



## Optimization of Last-Mile Logistics Operations in Saudi Megacities Using Data-Driven Decision Models

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### Abstract

Last-mile logistics in Saudi megacities such as Riyadh, Jeddah, and Dammam face unprecedented challenges driven by rapid urbanization, escalating e-commerce demand, extreme climatic conditions, and complex traffic dynamics. Traditional delivery systems struggle with inefficient routing, unpredictable demand fluctuations, inadequate capacity planning, and suboptimal service levels, resulting in elevated operational costs, delayed deliveries, and environmental concerns. This article examines the application of data-driven decision models to optimize last-mile logistics operations in Saudi urban contexts. Leveraging advanced routing algorithms, machine learning-based demand forecasting, dynamic capacity planning frameworks, and service-level optimization techniques, these models enable logistics providers to achieve significant improvements in cost efficiency, delivery time reliability, and customer satisfaction while reducing carbon emissions and traffic congestion. The integration of real-time traffic data, historical delivery patterns, customer preference profiles, and geospatial information facilitates adaptive decision-making that responds to urban mobility constraints and seasonal demand variations. Implementation considerations specific to Saudi megacities include infrastructure readiness, data quality assurance, regulatory compliance, and workforce capability development. Future directions emphasize integration with emerging smart city platforms, autonomous delivery technologies, and real-time adaptive logistics systems that leverage Internet of Things sensors, connected vehicle networks, and artificial intelligence-driven coordination mechanisms to create resilient and sustainable urban delivery ecosystems.

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### 1. Introduction

The rapid transformation of Saudi Arabia's urban landscape, driven by Vision 2030 initiatives and unprecedented economic diversification, has catalyzed exponential growth in e-commerce activities and consumer expectations for fast, reliable delivery services <sup>[1, 2]</sup>. Megacities including Riyadh, Jeddah, and Dammam have experienced substantial population growth, infrastructural expansion, and digital adoption, creating complex last-mile logistics environments characterized by high delivery density, diverse customer segments, and stringent service requirements <sup>[3, 4]</sup>. Last-mile delivery, defined as the final leg of the supply chain from distribution centers to end customers, represents the costliest and operationally challenging component of logistics networks, accounting for approximately forty to fifty percent of total supply chain costs <sup>[5, 6]</sup>.

Traditional last-mile delivery approaches in Saudi urban contexts rely heavily on manual route planning, static capacity allocation, and reactive operational adjustments, resulting in inefficiencies such as excessive vehicle kilometers traveled, prolonged delivery windows, suboptimal fleet utilization, and elevated fuel consumption <sup>[7, 8]</sup>.

These inefficiencies are exacerbated by unique regional characteristics including extreme summer temperatures exceeding forty-five degrees Celsius, traffic congestion during peak hours and religious observances, spatially dispersed residential developments, and cultural preferences for specific delivery time windows [9, 10]. Furthermore, the surge in online shopping during Ramadan, Eid periods, and promotional events creates dramatic demand spikes that conventional planning methods struggle to accommodate effectively [11, 12].

Data-driven decision models offer transformative potential for addressing these challenges through systematic integration of diverse data sources, advanced analytical techniques, and optimization algorithms that enhance routing efficiency, demand prediction accuracy, capacity allocation, and service quality [13, 14]. These models leverage historical delivery data, real-time traffic information, weather forecasts, customer behavior patterns, and geospatial characteristics to generate optimized delivery schedules, dynamic route assignments, and proactive resource deployment strategies [15, 16]. Machine learning algorithms enable continuous improvement through feedback mechanisms that adapt to changing urban conditions, customer preferences, and operational constraints [17, 18].

The implementation of data-driven logistics optimization aligns strategically with Saudi Arabia's smart city initiatives, which emphasize digital transformation, sustainability, and quality of life enhancement [19, 20]. Smart city platforms provide essential infrastructure for data collection, integration, and real-time information exchange among logistics stakeholders, traffic management systems, and municipal authorities [21, 22]. The convergence of logistics optimization with smart city ecosystems enables coordinated urban mobility management, reduced environmental impact, and improved citizen services [23, 24].

This article presents a comprehensive examination of data-driven decision models for optimizing last-mile logistics in Saudi megacities, addressing routing and scheduling, fleet optimization, capacity planning, service-level management, and sustainability considerations. The discussion encompasses data requirements, modeling methodologies, implementation strategies, contextual challenges, and future research directions relevant to Saudi urban logistics environments.

## 2. Last-Mile Logistics Challenges in Saudi Megacities

Saudi megacities present distinctive last-mile logistics challenges that differentiate them from urban environments in other global regions. The spatial configuration of cities such as Riyadh, which spans over seventeen hundred square kilometers with dispersed residential compounds and commercial districts, necessitates extensive travel distances and complex route networks [25, 26]. Urban sprawl patterns characteristic of Saudi development, featuring low-density residential areas interspersed with high-density commercial zones, create heterogeneous delivery densities that complicate efficient route planning and vehicle capacity utilization [27, 28].

Traffic congestion constitutes a critical impediment to delivery reliability and operational efficiency. Major arterial roads in Riyadh and Jeddah experience severe congestion during morning and evening peak periods, with average speeds declining below twenty kilometers per hour in central business districts [29, 30]. Religious observances, particularly

Friday prayers and daily prayer times, introduce predictable yet significant traffic flow variations that impact delivery time windows and route feasibility [31, 32]. Construction activities associated with megaprojects such as NEOM, the Red Sea Project, and Riyadh Metro expansion further contribute to dynamic traffic patterns and road network disruptions [33, 34].

Climatic conditions impose operational constraints that affect vehicle performance, delivery personnel productivity, and service quality. Summer temperatures frequently exceed forty-five degrees Celsius, necessitating temperature-controlled vehicles for certain product categories and limiting outdoor activity windows for delivery personnel [35, 36]. Dust storms and occasional flooding events during winter months create unpredictable service disruptions that require contingency planning and flexible resource allocation [37, 38]. Customer expectations in Saudi markets reflect cultural preferences and evolving service standards influenced by global e-commerce platforms. Preferences for specific delivery time windows, often concentrated in evening hours to accommodate work schedules and family routines, create temporal demand concentration that challenges capacity planning [39, 40]. The prevalence of residential compounds with centralized reception areas versus individual villa deliveries introduces variability in delivery procedures and time requirements [41]. The effectiveness of such integrated data platforms often depends on user adoption and system usability, where human-centered design has been shown to improve engagement and operational outcomes [42]. Furthermore, the increasing expectation for same-day and next-day delivery services, particularly in competitive retail segments, intensifies pressure on logistics providers to achieve rapid order fulfillment [43].

Seasonal demand fluctuations associated with Ramadan, Eid celebrations, and national promotional events such as the White Friday shopping period generate demand surges exceeding three hundred percent of baseline levels, requiring substantial capacity expansion and workforce augmentation. The unpredictability of precise timing for religious observances based on lunar calendar variations complicates advance planning and resource procurement.

Infrastructure limitations including incomplete address systems in certain neighborhoods, restricted access to gated communities, and limited availability of secure parcel delivery locations create operational friction and failed delivery attempts. The transition toward standardized addressing systems through national initiatives such as the National Address System represents progress, yet adoption remains incomplete across all urban areas.

## 3. Urban Demand Patterns and Delivery Network Characteristics

Understanding urban demand patterns constitutes a foundational requirement for effective last-mile logistics optimization in Saudi megacities. Demand exhibits spatial heterogeneity influenced by residential density, commercial activity concentration, socioeconomic characteristics, and proximity to retail centers. High-income neighborhoods typically generate higher per-capita parcel volumes with expectations for premium service levels, while commercial districts experience concentrated business-to-business delivery demands during specific operational windows. Temporal demand patterns display pronounced variations across multiple time scales. Intraday patterns show

concentration during evening hours between five and nine post meridiem, reflecting customer availability and cultural preferences. Day-of-week variations demonstrate increased weekend demand as consumers engage in leisure shopping activities, with Friday representing a distinct pattern due to religious observances. Monthly cycles correlate with salary payment schedules, typically concentrated around the beginning and middle of lunar months according to government and private sector payment practices.

Seasonal patterns exhibit extreme variability driven by religious calendars and cultural events. Ramadan generates sustained elevated demand for food, gifts, and household goods, with particularly intense activity during the final ten days preceding Eid al-Fitr. The Hajj season influences demand patterns in Jeddah and Makkah regions, creating logistical challenges associated with restricted access zones and population influx. Annual promotional events including White Friday, anniversary sales, and back-to-school periods create predictable yet substantial demand spikes requiring proactive capacity planning.

Delivery network characteristics in Saudi megacities reflect infrastructure development patterns and operational strategies adopted by logistics providers. Hub-and-spoke networks with strategically located distribution centers serve as primary models, with major facilities positioned in industrial zones on city peripheries to minimize land costs while maintaining accessibility to major highways. Micro-fulfillment centers and urban consolidation points represent emerging strategies for reducing last-mile distances and enabling faster delivery windows, particularly for high-demand product categories.

The prevalence of third-party logistics providers and crowdsourced delivery platforms introduces network complexity and coordination challenges. Multiple carriers often serve overlapping geographic areas, creating potential inefficiencies through redundant route coverage and missed consolidation opportunities. The emergence of platform-based models connecting independent drivers with delivery demand introduces flexibility but raises concerns regarding service quality consistency, driver training, and regulatory compliance.

Geographic information systems analysis reveals clustering patterns in delivery destinations that inform zone-based routing strategies and capacity allocation decisions. Commercial districts demonstrate tight clustering with high delivery densities, enabling efficient multi-stop routes with minimal inter-stop distances. Residential areas exhibit more dispersed patterns, particularly in villa compounds and low-density suburbs, necessitating longer travel times and lower stops per hour.

#### 4. Data Sources and Data Quality for Decision Modeling

Effective data-driven decision models require comprehensive, accurate, and timely data from diverse sources spanning operational systems, external platforms, and sensing infrastructure. Historical delivery data constitute the primary foundation, encompassing order details, delivery locations, time stamps, vehicle assignments, route trajectories, service times, and delivery outcomes. These data enable pattern recognition, performance benchmarking, and predictive model training essential for optimization algorithms.

Real-time traffic data sourced from municipal traffic management systems, connected vehicle networks, and

mobile navigation platforms provide critical inputs for dynamic routing and travel time estimation. Integration of traffic flow measurements, incident reports, road closure notifications, and congestion predictions enables adaptive route planning that responds to evolving urban mobility conditions. Collaboration with entities such as the Saudi Traffic Department and smart city operations centers facilitates access to authoritative traffic information.

Geospatial data including road network topology, address databases, points of interest, building footprints, and land use classifications support routing feasibility assessment and service area delineation. The National Address System provides standardized geocoding capabilities essential for precise delivery location identification, although data completeness and accuracy require continuous validation. Satellite imagery and street-level mapping data augment geospatial foundations, particularly for newly developed areas lacking comprehensive address coverage.

Weather and environmental data inform operational planning for extreme conditions. Temperature forecasts, dust storm predictions, and precipitation probabilities enable proactive scheduling adjustments, vehicle type selection, and personnel safety measures. Historical climate data support seasonal planning and long-term capacity investment decisions.

Customer profile data encompassing delivery preferences, time window specifications, contact information, and service history enable personalized delivery experiences and improve first-attempt success rates. Privacy-preserving data practices and compliance with personal data protection regulations represent essential considerations in customer data utilization.

Vehicle telemetry data from fleet management systems provide insights into vehicle location, speed, fuel consumption, maintenance status, and driver behavior. These data support performance monitoring, predictive maintenance scheduling, and driver coaching programs. Integration with vehicle sensors enables real-time visibility into delivery progress and facilitates dynamic re-optimization as conditions change.

Data quality challenges significantly impact model reliability and decision effectiveness. Incomplete address information, inconsistent geocoding accuracy, and temporal data gaps in traffic measurements introduce uncertainties that propagate through optimization algorithms. Data validation protocols, anomaly detection mechanisms, and data enrichment processes represent necessary investments for maintaining decision model integrity. Manual data correction processes, though resource-intensive, remain essential for addressing systematic errors and validating automated data processing outcomes.

Interoperability challenges arise from heterogeneous data formats, incompatible system interfaces, and fragmented data governance across organizational boundaries. Standardized data schemas, application programming interfaces, and data exchange protocols facilitate integration of diverse data sources into unified analytical platforms. Establishment of data quality metrics, monitoring dashboards, and continuous improvement processes ensures sustained data reliability over time.

#### 5. Data-Driven Decision Models for Routing and Scheduling

Routing and scheduling optimization represents the cornerstone application of data-driven decision models in

last-mile logistics, addressing the vehicle routing problem with time windows under capacity constraints, traffic dynamics, and service requirements. Classical formulations based on mixed-integer programming seek to minimize total travel distance or time while satisfying delivery time commitments and vehicle capacity limits. Advanced variants incorporate dynamic traffic conditions, stochastic travel times, and multiple delivery time window options to enhance real-world applicability.

Metaheuristic algorithms including genetic algorithms, simulated annealing, tabu search, and ant colony optimization provide practical solution approaches for large-scale routing problems that exceed computational tractability of exact methods. These algorithms generate high-quality solutions within acceptable computation times, enabling deployment in operational settings requiring rapid decision turnaround. Hybrid approaches combining metaheuristics with mathematical programming techniques leverage complementary strengths of both paradigms.

Machine learning models enhance routing optimization through improved travel time prediction, delivery duration estimation, and dynamic re-routing decisions. Neural networks trained on historical trajectory data learn complex relationships between route characteristics, traffic patterns, time of day, and actual travel times, outperforming traditional speed-based estimation methods. Random forest and gradient boosting models predict service times at delivery locations based on building characteristics, customer types, and historical service duration patterns.

Reinforcement learning frameworks enable adaptive routing strategies that learn optimal decision policies through interaction with the delivery environment. Deep reinforcement learning agents trained through simulation and real-world experience develop sophisticated routing heuristics that account for uncertain traffic conditions, customer availability, and operational disruptions. The ability to continuously improve performance through ongoing learning represents a significant advantage over static optimization approaches.

Cluster-first route-second methodologies provide scalable approaches for large delivery networks by decomposing the problem into geographic zone assignment followed by detailed route optimization within each zone. Clustering algorithms such as k-means, density-based spatial clustering, and hierarchical methods partition delivery locations into manageable groups aligned with vehicle capacities and driver territories. Subsequent route optimization within clusters employs specialized algorithms tailored to smaller problem instances.

Time window management strategies balance customer preferences with operational efficiency. Dynamic time window adjustment mechanisms incentivize customers to select delivery windows that align with efficient routing patterns through pricing differentiation or service enhancements. Soft time window formulations that permit controlled violations with penalty costs provide flexibility for achieving better overall routing efficiency while maintaining acceptable service levels.

Integration of routing optimization with warehouse order picking and staging processes enables coordinated supply chain execution. Route-optimized vehicle loading sequences reduce loading times and minimize delivery sequence disruptions caused by accessibility constraints within vehicles. Synchronized scheduling of order processing,

vehicle departure, and delivery execution ensures seamless operational flow.

## 6. Fleet Optimization, Capacity Planning, and Resource Allocation

Strategic fleet sizing and composition decisions determine long-term capital investments and operational flexibility. Optimization models balance acquisition costs, operational expenses, service level requirements, and demand variability to determine optimal fleet size and vehicle type mix. Consideration of heterogeneous vehicle types including vans, trucks, motorcycles, and potential future autonomous vehicles enables matching vehicle capabilities to delivery characteristics and urban mobility constraints.

Capacity planning addresses temporal demand variations across multiple planning horizons. Long-term capacity planning aligns fleet investments and facility developments with projected market growth and strategic expansion plans. Medium-term planning optimizes seasonal capacity adjustments for predictable demand fluctuations such as Ramadan and promotional periods through vehicle leasing, temporary workforce expansion, and partner network activation. Short-term planning focuses on daily resource allocation, shift scheduling, and dynamic capacity redeployment in response to actual demand realizations.

Stochastic optimization approaches account for demand uncertainty through scenario-based planning and robust optimization frameworks. Scenario trees representing alternative demand realizations inform capacity decisions that perform well across diverse potential outcomes. Robust optimization formulations identify solutions that maintain feasibility and acceptable performance under worst-case scenarios within specified uncertainty sets.

Workforce planning integrates driver scheduling, shift assignment, and workload balancing with vehicle routing decisions. Consideration of labor regulations, driver preferences, skill requirements, and fatigue management constraints ensures socially sustainable and legally compliant workforce utilization. Driver performance metrics including delivery completion rates, customer interaction quality, and safety records inform assignment decisions and training priorities.

Crowdsourced capacity represents an emerging resource that introduces flexibility but requires careful integration with core fleet operations. Optimization models determine optimal mix of owned fleet and crowdsourced drivers based on cost structures, service quality requirements, and demand variability characteristics. Dynamic surge pricing and incentive mechanisms attract crowdsourced capacity during peak demand periods while managing quality consistency.

Resource pooling and collaborative logistics strategies enable efficiency gains through shared vehicle utilization and consolidated deliveries among multiple retailers or logistics providers. Optimization frameworks for collaborative networks address partner selection, revenue sharing, route collaboration, and information exchange while respecting competitive sensitivities. Implementation challenges include trust development, contract structuring, and technology platform integration.

Facility location optimization determines strategic placement of distribution centers, cross-dock facilities, and micro-fulfillment centers to minimize last-mile distances while managing facility costs and operational constraints. Location-allocation models evaluate trade-offs between

proximity to customers, land availability, labor market access, and transportation network connectivity. Dynamic facility planning incorporates urban development forecasts and evolving demand patterns to ensure long-term network resilience.

### 7. Service-Level Optimization and Customer-Centric Delivery Strategies

Service-level optimization balances operational efficiency with customer experience objectives through thoughtful design of delivery options, communication protocols, and performance guarantees. Multi-echelon service portfolios offering differentiated delivery speeds, time window precision, and value-added services enable customer choice while optimizing resource utilization. Premium same-day services cater to urgent needs and high-value customers, while economy multi-day options provide cost-effective alternatives for price-sensitive segments.

Dynamic delivery time window assignment algorithms optimize the match between customer preferences and operational feasibility. Prediction models estimate customer acceptance probabilities for alternative time windows based on historical choice behavior, order characteristics, and contextual factors. Optimization algorithms select time window offerings that maximize customer satisfaction while maintaining routing efficiency and resource utilization.

Failed delivery management strategies minimize the operational and customer satisfaction costs of unsuccessful delivery attempts. Predictive models identify high-risk deliveries based on customer availability patterns, address quality, and historical failure rates, enabling proactive outreach and alternative arrangements. Optimization of failed delivery recovery processes through redelivery scheduling, depot pickup options, and neighbor delivery authorizations reduces total delivery costs.

Real-time delivery tracking and proactive customer communication enhance transparency and enable dynamic coordination. Push notifications informing customers of imminent delivery arrivals reduce missed delivery probabilities and improve first-attempt success rates. Two-way communication channels allowing customers to provide access instructions, modify delivery locations, or reschedule deliveries introduce flexibility that accommodates unexpected circumstances.

Personalization strategies leverage customer profile data and behavioral analytics to tailor delivery experiences. Recognition of preferred delivery locations, time window patterns, and special handling requirements enables consistent service quality and relationship development. Privacy-respecting personalization approaches balance service enhancement with data protection obligations.

Parcel locker networks and alternative pickup point ecosystems provide customer convenience while enabling delivery consolidation and extended access windows. Optimization of locker network design considers customer accessibility, locker capacity utilization, and integration with traditional delivery routes. Incentive structures encouraging locker utilization align customer choices with operational benefits.

Quality of service metrics extend beyond delivery time reliability to encompass parcel condition, customer interaction quality, and complaint resolution effectiveness. Comprehensive performance measurement frameworks incorporating customer feedback, service failure tracking,

and root cause analysis inform continuous improvement initiatives. Integration of quality metrics into driver performance evaluation and compensation structures aligns operational execution with service excellence objectives.

### 8. Sustainability, Emissions, and Green Last-Mile Logistics

Environmental sustainability considerations increasingly influence last-mile logistics strategy in response to regulatory pressures, corporate responsibility commitments, and stakeholder expectations. Transportation represents a significant contributor to urban air pollution and greenhouse gas emissions, with last-mile delivery vehicles contributing substantially to urban traffic and emissions in congested city centers. Saudi Arabia's commitment to reducing carbon emissions under Vision 2030 and participation in international climate agreements creates imperatives for logistics sector decarbonization.

Vehicle electrification represents a primary pathway for emissions reduction in last-mile logistics. Battery electric vehicles eliminate tailpipe emissions and reduce noise pollution, offering particular benefits for urban delivery applications with predictable route patterns and overnight charging opportunities. Total cost of ownership analyses accounting for fuel savings, maintenance reductions, and potential subsidies inform electric vehicle adoption decisions. Infrastructure requirements including charging station deployment and electrical grid capacity upgrades represent significant implementation considerations for Saudi contexts.

Route optimization with explicit emissions objectives minimizes environmental impact through reduced vehicle kilometers traveled, congestion avoidance, and speed profile optimization. Multi-objective optimization formulations balance delivery costs, service quality, and emissions to identify Pareto-efficient solutions. Eco-routing algorithms select routes that minimize fuel consumption through consideration of road gradients, traffic signal timing, and congestion patterns.

Delivery consolidation strategies reduce total vehicle movements through coordinated deliveries combining shipments from multiple retailers or to multiple customers in proximity. Urban consolidation centers enable freight aggregation and load optimization prior to final delivery execution. Collaborative logistics networks among non-competing retailers share delivery capacity and reduce redundant route coverage.

Alternative delivery modes including cargo bicycles, electric motorcycles, and drone delivery offer emissions reduction potential for specific delivery segments. Cargo bicycles provide effective solutions for dense urban cores with high delivery densities and short distances. Drone delivery technology, though nascent, presents opportunities for low-density areas and urgent deliveries subject to regulatory framework development.

Modal shift strategies encourage customers to utilize lower-emission alternatives such as parcel lockers, pickup points, or public transport-connected collection facilities. Behavioral economics approaches including default option framing, convenience optimization, and incentive alignment promote sustainable delivery choices.

Packaging optimization reduces material waste and improves vehicle loading efficiency through right-sized packaging, reusable container systems, and design for logistics

efficiency. Lightweighting initiatives reduce fuel consumption, while recyclable and biodegradable materials minimize environmental impact.

Carbon accounting and reporting frameworks enable measurement, monitoring, and communication of emissions performance. Standardized methodologies for scope one, two, and three emissions accounting provide transparency and support target setting. Integration of carbon metrics into operational dashboards facilitates data-driven decision making that considers environmental objectives alongside traditional performance measures.

## 9. Implementation Considerations in Saudi Urban Contexts

Successful implementation of data-driven last-mile logistics optimization in Saudi megacities requires careful consideration of technological, organizational, regulatory, and cultural factors specific to regional contexts. Technology infrastructure readiness varies across urban areas, with modern districts featuring comprehensive fiber connectivity and sensor networks while older neighborhoods may lack digital infrastructure. Investment in network connectivity, edge computing capabilities, and cloud platforms establishes foundational requirements for real-time optimization systems.

Organizational capabilities including analytical expertise, change management capacity, and cross-functional collaboration determine implementation success. Development of internal data science teams or partnerships with specialized analytics providers enables effective model development and deployment. Training programs building logistics domain expertise among data scientists and analytical literacy among operations teams facilitate productive collaboration.

Change management strategies address resistance to algorithmic decision making and workforce concerns regarding automation. Transparent communication of optimization objectives, meaningful involvement of operational personnel in model development, and demonstration of tangible benefits build acceptance and engagement. Phased implementation approaches beginning with pilot programs in limited geographic areas allow learning and refinement before full-scale rollout.

Integration with existing enterprise systems including transportation management systems, warehouse management systems, and customer relationship management platforms ensures seamless data flow and operational execution. Application programming interfaces, data pipelines, and middleware platforms facilitate system interoperability. Legacy system constraints may necessitate workarounds or incremental modernization strategies.

Regulatory compliance encompasses labor regulations, traffic laws, data protection requirements, and safety standards. Adherence to working hour limitations, driver qualification requirements, and vehicle inspection standards ensures legal compliance. Implementation of privacy-preserving data practices and cybersecurity measures protects sensitive customer and operational information.

Cultural considerations influence customer acceptance and operational practices. Sensitivity to prayer time scheduling, gender-specific delivery preferences in certain contexts, and communication style expectations enhances service quality. Recruitment and training of delivery personnel with appropriate cultural competency and language skills supports

effective customer interactions.

Infrastructure constraints including limited parcel locker availability, inconsistent address systems in certain areas, and access restrictions in gated communities require adaptive operational strategies. Collaboration with property developers, municipal authorities, and residential compound management facilitates infrastructure improvements and access protocols.

Investment economics and financial viability assessment inform technology adoption decisions. Rigorous cost-benefit analyses accounting for implementation costs, operational savings, service quality improvements, and competitive positioning guide investment prioritization. Consideration of appropriate time horizons for return on investment evaluation recognizes that benefits from optimization systems accumulate over extended periods.

## 10. Challenges, Ethical, and Regulatory Considerations

Implementation of data-driven logistics optimization confronts technical, operational, and societal challenges requiring thoughtful management. Algorithm bias and fairness concerns arise when optimization models inadvertently produce discriminatory outcomes based on geographic location, customer characteristics, or socioeconomic factors. Service level disparities between affluent neighborhoods and lower-income areas undermine equitable access to delivery services. Fairness-aware optimization formulations incorporating equity constraints and auditing processes for discriminatory patterns represent important mitigation approaches.

Data privacy and security considerations intensify as logistics operations generate granular location data, customer behavior profiles, and operational intelligence. Compliance with emerging data protection regulations and implementation of privacy-preserving analytical techniques such as differential privacy and federated learning protect individual privacy while enabling valuable insights. Cybersecurity measures protecting operational systems from disruption and data from unauthorized access represent critical safeguards.

Workforce implications of automation and algorithmic management raise ethical considerations regarding employment quality, worker autonomy, and human dignity. Concerns that optimization systems intensify work pace, reduce decision authority, and create surveillance environments necessitate balanced approaches respecting worker welfare. Participatory design processes involving workers in optimization system development and implementation of algorithmic transparency measures enhance fairness and legitimacy.

Reliability and resilience challenges emerge from dependencies on technology systems, data connectivity, and algorithmic decision making. System failures, cyberattacks, or data quality degradation can disrupt operations and compromise service quality. Contingency planning, redundancy measures, and hybrid human-algorithmic decision frameworks ensure operational continuity under adverse conditions.

Regulatory frameworks for autonomous vehicles, drone delivery, and data-driven logistics remain under development in Saudi Arabia and globally. Proactive engagement with regulatory authorities, participation in industry standard-setting processes, and adaptive operational strategies that accommodate evolving regulations position organizations for successful long-term implementation. Clear regulatory

frameworks balancing innovation encouragement with public safety, fair competition, and consumer protection create enabling environments for technology adoption.

Environmental justice considerations arise when emissions reduction strategies shift environmental burdens across communities. Concentration of distribution facilities in industrial areas may disproportionately impact nearby residents with noise, traffic, and air quality degradation. Equitable distribution of environmental benefits and burdens through facility location decisions and community engagement processes advances environmental justice objectives.

Market concentration and competitive dynamics in logistics markets raise concerns about market power, pricing, and service quality in markets dominated by few large platforms. Regulatory oversight ensuring competitive markets, transparent pricing, and service quality standards protects consumer interests. Policies supporting market entry for innovative providers and preventing anticompetitive practices maintain market dynamism.

### 11. Future Directions in Data-Driven Urban Logistics

Evolution of data-driven urban logistics will be shaped by technological innovations, changing urban environments, and shifting societal expectations. Integration with comprehensive smart city platforms enables coordinated optimization across transportation modes, infrastructure utilization, and urban services. Real-time data exchange between logistics systems, traffic management, parking management, and public transit enables holistic urban mobility optimization.

Autonomous vehicle deployment represents a transformative prospect for last-mile delivery, offering potential reductions in labor costs, extended operational hours, and improved safety. Progressive automation pathways including driver-assistance systems, platooning, and fully autonomous operation enable incremental capability development. Regulatory frameworks, infrastructure adaptations, and public acceptance represent critical enablers for autonomous delivery vehicle deployment.

Artificial intelligence advancement will enhance predictive accuracy, decision quality, and adaptive capabilities of logistics systems. Deep learning models processing multimodal data including imagery, text, and sensor streams enable richer environmental understanding and decision making. Explainable artificial intelligence techniques providing transparency into algorithmic decisions support trust development and regulatory compliance.

Internet of Things proliferation with ubiquitous sensors on vehicles, parcels, infrastructure, and urban environments generates unprecedented data richness for optimization. Real-time parcel tracking, vehicle condition monitoring, and environmental sensing enable fine-grained visibility and control. Edge computing architectures processing data locally reduce latency and enable real-time adaptive decisions.

Digital twin technologies creating virtual replicas of logistics networks enable sophisticated scenario analysis, predictive maintenance, and optimization experimentation without operational disruption. Integration of real-time data streams with physics-based simulation models produces high-fidelity representations supporting decision making. Applications span network design, capacity planning, and operational

strategy evaluation.

Blockchain applications in logistics enable transparent, tamper-resistant records of shipment custody, delivery verification, and service quality documentation. Smart contracts automate payment settlement, service level agreement compliance verification, and multi-party coordination. Distributed ledger architectures facilitate trust and collaboration in multi-stakeholder logistics ecosystems.

Hyperlocal fulfillment strategies bringing inventory closer to customers through micro-fulfillment centers, dark stores, and inventory positioning algorithms enable ultra-fast delivery while reducing last-mile distances. Machine learning models predict localized demand patterns to optimize inventory placement across distributed fulfillment networks.

Circular economy integration transforms last-mile logistics to support reverse flows for returns, repairs, recycling, and reuse. Optimization models for reverse logistics address collection route planning, facility location for processing centers, and coordination of forward and reverse flows. Sustainable logistics strategies incorporating circularity principles reduce waste and environmental impact.

### 12. Conclusion

Data-driven decision models offer substantial potential for optimizing last-mile logistics operations in Saudi megacities, addressing critical challenges of routing efficiency, capacity planning, service quality, and environmental sustainability. The unique characteristics of Saudi urban environments including rapid growth, extreme climate, cultural preferences, and seasonal demand variations necessitate context-specific optimization approaches that extend beyond generic solutions. Successful implementation requires comprehensive data infrastructure, advanced analytical capabilities, organizational change management, and regulatory compliance, supported by strategic investments in technology platforms and workforce development.

The integration of routing optimization, demand forecasting, fleet management, and service-level optimization enables holistic improvement in operational performance, achieving reductions in delivery costs, enhanced reliability, improved customer satisfaction, and decreased environmental impact. Real-time adaptive capabilities responding to dynamic traffic conditions, demand fluctuations, and operational disruptions provide resilience and responsiveness essential in complex urban logistics environments. The convergence of logistics optimization with broader smart city initiatives creates opportunities for coordinated urban mobility management and sustainable urban development aligned with Saudi Vision 2030 objectives.

Future directions emphasizing autonomous vehicles, artificial intelligence advancement, Internet of Things integration, and circular economy principles will continue transforming last-mile logistics. Proactive engagement with technological innovation, thoughtful consideration of ethical implications, and collaborative partnerships among logistics providers, technology developers, regulators, and urban planners will shape the evolution toward intelligent, sustainable, and customer-centric urban delivery ecosystems. Continued research addressing regional contexts, implementation experiences, and emerging challenges will advance knowledge and practice in data-driven urban logistics optimization.

13. Figures

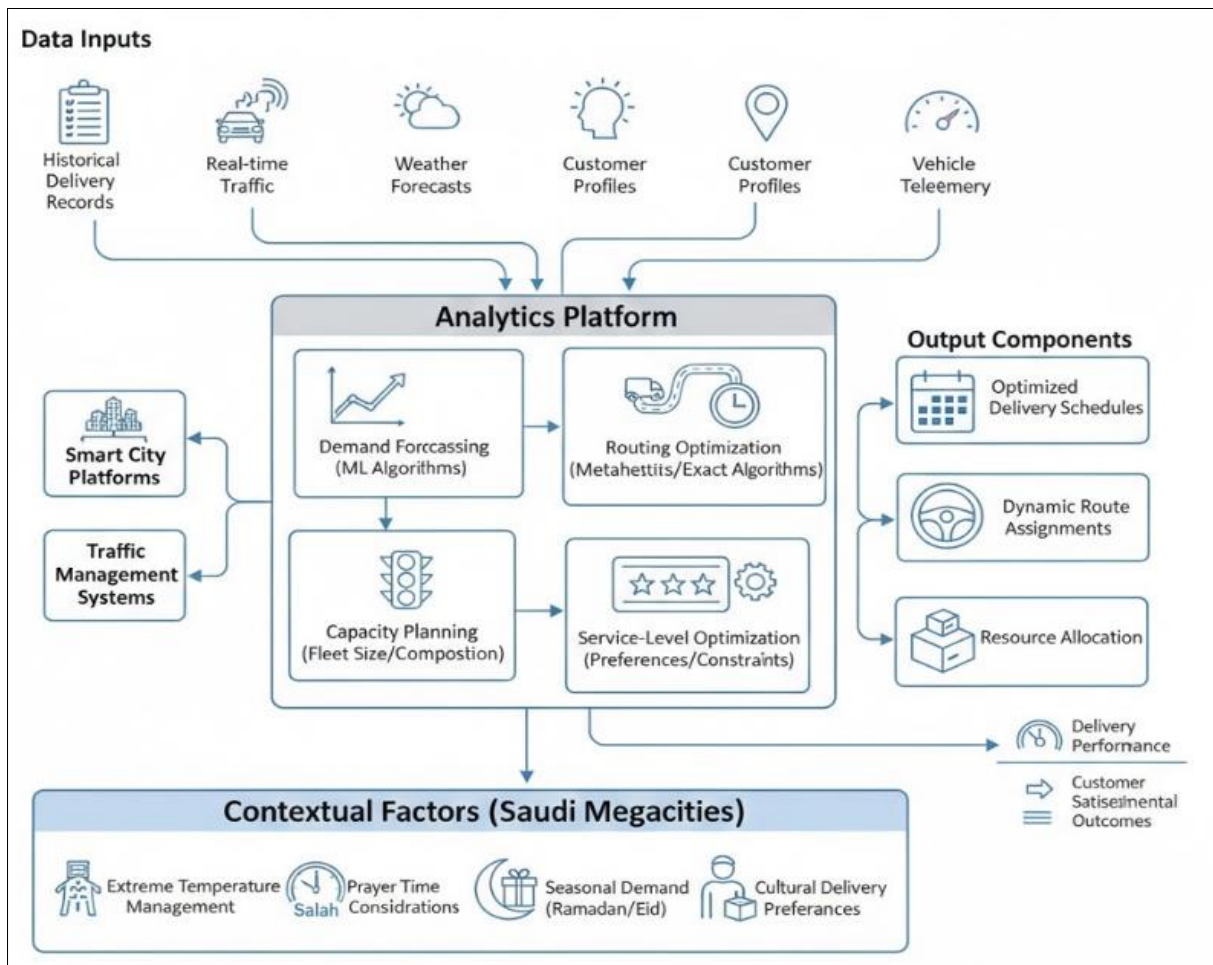


Fig 1: Conceptual framework for data-driven last-mile logistics optimization in Saudi megacities

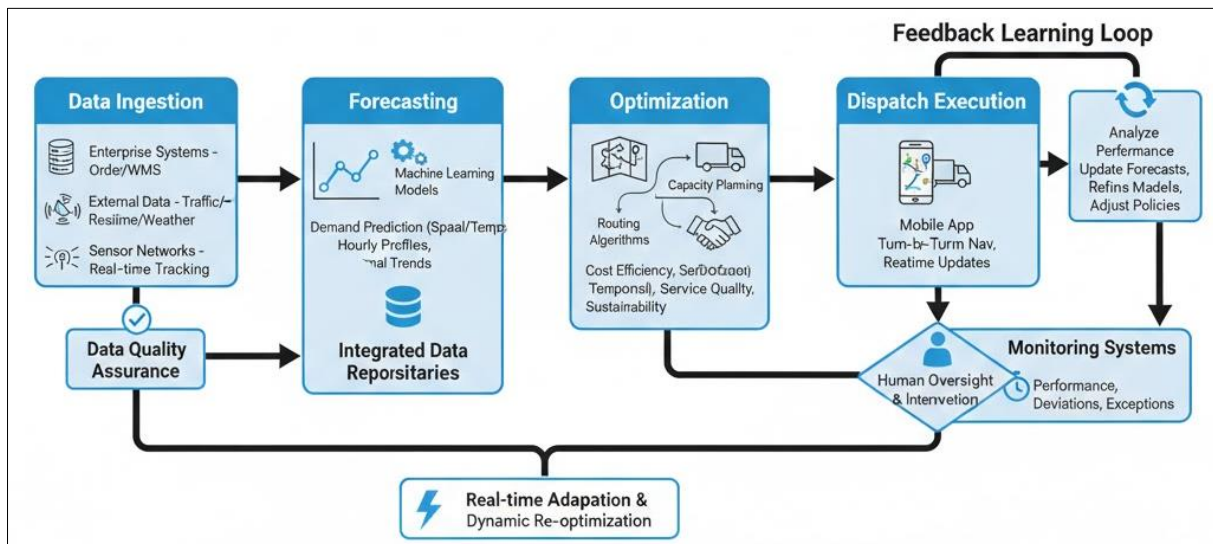


Fig 2: Decision modeling workflow showing data ingestion, forecasting, optimization, dispatch execution, and feedback learning loop

14. Tables

**Table 1:** Comparison of conventional last-mile delivery practices versus data-driven optimization approaches

Aspect	Conventional Practices	Data-Driven Optimization Approaches
Route planning methodology	Manual planning based on driver experience and static geographic territories; limited consideration of daily traffic variations or customer time preferences	Algorithmic routing using real-time traffic data, predictive analytics, and optimization algorithms; dynamic route adjustment responding to actual conditions
Demand forecasting	Historical averages and subjective judgment; reactive capacity adjustment to observed demand surges	Machine learning models incorporating multiple variables including seasonality, promotional events, weather, and trends; proactive capacity planning
Fleet utilization	Fixed vehicle assignments with limited flexibility; underutilization during off-peak periods and capacity shortages during peaks	Dynamic fleet sizing and vehicle type selection; integration of owned and crowdsourced capacity matching supply to demand patterns
Delivery time windows	Broad time windows with limited customer choice; high variability in actual arrival times	Precise time window options informed by customer preferences and operational feasibility; predictive arrival time notifications
Service failure management	Reactive handling of failed deliveries through redelivery attempts without systematic analysis	Predictive identification of high-risk deliveries; proactive customer communication and alternative arrangement offerings
Performance measurement	Aggregate metrics such as daily delivery counts and average cost per delivery; limited granular analysis	Comprehensive dashboards tracking route efficiency, first-attempt success rates, customer satisfaction scores, and emissions; continuous improvement analytics
Decision speed and frequency	Daily or weekly planning cycles; slow response to changing conditions	Real-time or near-real-time optimization enabling rapid response to disruptions and continuous plan refinement
Scalability and complexity handling	Manual approaches become impractical with increasing delivery volumes and network complexity	Automated optimization scales to large networks; handles multifaceted constraints systematically

**Table 2:** Key data sources for last-mile logistics in Saudi megacities and their operational relevance

Data Source Category	Specific Data Elements	Operational Relevance	Acquisition Channels
Historical delivery data	Order details, delivery locations, timestamps, service durations, delivery outcomes, customer feedback	Pattern identification for demand forecasting; performance benchmarking; model training; route optimization	Internal transaction systems, customer relationship management platforms, driver mobile applications
Real-time traffic information	Traffic flow speeds, congestion levels, incident reports, road closures, construction zones, traffic signal timing	Dynamic route planning; travel time prediction; congestion avoidance; delivery time estimation	Municipal traffic management systems, navigation service providers, connected vehicle networks, crowdsourced traffic applications
Geospatial data	Road network topology, address databases, building locations, points of interest, land use classifications	Route feasibility assessment; geocoding accuracy; service area definition; facility location planning	National Address System, mapping service providers, municipal planning departments, satellite imagery
Weather and environmental data	Temperature forecasts, dust storm predictions, precipitation probabilities, historical climate patterns	Operational planning for extreme conditions; vehicle type selection; personnel safety measures; seasonal capacity planning	Meteorological services, weather forecast providers, environmental monitoring networks
Customer profile information	Delivery preferences, time window selections, contact details, service history, feedback ratings	Personalized service delivery; failed delivery risk assessment; customer satisfaction enhancement; targeted communication	Customer registration systems, preference management interfaces, interaction history databases
Vehicle telemetry and fleet data	Vehicle locations, speeds, fuel consumption, maintenance status, driver behavior, cargo capacity utilization	Performance monitoring; predictive maintenance; driver coaching; real-time visibility; resource allocation	Fleet management systems, vehicle onboard diagnostics, GPS tracking devices, fuel management systems
Market and economic indicators	E-commerce growth trends, competitor service offerings, promotional event calendars, economic activity indicators	Strategic demand forecasting; competitive positioning; capacity investment planning; market opportunity assessment	Industry reports, market research firms, retail partners, economic statistical agencies

**Table 3:** Summary of decision models used in last-mile optimization and their objectives and outputs

Model Category	Primary Objectives	Key Inputs	Outputs	Solution Approaches
Vehicle routing with time windows	Minimize total travel distance or time; satisfy delivery time commitments; respect vehicle capacity constraints	Delivery locations and demands, time windows, vehicle capacities, travel time matrix, depot locations	Optimized routes assigning deliveries to vehicles with visitation sequences; estimated completion times	Mixed-integer programming, metaheuristic algorithms including genetic algorithms and simulated annealing, cluster-first route-second methods
Demand forecasting	Predict future delivery volumes at various spatial and temporal granularities; estimate demand uncertainty	Historical delivery data, calendar features, promotional schedules, weather forecasts, economic indicators	Demand predictions by geographic zone and time period; prediction intervals quantifying uncertainty	Time series models, machine learning techniques including random forests and gradient boosting, deep learning for complex patterns
Fleet sizing and composition	Determine optimal fleet size and vehicle type mix balancing capital investment, operational costs, and service levels	Demand forecasts, vehicle acquisition and operating costs, service level requirements, vehicle capability specifications	Recommended fleet size by vehicle type; timing for capacity expansions or reductions	Stochastic optimization, simulation-based analysis, scenario planning, robust optimization under uncertainty
Capacity planning and resource allocation	Allocate delivery capacity across geographic areas and time periods; determine workforce sizing and shift schedules	Demand forecasts, available vehicle capacity, driver availability, labor regulations, operational cost structures	Daily vehicle and driver assignments to zones; shift schedules; capacity gap identification	Linear programming, workforce scheduling algorithms, queuing models for capacity dimensioning
Service-level optimization	Balance operational efficiency with customer satisfaction; optimize delivery time window offerings	Customer preference distributions, operational cost trade-offs, competitive service standards, routing constraints	Time window offerings by customer segment and zone; service portfolio design recommendations	Multi-objective optimization, choice modeling predicting customer acceptance, simulation for service level evaluation
Facility location	Determine optimal locations for distribution centers, micro-fulfillment centers, and cross-dock facilities	Customer locations and demand densities, potential facility sites, land costs, transportation network characteristics	Recommended facility locations; service area assignments; network configuration	Location-allocation models, gravity models for demand-facility matching, scenario analysis for long-term planning

**Table 4:** Performance metrics for evaluating last-mile delivery efficiency, reliability, and customer experience

Metric Category	Specific Metrics	Measurement Methodology	Target Ranges or Benchmarks
Cost efficiency	Cost per delivery, cost per parcel, vehicle operating cost per kilometer, labor cost per delivery, total logistics cost as percentage of revenue	Aggregate operational expenses divided by delivery volumes; detailed cost accounting by cost component	Cost per delivery between eight and fifteen Saudi Riyals for standard urban delivery; continuous reduction trend through optimization
Route efficiency	Average stops per vehicle per day, vehicle utilization percentage, average distance per delivery, route adherence percentage	Count of deliveries per vehicle shift; vehicle capacity usage; distance metrics from telematics; comparison of actual versus planned routes	Fifteen to twenty-five stops per vehicle per day depending on density; vehicle utilization above seventy-five percent; route adherence above eighty-five percent
Delivery reliability	On-time delivery percentage, first-attempt success rate, average delivery time accuracy, service level agreement compliance rate	Count of deliveries within committed time windows divided by total deliveries; successful first attempts versus total attempts	On-time delivery above ninety-five percent; first-attempt success above eighty-five percent for planned time windows
Customer satisfaction	Customer satisfaction scores, net promoter scores, complaint rates, customer retention rates	Customer surveys following deliveries; feedback collection through applications; complaint tracking systems	Customer satisfaction scores above four point five out of five; net promoter scores above sixty; complaint rates below two percent
Productivity	Deliveries per driver per hour, parcel handling time, vehicle turnaround time at facilities	Time and motion studies; activity logging in mobile applications; facility throughput measurements	Two to three deliveries per hour in dense urban areas; one to one point five deliveries per hour in dispersed suburban areas
Environmental impact	Carbon dioxide emissions per delivery, fuel consumption per kilometer, electric vehicle adoption percentage, deliveries per vehicle kilometer	Emissions calculations based on fuel consumption and vehicle types; tracking of alternative fuel vehicle deployment	Reduction of twenty to thirty percent in emissions per delivery through optimization; progressive increase in electric vehicle share
Service quality	Parcel damage rates, delivery accuracy, customer interaction quality ratings, response time to customer inquiries	Quality control audits; customer feedback; mystery shopper evaluations; communication system response tracking	Damage rates below zero point five percent; delivery accuracy above ninety-nine percent; inquiry response within two hours

**Table 5:** Constraints and contextual factors affecting last-mile logistics in Saudi megacities and mitigation strategies

Constraint or Factor Category	Specific Challenges	Operational Impacts	Mitigation Strategies
Climatic extremes	Summer temperatures exceeding forty-five degrees Celsius; dust storms; occasional flooding	Vehicle breakdowns; driver heat stress; reduced productivity during extreme conditions; product quality degradation for temperature-sensitive items	Deployment of temperature-controlled vehicles; scheduling deliveries during cooler hours; enhanced vehicle maintenance programs; heat safety protocols for drivers; weather-responsive scheduling algorithms
Traffic congestion	Severe congestion during peak hours with speeds below twenty kilometers per hour; prayer time traffic variations; construction-related disruptions	Extended travel times; delivery delays; increased fuel consumption; unpredictable arrival times	Real-time traffic-aware routing; delivery time window design avoiding peak congestion; strategic facility location near customers; micro-fulfillment centers reducing last-mile distances
Cultural and religious considerations	Prayer time observances affecting traffic and customer availability; Ramadan working hour changes; gender-specific delivery preferences in some contexts	Reduced operational windows; concentrated demand in specific hours; special handling requirements	Flexible scheduling accommodating prayer times; culturally trained delivery workforce; proactive communication with customers regarding delivery coordination
Seasonal demand fluctuations	Ramadan demand surges exceeding three hundred percent of baseline; Eid shopping peaks; promotional event spikes	Capacity shortages; service quality degradation; increased costs from overtime and premium capacity	Demand forecasting models incorporating seasonal patterns; advance capacity planning with temporary workforce and vehicle leasing; partnership networks for capacity sharing; early customer communication encouraging demand smoothing
Infrastructure limitations	Incomplete address standardization; restricted access to gated communities; limited parcel locker availability; newly developed areas lacking complete mapping	Failed deliveries; extended search times; customer frustration; operational inefficiencies	Collaboration with National Address System expansion; partnerships with residential compound management; investment in parcel locker networks; continuous geospatial data enrichment
Regulatory and labor constraints	Working hour limitations; driver qualification requirements; vehicle inspection standards; data protection regulations	Operational complexity; compliance costs; workforce availability constraints	Comprehensive workforce planning respecting regulations; investment in driver training and certification; privacy-preserving data practices; proactive regulatory engagement
Geographic dispersion	Low-density suburban developments; extensive urban sprawl spanning hundreds of square kilometers	Long distances between stops; reduced stops per hour; higher fuel consumption; difficulty achieving efficient routes	Strategic zone design balancing density with coverage; dynamic pricing incentivizing consolidation; investment in distributed fulfillment network; route optimization algorithms specialized for low-density areas

**Table 6:** Implementation roadmap outlining phases, stakeholders, enabling technologies, and expected outcomes

Implementation Phase	Duration	Key Activities	Stakeholders Involved	Enabling Technologies	Expected Outcomes
Phase 1: Assessment and planning	Three to six months	Current state analysis of delivery operations; data availability and quality assessment; technology infrastructure evaluation; stakeholder requirement gathering; business case development; pilot scope definition	Internal logistics operations teams, IT departments, finance departments, external consulting partners, technology vendors	Data analytics platforms for current performance analysis; business intelligence tools; process mapping software	Comprehensive understanding of baseline performance; identified improvement opportunities; validated business case; detailed implementation plan; committed resources
Phase 2: Data infrastructure and integration	Six to nine months	Data architecture design; integration of operational systems; implementation of data pipelines; data quality framework establishment; historical data preparation; real-time data feed configuration; analytics platform deployment	IT departments, data engineering teams, system integration vendors, operational system administrators, external data providers	Cloud computing platforms; data integration middleware; application programming interfaces; data warehousing solutions; streaming data platforms	Unified data infrastructure supporting optimization models; real-time data availability; validated data quality; operational system connectivity
Phase 3: Model development and testing	Six to twelve months	Demand forecasting model development and validation; routing optimization algorithm implementation; capacity planning model configuration; pilot area selection; simulation testing with historical data; algorithm parameter tuning; user interface design	Data scientists, operations research specialists, logistics domain experts, driver representatives, pilot area operational teams	Machine learning frameworks; optimization solvers; simulation software; geospatial analysis tools; mobile application development platforms	Validated optimization models demonstrating performance improvements; configured algorithms meeting operational requirements; user-friendly interfaces for operational teams
Phase 4: Pilot deployment	Three to six months	Pilot launch in selected geographic areas; operational team training; change management	Pilot area operational teams, drivers, customer	Mobile driver applications; dispatcher control systems;	Demonstrated operational improvements in pilot areas; validated model

		implementation; performance monitoring; issue identification and resolution; model refinement based on real-world feedback; success criteria evaluation	service representatives, IT support teams, change management specialists	performance dashboards; real-time monitoring tools; communication platforms	performance in real-world conditions; refined processes and procedures; trained operational teams; organizational readiness for scaling
Phase 5: Scaling and expansion	Twelve to eighteen months	Phased geographic expansion beyond pilot areas; capacity building for expanded operations; continuous improvement processes; advanced feature implementation; integration with emerging technologies; best practice documentation	Expanded operational teams, additional geographic areas, technology support teams, continuous improvement specialists	Scalable cloud infrastructure; automated deployment tools; advanced analytics features; integration frameworks for smart city platforms	Organization-wide deployment of optimization capabilities; sustained performance improvements; established continuous improvement culture; competitive advantage through operational excellence
Phase 6: Advanced capabilities and innovation	Ongoing beyond initial deployment	Integration with autonomous vehicles as technology matures; artificial intelligence capability enhancement; Internet of Things sensor integration; digital twin development; exploration of emerging technologies; participation in smart city ecosystem evolution	Innovation teams, research partnerships, technology vendors, regulatory authorities, smart city platform operators, industry collaborators	Autonomous vehicle systems; advanced artificial intelligence platforms; Internet of Things networks; digital twin technologies; blockchain for supply chain transparency	Sustained competitive leadership through innovation; participation in smart city ecosystem; ongoing operational excellence; adaptation to evolving customer expectations and market conditions

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