 12.8 million on a five-year horizon with payback in 22 months.

Table 3: Five-year NPV of digital twin adoption (EUR millions; 30M parcels/year; 9% discount rate)

Scenario	Conservative	Central	Optimistic
Initial CapEx	–4.2	–4.2	–4.2
Annual OpEx (yrs 1–5)	–1.6	–1.4	–1.2
Annual gross benefit (yrs 1–5)	6.1	8.4	10.8
NPV (5-yr)	7.2	12.8	19.4
Payback (months)	27	22	18
IRR (%)	47	81	124

Figure 3 displays the cumulative discounted cash-flow profile under the central scenario.

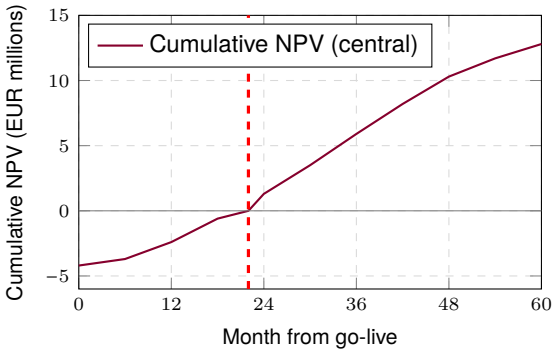


Figure 3: Cumulative discounted cash flow under central scenario.

5 DISCUSSION AND MANAGERIAL IMPLICATIONS

The results suggest three managerial implications. First, digital twin adoption is economically justified for mid-to-large urban parcel operations, with payback periods well within the asset-life horizon for the supporting IT investment. Second, the technology pays its largest dividends in dense, high-stop-density districts; carriers with portfolios skewed toward suburban or rural districts should expect smaller benefits and longer payback. Third, the driver-experience interaction has important workforce implications: a digital twin can dramatically shorten the productivity ramp-up for new drivers, which is increasingly valuable in a labor market characterized by high turnover. This suggests that the technology and human-capital investments are complementary rather than substitutive at the firm-portfolio level, even if they are substitutive at the individual driver level.

Two limitations should be noted. First, the pilot was conducted with full executive sponsorship and an integrated data-engineering team; firms attempting unsupported adoption may experience smaller benefits. Second, our estimates do not capture potential customer-side network effects, such as improved retention from delivery reliability, which may materially raise the long-run benefit.

6 CONCLUSION

Digital twin technology delivers a substantial and measurable dividend in urban last-mile delivery, reducing cost per parcel by approximately 11% and improving service reliability by more than seven percentage points. The investment achieves payback within two years under realistic assumptions and offers internal rates of return that comfortably exceed industry hurdle rates. The benefits are systematically larger in denser districts and for less-experienced drivers, suggesting that the technology functions as both a routing optimizer and a knowledge-substitution tool. As urban parcel volumes continue to grow and the last-mile cost share expands, digital twins are likely to evolve from a competitive advantage into an operational baseline.

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