An Integrated Information System for Parcel Tracking and Last-Mile Delivery Efficiency in National Postal Operators

JURAEV NURMAKHAMAD[1],* NABIYEVA ZIYODAKHON[2]

[1] Associate Professor, Department of Telecommunication Engineering, Fergana State Technical University, Fergana, Republic of Uzbekistan
e-mail: nmjuraev61@gmail.com

[2] Student (group 670-24), Postal Communication Technologies, Faculty of Information Technologies and Telecommunications, Fergana State Technical University, Fergana, Republic of Uzbekistan
e-mail: zydnxnnbyva1213m@gmail.com

*Corresponding author

Abstract. *Electronic commerce is changing the operating model of national postal operators: parcel volumes are rising, customers expect event-level visibility, and last-mile delivery remains the most expensive and least efficient stage of the logistics chain. In many operators of developing countries, however, acceptance, sorting, transport and delivery are still supported by separate information systems, so that tracking data are delayed, duplicated or lost. This paper proposes and evaluates an integrated information system for parcel tracking and last-mile delivery planning. Following a design science research approach, the study (i) analyzes the as-is parcel workflow and identifies six information gaps, (ii) designs a four-layer target architecture comprising data capture, an integration and tracking database, a route planning module and a customer service layer, (iii) defines five key performance indicators and a before-and-after evaluation protocol, and (iv) demonstrates the planning and data-capture components in a computational experiment on 90 synthetic delivery instances representing urban, suburban and rural districts. Relative to a sector-based nearest-neighbour baseline that mimics manual courier sequencing, route improvement reduced total travel distance by 12.4–14.1%, and a savings-based assignment combined with 2-opt improvement achieved reductions of 16.6% and 18.2% in suburban and rural districts. Real-time event transmission with offline buffering reduced mean tracking-event latency from about 60 min under two-hour batch synchronization to 0.2 min in urban and 6.2 min in rural conditions. The results indicate that substantial efficiency gains are attainable with low-cost, open algorithms, while confirmation of service-level effects requires a field pilot using the proposed evaluation protocol. The framework is intended for postal operators undergoing digital transformation with limited information technology resources.*

Key words. *e-commerce, information system, last-mile delivery, parcel tracking, postal logistics, route optimization, design science, vehicle routing*

Introduction

Postal services worldwide are moving from letter-based operations to parcel-oriented logistics driven by online commerce. Letter mail volumes have been declining for more than a decade, while domestic and cross-border parcel flows have grown and now account for a rising share of postal revenue [1]. This shift changes both the volume and the nature of service requirements placed on postal networks: customers now expect accurate delivery windows, event-level tracking from acceptance to hand-over, and flexible options such as redirection, pick-up points or parcel lockers. At the same time, last-mile delivery is widely recognized as one of the most expensive, least efficient and most polluting parts of the supply chain, accounting for a large share of total logistics cost [2], [3].

The pressure is particularly visible in urban areas, where the growth of business-to-consumer deliveries has increased the number of light goods vehicle trips, failed delivery attempts and repeat visits [4], [5]. City logistics research has shown that fragmented, low-density delivery patterns, narrow time windows and customer absence are the main drivers of high last-mile costs [6]. Universal-service postal operators face these challenges under additional constraints: they must serve the entire national territory at uniform tariffs, handle mixed flows of letters, small packets and parcels in the same network, and modernize while operating legacy infrastructure.

In many national postal operators, including those of Central Asian countries, tracking data are fragmented across separate systems for acceptance, sorting, transport and delivery. Events are frequently recorded on paper or in local databases and uploaded to the central system in batches at the end of a shift. This practice causes delayed status updates, duplicated data entry, inconsistencies between systems and limited ability to plan courier routes using current information. Courier routes are usually fixed by postal sector and sequenced by the experience of individual couriers, so the potential of route optimization and customer notification remains unused.

The aim of this study is to design an integrated information system that unifies these data flows and to define and demonstrate a measurable framework for assessing its effect on delivery efficiency. The study addresses three research questions: (RQ1) Which functional components and data flows are required for an integrated parcel tracking and delivery planning system in a national postal operator? (RQ2) Which indicators reflect the operational and service impact of such a system, and how should they be measured? (RQ3) What magnitude of improvement in route efficiency and tracking-event latency can be expected from the planning and data-capture components under typical urban, suburban and rural conditions?

The contribution of the paper is threefold. First, it provides a four-layer reference architecture that can be implemented incrementally with limited information technology resources. Second, it specifies a set of five key performance indicators with explicit definitions and a before-and-after evaluation protocol. Third, it reports a reproducible computational experiment that quantifies the expected gains of the planning and data-capture components and thereby provides a benchmark for future field pilots. The remainder of the paper is organized as follows: the next section reviews related work, followed by the materials and methods, the results, their discussion and the conclusions.

Literature Review

A. Last-mile delivery concepts

Research on last-mile logistics addresses

delivery concepts, urban logistics innovation and operational planning. Gevaers et al. describe the characteristics and typology of last-mile logistics from an innovation perspective and identify customer service level, security, geographical area, market density and fleet type as the main cost drivers [2]. Boysen et al. survey last-mile delivery concepts from an operational research point of view, including crowdsourced delivery, parcel lockers, mobile depots and drone-based options, and discuss the planning problems associated with each concept [3]. Systematic reviews by Olsson et al. [7] and Mangiaracina et al. [8] classify the field into themes such as delivery modes, technology, efficiency improvement and sustainability, and conclude that information-driven solutions, including tracking, customer communication and route optimization, are among the most effective levers for business-to-consumer delivery efficiency. Lim et al. [9] propose a design framework that links consumer requirements to last-mile distribution structures and emphasize the role of information visibility.

Several studies examine alternatives to attended home delivery. Punakivi et al. show that unattended reception boxes and delivery boxes can reduce home-delivery costs substantially by removing time-window constraints [10]. Iwan et al. analyze parcel locker efficiency in Poland and find high utilization and customer acceptance [11], while Song et al. quantify the transport impacts of collection and delivery points [12]. Morganti et al. document the rapid growth of pick-up point networks in France and Germany as a response to failed home deliveries [5]. These concepts depend on reliable tracking and notification, since customers must be informed when and where a parcel can be collected.

B. Route planning

Route planning for delivery fleets traces back to the vehicle routing problem (VRP) introduced by Dantzig and Ramser [13]. Clarke and Wright proposed the savings heuristic, which remains one of the most widely used constructive methods because of its simplicity and good solution quality [14]. Gillett and Miller introduced the sweep algorithm, which partitions customers into angular sectors around a depot [15], a logic that closely corresponds to the fixed postal-sector organization of courier work. Local improvement procedures such as 2-opt [16] are commonly used to refine routes. The VRP has since been extended with time windows [17], capacity limits and heterogeneous fleets [18], and dynamic and stochastic demand, in which new requests and real-time information are incorporated during execution [19]. These extensions are directly relevant to postal operations, but their practical use requires timely and accurate data on parcels, addresses and courier positions.

C. Tracking technologies and information systems

Studies on tracking technologies emphasize the role of barcodes, radio-frequency identification (RFID) and Internet of Things (IoT) sensing in providing real-time visibility across supply chains [20], [21]. Barcode scanning with mobile devices remains the dominant and most cost-effective technology in postal networks, whereas RFID is used selectively for containers and quality-of-service measurement. The success of such systems depends not only on technology but also on information quality, system quality and user acceptance, as described by the DeLone and McLean information systems success model [22].

D. Research gap

Much of the literature focuses on private express and courier companies operating in dense urban markets with modern information technology. The conditions of universal-service

postal operators in developing countries, such as nationwide geographic coverage, a high share of rural delivery, mixed mail and parcel flows, legacy infrastructure, intermittent mobile network coverage and limited budgets, receive considerably less attention. In addition, few studies combine an implementable system architecture with an explicit evaluation framework and a quantitative estimate of expected benefits. The present study addresses this gap.

Materials and Methods

A. Research design

The study follows the design science research methodology for information systems [23], [24], which is appropriate when the goal is to create and evaluate an artifact that solves an identified organizational problem. The process consists of four stages: (1) problem identification through analysis of the current (as-is) parcel processing workflow from acceptance to delivery; (2) definition of design objectives derived from the identified information gaps; (3) design of the target information system architecture; and (4) demonstration and evaluation, comprising a computational experiment for the planning and data-capture components and a before-and-after field evaluation protocol for the full system.

B. As-is workflow analysis

The as-is workflow was modeled as a sequence of five process stages: acceptance at the post office counter, transport to the regional sorting center, sorting, line-haul transport to the delivery office, and last-mile delivery. For each stage, the information recorded, the recording medium, the transmission method and the users of the information were identified. Information gaps were defined as points at which data are not captured, captured manually, transmitted with delay or not available to the next stage or to the customer. The identified gaps are summarized in Table I and serve as design objectives for the target system.

Table 1. Information Gaps in the As-Is Parcel Workflow and Design Responses

Stage	Information gap	Design response
Acceptance	Manual entry of sender and addressee data; no unique identifier for domestic parcels	Barcode label with unique parcel identifier generated at acceptance
Transport	Container dispatch not linked to parcel records	Container-to-parcel association scan at dispatch and arrival
Sorting	Events uploaded in end-of-shift batches	Real-time event interface to central database
Delivery office	Courier routes fixed by sector and sequenced manually	Daily route planning module
Delivery	Delivery attempts recorded on paper; failures not reported	Mobile courier application with offline event queue
Customer	No proactive information on delivery time	Notification service with expected delivery time

C. Target system architecture

The proposed system has four layers, shown in Fig. 1:

Data capture layer: barcode or RFID scanners at counters, sorting centers and transport hubs, and a mobile courier application used at delivery. Each scan generates an event containing the parcel identifier, event code, location code, operator identifier and timestamp. The mobile application stores events in a local queue when the network is unavailable and transmits them automatically when connectivity is restored (store-and-forward).

Integration and database layer: a central tracking database that receives events through a standardized application programming interface, validates them against master data (offices, operators, event codes), and maintains a timestamped status history for each unique parcel identifier. Legacy systems are connected through adapters rather than replaced.

Planning layer: a route optimization module that assigns parcels ready for delivery to couriers and sequences each route using delivery addresses, vehicle capacity and, where available, customer time windows. A savings-based construction heuristic [14] followed by 2-

opt improvement [16] was selected because it is fast, transparent and implementable with open-source tools.

Service layer: a customer portal and text-message or messenger notification service that shows parcel status, informs the addressee of the expected delivery day and time window, and allows the customer to request redirection to a pick-up point.

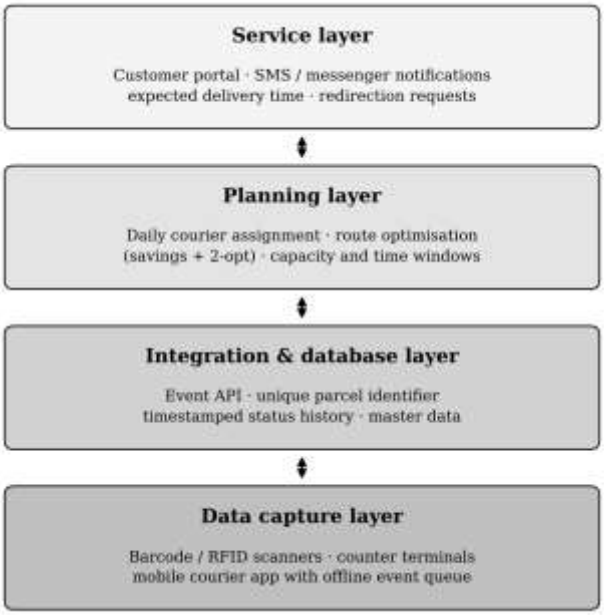


Fig. 1. Four-layer architecture of the integrated parcel tracking and delivery planning system.

D. Performance indicators and evaluation protocol

Evaluation of the full system uses five key performance indicators, listed in Table II: on-time delivery rate, first-attempt delivery success rate, cost per delivered parcel, tracking-event latency and complaint rate per 1,000 parcels. The indicators cover efficiency (cost), service quality (on-time and first-attempt delivery), information quality (latency) and customer outcome (complaints), in line with the dimensions of information systems success [22].

TABLE II
PERFORMANCE INDICATORS FOR SYSTEM EVALUATION

Indicator	Definition	Unit
On-time delivery rate	Parcels delivered within promised time / all delivered parcels	%
First-attempt success	Parcels delivered on first attempt / all delivered parcels	%
Cost per parcel	Total delivery cost / delivered parcels	currency
Event latency	Time between physical scan and system update	min
Complaint rate	Complaints per 1,000 parcels	count

The field evaluation protocol compares a baseline period of at least eight weeks before implementation with an equal period after a stabilization phase of four weeks in the same delivery offices. To control for seasonal effects and volume changes, a difference-in-differences design with comparable control offices that do not receive the system is recommended. Indicators are computed weekly from the tracking database, cost records and the complaint register, and differences are tested with appropriate statistical tests at the 5% significance level.

E. Computational experiment

Because field data were not yet available, the planning and data-capture components were demonstrated in a computational experiment on synthetic instances. Three district types were generated: an urban district with 160 delivery points uniformly distributed over an 8 × 8 km area; a suburban district with 120 points grouped around three settlements in a 15 × 15 km area; and a rural district with 70 points grouped around six villages in a 30 × 30 km area. In each case the delivery office was located at the center of the area. Thirty random instances were generated per district type (90 in total). Road distances were approximated by Euclidean distances multiplied by a detour factor of 1.3, vehicle capacity was 40 parcels per route, average speeds were 20, 30 and 45 km/h, and the service time was 4 min per stop.

Three planning methods were compared. The baseline (B0) reproduces current practice: delivery points are divided into equal angular

sectors around the office, one per courier, and each courier visits the nearest unvisited address next (nearest-neighbour rule). Method B1 keeps the sectors but improves each route with 2-opt, isolating the effect of sequencing. The proposed method (P) assigns parcels to routes with the Clarke–Wright savings heuristic under the capacity constraint and improves each route with 2-opt, thus optimizing both assignment and sequencing. Total route length and the duration of the longest route were recorded.

Tracking-event latency was simulated for 20,000 scan events uniformly distributed over a working day from 08:00 to 18:00 under three transmission modes: end-of-shift upload at 18:30, batch synchronization every two hours, and real-time transmission with an offline queue. For real-time transmission, mobile network availability was set to 97% with a mean outage duration of 5 min in urban areas and to 80% with a mean outage duration of 30 min in rural areas, with exponentially distributed outages. All computations were performed in Python with fixed random seeds to ensure reproducibility.

Results

A. Route efficiency

Table III and Fig. 2 summarize the route planning results. In all three district types both improved methods reduced total route length compared with the baseline. Improving the sequence within fixed sectors (B1) reduced travel distance by 14.1% in the urban, 13.3% in the suburban and 12.4% in the rural district. The proposed savings-based method (P) achieved the largest reductions in the suburban (16.6%) and rural (18.2%) districts, where delivery points are clustered and fixed angular sectors often split a settlement between couriers or combine distant villages in one route. In the urban district with uniformly distributed addresses, the proposed method reduced distance by 12.9%, slightly less than B1, and used on average 4.2 instead of 4.0 routes.

TABLE III
Route Planning Results (Mean ± SD Over 30 Instances)

Indicator	Urban	Suburban	Rural
B0 total length, km	139.9 ± 6.7	112.2 ± 18.2	192.7 ± 28.3
B1 total length, km	119.9 ± 3.3	97.5 ± 17.4	168.8 ± 26.2
P total length, km	121.7 ± 4.0	93.4 ± 14.3	157.2 ± 21.6
Reduction B1 vs B0, %	14.1 ± 3.2	13.3 ± 3.5	12.4 ± 4.2
Reduction P vs B0, %	12.9 ± 3.4	16.6 ± 4.2	18.2 ± 5.2
Routes B0 / P	4.0 / 4.2	3.0 / 3.3	2.0 / 2.0
Longest route B0 / P, min	276 / 261	247 / 225	281 / 270

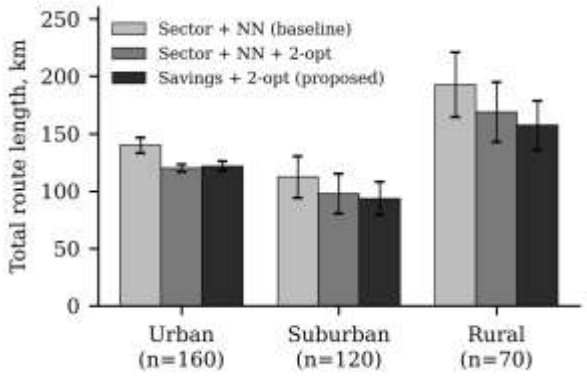


Fig. 2. Total route length by district type and planning method (mean ± SD, 30 instances each).

The duration of the longest route, which determines when the last parcel of the day is delivered, decreased from 276 to 261 min in the urban, from 247 to 225 min in the suburban and from 281 to 270 min in the rural district under the proposed method. All routes remained within an eight-hour working day.

B. Tracking-event latency

Table IV presents the simulated tracking-event latency. With end-of-shift upload, the mean latency was about 5.5 h and no event reached the central database within 15 min. Two-hour batch synchronization reduced the mean latency to about 60 min, but only 12.5% of events were available within 15 min. Real-time transmission with an offline queue reduced

the mean latency to 0.2 min in urban conditions, with 99.9% of events available within 15 min. Under rural network conditions the mean latency was 6.2 min and the 95th percentile 42.5 min, and 87.5% of events were available within 15 min.

TABLE IV
SIMULATED TRACKING-EVENT LATENCY BY TRANSMISSION MODE

Mode / area	Mean, min	95th pct., min	≤ 15 min, %
End-of-shift upload	329.5	598.8	0.0
Batch every 2 h	59.9	114.0	12.5
Real-time, urban	0.2	< 0.1	99.9
Real-time, rural	6.2	42.5	87.5

[Field pilot results to be inserted: baseline and post-implementation values of the five indicators in Table II for the pilot and control delivery offices, presented in a table and interpreted according to the evaluation protocol described in the Materials and Methods section.]

Discussion

With respect to RQ1, the as-is analysis shows that the main weaknesses of the current workflow are informational rather than physical: parcels are moved and delivered, but the corresponding events are captured late, incompletely or not at all, and the information that exists is not used for planning. The proposed architecture addresses these gaps by establishing a single parcel identifier from acceptance, a single event store, and two consumers of the event data, the planning module and the customer service layer. Its layered structure allows an operator to implement the system incrementally, starting with data capture and the central database, which deliver value on their own, and adding planning and notification functions afterwards.

With respect to RQ3, the computational experiment indicates that a large share of the achievable distance savings comes from improving the sequence of stops within existing sectors, which requires no change to the organization of courier work and can therefore be introduced first. Changing the assignment of parcels to couriers adds further savings mainly where delivery points are clustered, which is typical of suburban and rural postal districts. In uniformly dense urban areas, fixed sectors are already close to efficient, and the savings heuristic, which does not limit the number of routes, may open an additional route. This suggests that the planning module should allow the fleet size to be fixed and should combine sector-based and optimization-based assignment depending on the district type. The magnitude of the savings, 12–18%, is consistent with the efficiency potential of information-driven solutions reported in the literature [7], [8]. Because vehicle cost and courier time are largely proportional to distance and route duration, savings of this order translate directly into lower cost per delivered parcel or higher delivery capacity with the same fleet.

The latency results show that the transmission mode matters more than network quality. Even under rural conditions with 20% network unavailability, real-time transmission with an offline queue reduced mean latency by roughly an order of magnitude compared with two-hour batches. Low latency is a precondition for accurate customer notifications, for dynamic re-planning [19] and for alternative delivery options such as redirection to parcel lockers or pick-up points [10]–[12], all of which aim to reduce failed first attempts. The effect on first-attempt success and complaints, however, depends on customer behavior and cannot be estimated from simulation; it must be measured in the field using the indicators in Table II, which addresses RQ2.

The study has several limitations. First, the experiment used synthetic instances with Euclidean distances and a uniform detour factor; real street networks, one-way streets and

access restrictions may change the absolute values, although the relative ranking of methods is expected to be robust. Second, time windows, heterogeneous vehicles and parcel volume or weight were not modeled. Third, the latency model assumes independent exponential outages and does not include device failures or human delays in scanning. Fourth, the success of the system depends on data quality at scanning points, address quality and staff training [22]; in many districts, incomplete or informal addresses will require geocoding support or courier-confirmed coordinates. Finally, costs of implementation, devices and connectivity were not assessed and should be included in a cost-benefit analysis during the pilot.

Conclusion

This paper presented an integrated information system architecture and evaluation framework for parcel tracking and last-mile delivery in national postal operators. Based on an analysis of the as-is workflow, which identified six information gaps, the approach connects data capture, a unified tracking database, route planning and customer notification in one workflow. Five key performance indicators and a before-and-after evaluation protocol with control offices were defined. A computational experiment on 90 synthetic instances showed that route sequencing alone can reduce travel distance by 12–14% and that optimization of courier assignment can raise the reduction to 17–18% in suburban and rural districts, while real-time event transmission with offline buffering reduces tracking-event latency from about one hour to minutes even under weak network coverage.

The results suggest that national postal operators with limited resources can obtain substantial efficiency and transparency gains by using standard barcode technology, a central event database and open, well-established routing heuristics, and that implementation can proceed incrementally. Future research should test the system in a pilot region using the proposed protocol, use real street-network distances and time windows, extend route optimization with real-time traffic data and dynamic re-planning, and evaluate parcel lockers and pick-up points as additional delivery options within the same information system.

References

[1] Universal Postal Union, "State of the postal sector 2023," Berne, Switzerland: UPU, 2023.

[2] R. Gevaers, E. Van de Voorde, and T. Vanelslander, "Characteristics and typology of last-mile logistics from an innovation perspective in an urban context," in City Distribution and Urban Freight Transport. Cheltenham, U.K.: Edward Elgar, 2011, pp. 56-71.

[3] N. Boysen, S. Fedtke, and S. Schwerdfeger, "Last-mile delivery concepts: a survey from an operational research perspective," OR Spectrum, vol. 43, pp. 1-58, 2021.

[4] J. Allen et al., "Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas: The case of London," Transportation Research Part D, vol. 61, pp. 325-338, 2018.

[5] E. Morganti, S. Seidel, C. Blanquart, L. Dablanc, and B. Lenz, "The impact of e-commerce on final deliveries: alternative parcel delivery services in France and Germany," Transportation Research Procedia, vol. 4, pp. 178-190, 2014.

[6] M. Savelsbergh and T. Van Woensel, "50th anniversary invited article—City logistics: Challenges and opportunities," Transportation Science, vol. 50, no. 2, pp. 579-590, 2016.

[7] J. Olsson, D. Hellström, and H. Pålsson, "Framework of last mile logistics research: A systematic review of the literature," Sustainability, vol. 11, no. 24, Art. no. 7131, 2019.

[8] R. Mangiaracina, A. Perego, A. Seghezzi, and A. Tumino, "Innovative solutions to increase last-mile delivery efficiency in B2C e-commerce: a literature review," International Journal of Physical Distribution & Logistics Management, vol. 49, no. 9, pp. 901-920, 2019.

[9] S. F. W. T. Lim, X. Jin, and J. S. Srai, "Consumer-driven e-commerce: A literature review, design framework, and research agenda on last-mile logistics models," International Journal of Physical Distribution & Logistics Management, vol. 48, no. 3, pp. 308-332, 2018.

[10] T. Punakivi, H. Yrjölä, and J. Holmström, "Solving the last mile issue: reception box or delivery box?," International Journal of Physical Distribution & Logistics Management, vol. 31, no. 6, pp. 427-439, 2001.

[11] S. Iwan, K. Kijewska, and J. Lemke, "Analysis of parcel lockers' efficiency as the last mile delivery solution – the results of the research in Poland," Transportation Research Procedia, vol. 12, pp. 644-655, 2016.

[12] L. Song, T. Cherrett, F. McLeod, and W. Guan, "Addressing the last mile problem: transport impacts of collection and delivery points," Transportation Research Record, vol. 2097, pp. 9-18, 2009.

[13] G. B. Dantzig and J. H. Ramser, "The truck dispatching problem," Management Science, vol. 6, no. 1, pp. 80-91, 1959.

[14] G. Clarke and J. W. Wright, "Scheduling of vehicles from a central depot to a number of delivery points," Operations Research, vol. 12, no. 4, pp. 568-581, 1964.

[15] B. E. Gillett and L. R. Miller, "A heuristic algorithm for the vehicle-dispatch problem," Operations Research, vol. 22, no. 2, pp. 340-349,

1974.

[16] G. A. Croes, "A method for solving traveling-salesman problems," Operations Research, vol. 6, no. 6, pp. 791-812, 1958.

[17] M. M. Solomon, "Algorithms for the vehicle routing and scheduling problems with time window constraints," Operations Research, vol. 35, no. 2, pp. 254-265, 1987.

[18] P. Toth and D. Vigo, Eds., Vehicle Routing: Problems, Methods, and Applications, 2nd ed. Philadelphia, PA, USA: SIAM, 2014.

[19] V. Pillac, M. Gendreau, C. Guéret, and A. L. Medaglia, "A review of dynamic vehicle routing problems," European Journal of Operational Research, vol. 225, no. 1, pp. 1-11, 2013.

[20] A. Whitmore, A. Agarwal, and L. Da Xu, "The Internet of Things—A survey of topics and trends," Information Systems Frontiers, vol. 17, no. 2, pp. 261-274, 2015.

[21] X. Zhu, S. K. Mukhopadhyay, and H. Kurata, "A review of RFID technology and its managerial applications in different industries," Journal of Engineering and Technology Management, vol. 29, no. 1, pp. 152-167, 2012.

[22] W. H. DeLone and E. R. McLean, "The DeLone and McLean model of information systems success: A ten-year update," Journal of Management Information Systems, vol. 19, no. 4, pp. 9-30, 2003.

[23] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," MIS Quarterly, vol. 28, no. 1, pp. 75-105, 2004.

[24] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, "A design science research methodology for information systems research," Journal of Management Information Systems, vol. 24, no. 3, pp. 45-77, 2007.