

**University of Pardubice Faculty
of Transport Engineering**

**DELIVERY SYSTEM FOR E-
COMMERCE SHIPMENTS IN CITIES
WITH REGARD
TO CUSTOMER REQUIREMENTS
DOCTORAL THESIS STATEMENTS**

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1 STATE OF THE ART

Last-mile delivery (LMD) represents one of the main challenges of contemporary e-commerce logistics [1]. The rapid growth of online shopping increases demands on delivery systems that must ensure fast, reliable, and sustainable services [2]. Empirical studies repeatedly confirm that delivery speed and reliability are crucial determinants of customer loyalty [3]. Consumers expect flexible time-windows, real-time tracking, and a high level of adaptability [4].

Recent developments highlight the expansion of parcel lockers and pick-up points, enabling customers to collect parcels independently of the courier. Other innovations include in-car delivery and experimental use of drones or autonomous vehicles, which promise faster and more efficient transport. From the environmental perspective, the shift towards zero-emission transport modes is evident. Pilot projects with electric vans and cargo bikes demonstrate significant potential for reducing CO₂ emissions and noise pollution. Night-time delivery schemes have also proved effective in shortening delivery times and lowering emissions in large cities [2].

On the theoretical level, last-mile delivery is modelled as a Vehicle Routing Problem (VRP), which extends the classical Travelling Salesman Problem (TSP). Fundamental mathematical formulations were elaborated by Toth and Vigo [5] and Laporte [6]. Exact algorithms are applicable only to small instances; therefore, heuristics and metaheuristics are predominantly used in practice. Widely applied approaches include the Clarke–Wright savings algorithm [7], nearest-neighbor heuristics [8], 2-opt and 3-opt local search [9] [10], simulated annealing [11], tabu search [12], genetic algorithms [13], and hybrid methods [14] [15].

The synthesis of these analyses thus reveals a critical gap at the intersection of academic research and practical, transparent software tools. While academic literature offers theoretically advanced but difficult-to-transfer optimization models, commercial software remains too costly and proprietary for research and pilot purposes. Open-source libraries offer flexibility, but their fragmentation and implementation complexity hinder the creation of a comprehensive, user-friendly solution for urban logistics.

2 RESEARCH OBJECTIVES

The main goal of this dissertation is: **to optimize the last-mile delivery system for e-commerce shipments in urban areas**. To achieve this main goal, the following supporting objectives were met:

- Analysis of existing approaches to last-mile delivery of shipments.
- Identification of customer needs through a quantitative questionnaire survey focused on factors influencing decision-making regarding the method of shipment delivery.
- Analysis of current optimization methods for last-mile delivery, their critical evaluation, and the proposal of improvements.
- Design and implementation of a related software tool for route planning, which utilizes data from the questionnaire survey, geographic baselines, traffic network information, and the location of service points. The designed software tool will optimize delivery routes according to key criteria identified by the implemented questionnaire survey. The software tool will also include a proposal for a procedure for planning and comparing various delivery scenarios. The functionality of the designed software tool will be verified through a case study in Pardubice.

3 RESEARCH METHODOLOGY

The overall research workflow followed the structured process illustrated in figure 1.

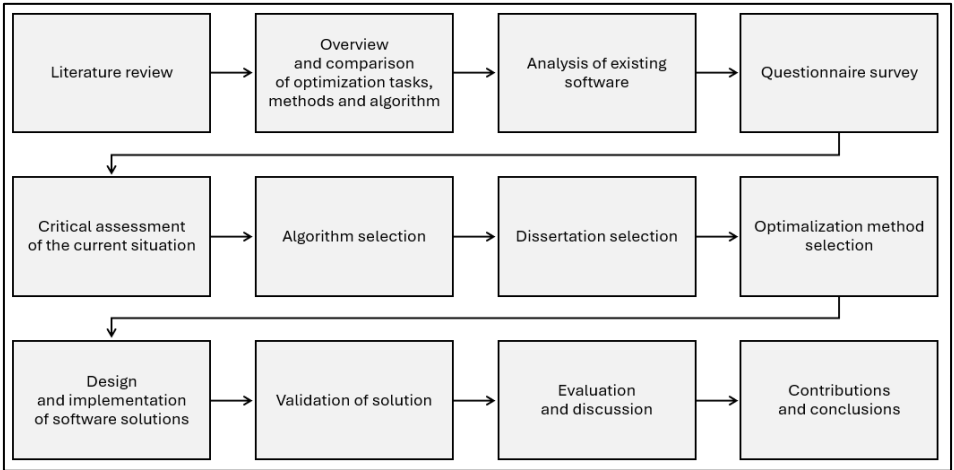


Figure 1 Research methodology flowchart (Author)

The workflow was divided into three main phases:

1. **Analytical phase:** This initial stage involved a literature review, an overview of optimization methods, an analysis of existing software solutions, and a questionnaire survey to identify customer requirements.
2. **Design phase:** Based on a critical assessment of the analytical phase, the main objective of the dissertation was defined, leading to the selection of the specific optimization approach a combination of the Christofides approximation algorithm and the 2-opt heuristic.
3. **Implementation phase:** The final stage included the design and implementation of the software solution, its practical and numerical validation, and the subsequent evaluation and discussion of the results, which formed the basis for the contributions and conclusions.

The methodological framework of this dissertation combines theoretical approaches of operations research, literature analysis, and applied software development. This procedure enables a systematic examination of last-mile delivery and the creation of a practical solution tested on real data. At the general methodological level, forecasting methods [16], logical methods [17], and analytical approaches were employed. Forecasting aided in scenario modelling and assessment, logical methods in structuring knowledge and defining objectives, and analytical methods in evaluating solution parameters. For route optimization, various operations research methods, including heuristics and metaheuristics as discussed in the State of the Art, were considered. After evaluating the trade-offs between solution quality and computational requirements for urban logistics, the Christofides approximation algorithm [18] was selected as the core approach. This method provides a theoretical guarantee on solution quality while maintaining computational efficiency. To further enhance practical performance, it was combined with a 2-opt post-optimization step. Crucially, this combined approach was specifically modified to address the five operational delivery scenarios, including the critical open-route scenarios with flexible or fixed start and end points, which constitutes a significant methodological contribution of this work.

The software implementation was based on the Django framework and PostgreSQL/PostGIS for efficient handling of spatial data [19] [20]. Graph operations and the implementation of the heuristic algorithms were supported by the NetworkX library [21], while visualizations were carried out in Leaflet [22]. The core data source was OpenStreetMap [23] in PBF format, processed on local OSRM and Valhalla servers [24] [25], which provided static, dynamic, and historical distance–time matrices with full control over data and computations. Map backgrounds were generated using TileServer GL [26].

The entire system was operated locally, eliminating dependence on commercial providers and ensuring transparency and reproducibility. Primary data on customer preferences were collected through a questionnaire survey conducted in 2023–2025 with 427 respondents, ensuring sample representativeness [27]. Validation methods included both practical and computational aspects. Practical validation tested the functionality of the developed software tool in the city of Pardubice, while computational validation assessed the accuracy of the modified heuristic against exact optima for small instances. The tests examined the quality of the obtained routes, runtime requirements, and algorithmic stability across various delivery scenarios.

The methodological approach was therefore based on three pillars: the theoretical foundation of optimization methods, empirical research of customer preferences, and the development of a modular software tool.

4 ACHIEVED RESULTS

To address this gap, the primary methodological result was the modification of the Christofides approximation algorithm. While the original algorithm is limited to closed tours, this work successfully adapted it, in combination with a 2-opt heuristic to solve five distinct delivery scenarios, including the critical open-route cases with fixed or flexible start/end points. This modified algorithm forms the core of the main practical result: the implemented software tool VrbaRouteLab. The system is built on a locally operated, open-source stack (Django, PostgreSQL/PostGIS, OSRM, and Valhalla). It successfully integrates static, dynamic (factoring in traffic and weather), and historical data matrices to provide a robust platform for route planning. The solution's accuracy and functionality were confirmed through a two-part validation:

- **Practical Validation:** The tool was tested in the real-world environment of Pardubice, using both passenger cars and cargo bikes. The generated routes were confirmed to be operationally sound and logically aligned with the city's transport network.
- **Numerical Validation:** The modified algorithm was benchmarked against the exact optimum on smaller 10-node instances. The results demonstrated high accuracy, with the algorithm finding the optimal solution in several scenarios. The maximum deviation was 8.33% (distance) and 6.62% (time), with average deviations remaining low (3.1% and 4.3% respectively). All calculations were completed within milliseconds.

It is important to note the solution's limitations. The quality of the results depends heavily on the accuracy of the underlying OpenStreetMap data, which may lack detail in complex areas (e.g., shopping centres). Furthermore, as a heuristic, the modified algorithm provides near-optimal solutions (max deviation 8.33%) but does not guarantee the exact optimum in all scenarios.

5 CONTRIBUTIONS OF THE DISSERTATION

The dissertation provides a set of theoretical and practical contributions, verified both analytically and through software implementation and testing in the city of Pardubice.

5.1 Theoretical contributions

- **Systematization of knowledge:** The work consolidates findings on last-mile delivery, heuristics, metaheuristics, and transport models into a comprehensive framework that links transport planning, algorithmic approaches and user preferences.
- **Extension of Christofides' algorithm:** The algorithm was successfully adapted for open-route scenarios and enhanced with a 2-opt improvement step, proving sufficient accuracy and speed for urban delivery applications.
- **Multi-scenario framework:**
A methodological concept was introduced that covers closed tours, fixed start/end routes, and scenarios with only a defined start or destination.

5.2 Practical contributions

- **Functional software tool:** A working application was developed based on open-source technologies, capable of operating with static, dynamic, and historical traffic data.
 - **Flexible optimization criteria:** Users can choose between time and distance-based optimization, with the secondary metric displayed simultaneously.

- **Financial Accessibility:** The absence of licensing fees for the proposed software means zero acquisition costs for potential users. Operational costs are related exclusively to providing the necessary computational capacity and system maintenance. The software tool is, under its licensing terms, initially suitable for research purposes, academic projects, pilot validation in urban environments, or for municipal needs, with potential for commercial interest in the longer term.
- **Algorithm validation:** The modified algorithm was verified on real and synthetic datasets, showing high accuracy, stability, and low computational requirements.
- **Flexible analysis platform:** The tool is designed as a flexible platform for analysis and optimization in transport engineering, operations research, and urban logistics. Its architecture allows for testing and comparing various optimization methods, from classic heuristics to metaheuristics, as well as modelling and evaluating new delivery methods, such as the deployment of cargo bikes, the use of micro-depots, or night delivery. This provides a practical basis for a wide range of analyses and experimental verifications
- **Integration of customer preferences:** A survey of 427 respondents identified key factors (price, delivery location, time flexibility), which were incorporated into the system's functions.
- **Interactive accessibility maps:** The tool includes visualization of parcel locker service areas, enabling the identification of underserved zones and supporting strategic decisions on network expansion.

5.3 Future Research Directions

The results of this dissertation provide a solid foundation that can be built upon by expanding methodological approaches, deepening experimental validation, and applying the solution in different operational conditions.

- **Theoretical directions:** Future research can be expanded to include more advanced variants of routing problems, considering capacity constraints, time windows, multiple depots, or open routes. There is also scope for a systematic comparison of different algorithmic approaches on a unified basis and a deeper analysis of their behaviour under dynamic and stochastic conditions.
- **Practical directions:** Practical development should focus on expanding the solution's capabilities by integrating additional data sources, enhancing the user interface, connecting to existing logistics systems, and further testing in diverse operational settings.

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SOUHRN/ABSTRACT

Disertační práce se zabývá optimalizací rozvozu e-commerce zásilek na poslední míli v městském prostředí. Práce analyzuje současné logistické modely, softwarové nástroje a na základě dotazníkového šetření mezi 427 respondenty identifikuje klíčové požadavky zákazníků. Hlavním výstupem je návrh a implementace otevřeného softwarového nástroje VrbaRouteLab. Nástroj využívá kombinaci Christofidesova aproximačního algoritmu a heuristiky 2-opt, přičemž klíčovým přínosem je úprava tohoto přístupu pro řešení pěti scénářů doručování, včetně otevřených tras s různým startem a cílem. Systém integruje statická, dynamická (dopravní omezení, počasí) i historická data pro plánování tras. K věření funkčnosti a přesnosti navrženého řešení byla využita praktická validace v reálném provozu města Pardubice a numerická validace porovnáním výsledků algoritmu s exaktním optimem.

This dissertation addresses the optimization of last-mile e-commerce shipment delivery in an urban environment. The work analyses current logistics models and software tools and based on a questionnaire survey of 427 respondents, it identifies key customer requirements. The main output is the design and implementation of an open-source software tool, VrbaRouteLab. The tool uses a combination of the Christofides approximation algorithm and the 2-opt heuristic, with the key contribution being the modification of this approach to solve five delivery scenarios, including open routes with different start and end points. The system integrates static, dynamic (traffic restrictions, weather), and historical data for route planning. To verify the functionality and accuracy of the proposed solution, practical validation was conducted in the real-world operations of the city of Pardubice and numerical validation by comparing the algorithm's results with the exact optimum.