DISTRIBUTION STRATEGY PLANNING FOR LAST-MILE DELIVERY AMID POTENTIAL URBAN POLICY TRAFFIC CHANGES: A DECISION MAKING MODEL APPROACH

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Abstract

In our prior research, we formulated a technique for planning distribution strategy amid future uncertainties. Conventional planning methods, which involve designing potential scenarios and defining probabilities, frequently face difficulties because of unforeseeable future events. Suboptimal strategies can emerge if the probabilities were assigned incorrectly at the beginning. The contribution of this article is a new method that avoids making rigid assumptions about the exact probability of each future scenario. Instead, it explores the entire allowable probability space and selects an optimal strategy in most situations. In the case study, the method's usability is shown on a real-world company operating in Prague. We use it to model the impact of a city policy on the company's operations within the city limits. Due to the frequent traffic restrictions in other major European cities and the overall trend of following more environmentally friendly policies, Prague is also expected to take this path. Accordingly, the company's operations could be significantly affected. By utilizing historical delivery data from the company and specialized simulation software, we model diverse distribution network scenarios under potential traffic restrictions, already in effect in other European cities, and probabilistically assess the future the company is facing.

Keywords: Distribution strategy planning, concurrent optimization model, last mile delivery, uncertainty

1. INTRODUCTION

This article introduces a reliable methodology for tackling the complex issue of distribution strategy planning in an environment with high volatility and uncertainty. Distribution strategy planning is a process that each company with a large amount of transported goods through their network needs to do. Modifying the Bayesian network-based model, first introduced in our previous work [1], we model the share of cases when a distribution strategy is optimal without making rigid assumptions regarding the future development. Moreover, unlike many existing applications, we test our methodology on real data so as not to distort our result with simulated data, which are prone to be based on biased assumptions. The presented methodology is applied to assess the impact of a city policy on an existing company operating in the Czech capital, Prague.

Urban freight transportation has become an essential factor in the development of cities. Various measures are being implemented to mitigate the negative impacts of transportation on the environment and city dwellers. A review of urban freight management measures conducted in 56 cities worldwide identified various initiatives, including vehicle-related strategies and traffic management [2]. In the context of the European Union, Prague has been placed in the fourth of five groups of EU27 capitals for the implementation of city logistics measures [3], which means that the majority of European cities have already implemented more policy measures than the Czech capital and that the city could benefit from them. European cities, such as Milan, Rotterdam, and Paris, have adopted extensive transportation restrictions, including congestion charges, emission requirements, and limited access to specific city areas. In combination with the general trend of following more environmentally friendly policies, this implies that the city of Prague is expected to follow this path as well.

When writing this article, the Prague city center announced that for the first time, entering the city part for nonresidents would not be free[1].

City logistics is an important area of urban logistics because it encapsulates the research domains of transportation, economics, and operations research and also for its close interdependence with the welfare of the citizen and the public administration [4]. E-commerce has recently been the prime factor affecting city logistics, in particular. The entire segment is expected to grow a further 47% in the EU by 2027[2]. The company we use for empirical evaluation operates in the segment of last-mile delivery, delivering e-commerce orders to the final customers. Last mile delivery encompasses various aspects such as delivery, transportation, and logistics, each impacting the strategic, tactical, and operational levels of supply chain management [5]. Effective strategies include the multi-criteria decision-making for micro-hub locations, considering factors like distances and costs, vital for sustainable last mile delivery [6]. Additionally, an integrated planning framework aligns last mile logistics with broader business strategies and regional demands, enhancing efficiency and customer satisfaction [7]. Furthermore, understanding market risks and opportunities in last mile logistics is crucial and innovative delivery techniques and environmentally sustainable systems are essential for advancement in the last mile logistics services [8]. This segment is also highly prone to inefficiencies [4]. Consequently, any traffic restriction measures adopted by the city that impact the company's operations would likely also be reflected in its service toward customers - in costs or service level. Although the impact of e-Commerce on last-mile logistics has been specifically identified as an essential factor in urban areas, with an exception [9], there is a lack of empirical literature covering this growing phenomenon [10]. This article fills the gap in existing research. We propose a way to evaluate distribution strategies without making rigid assumptions regarding future development and apply it to study the effect of the adoption of possible traffic restrictions in Prague on the last-mile delivery company. Our findings can serve as a base for traffic policymakers in Prague and as a blueprint for other fellow researchers for studies of similar kind.

2. NOTATION

Our model searches for the optimum long-term distribution strategy given a set of business scenarios and a set of feasible potential distribution strategies. Business scenarios can be, for example, different sales growth trajectories, shifts in consumer behavior or possible public policies, as in this case. Distribution strategies are different configurations of the company distribution network. For the presented optimization procedure, they must be evaluated across all considered business scenarios. For clarity, we use the same basic notation as in our previous work [1], when appropriate.

The distribution strategy is designed for n consecutive time periods. Variable A^i, $i \in 1 \dots n$, is the modeled company in the period i and its states $a_j^i, j \in 1 \dots m^i$ are the possible business scenarios where the company can be in that period. $A = \{A^1, \dots, A^n\}$ is the set of all company nodes at all time periods. The company must then design a number d of feasible distribution networks Z, which could accommodate the needs of company A. Symbol $Z_f^i, i \in \{1, \dots, n\}, f \in \{1, \dots, d\}$ then refers to a strategy Z_f implemented during a specific period i.

Next, it is necessary to choose a KPI which will be used to evaluate each business scenario - distribution network combination. We define the distribution network operating costs as the one most frequently used in practice, from our experience. Distribution network operating costs for a company are costs related to network operations. $c_{j,f}^i, i \in \{1, \dots, n\}, j \in \{1, \dots, m^i\}, f \in \{1, \dots, d\}$ stands for distribution network operating costs in a state a_j^i while operating a distribution network Z_f. The tool to obtain all estimates c_j^i can be chosen freely, but it must be possible for every Z_f at every state a_j^i included in the model.

[1] https://ct24.ceskatelevize.cz/regiony/3585261-praha-planuje-zpoplatnit-vjezd-do-historickeho-centra-vyjimku-meli-rezidenti
[2] https://www.statista.com/forecasts/715663/e-commerce-revenue-forecast-in-europe

3. METHODOLOGY FOR MODELING THE SHARE OF CASES WHEN A DISTRIBUTION STRATEGY IS OPTIMAL

While facing the long-term planning task and creating a robust strategy, expectations about future development are required. This can be obtained using data and mathematical forecasting methods (such as regressions, neural networks, and such) or experts and their opinions and educated guesses. Having worked on various distribution strategy design projects, we discovered that it is challenging to assign probabilities to the business scenarios using either data or expert knowledge, especially in a long horizon of more years. Underlying data are usually too sparse for robust predictions, prone to unforeseen events, and expert knowledge is hard to obtain in a precise form. The causal transitions among states between company nodes are difficult to capture and notoriously prone to misspecification. To address this difficulty, we design a process that helps experts fill their expectations into the model and calculation even though they are very imprecise. We propose to limit the possible future scenarios to a smaller area (viable options). In this area of potential future development, we estimate the percentage share when a distribution strategy is optimal. This answers strategists and planners on the chance that the selected path will be correct, which is significant information in the planning process. The advantage of this approach is its robustness to the user's misperception of the likelihood of future development scenarios. On the other hand, even with this approach, evaluating the future distribution network scenario is necessary as it is an essential input for calculations. We use a proprietary software, Distribution Wizard by Logio[3], which allows us to do such calculations.

The computations in the presented model are conducted separately for each company node A^i, $i \in 1...n$ from the network. Accordingly, we assume the independence of different company nodes. However, the users have demonstrated a far better ability to accurately describe the probability of a_j^i by an interval than by an exact figure. Therefore, we allow the user to restrict the probability of each state a_j^i in the network, to model his assumptions about the state's a_j^iprobability. The user-restricted probability space **P** can be defined as:

$$\boldsymbol{P} = P\left(A^i = a_j^i\right) \in \left[\overline{w_j^i}, \widehat{w_j^i}\right], i \in \{1,2,\dots,n\}, j \in \{1,2,\dots,m^i\}, \overline{w_j^i} \in [0,1], \widehat{w_j^i} \in [0,1],$$

where the $\overline{w_j^i}$ and $\widehat{w_j^i}$ are the lower and upper limit for the probability that the state a_j^i can have. In the application presented in this article, we model business scenarios in which the modeled company is assumed to shift a part of its wholesale from Czechia to Poland. The user-restricted probability space **P** allows us to model the situation when, for example, the scenario in mind has a probability of at least 10% and a maximum of 60% to happen in the future.

Now let us define a subspace $\mathbf{W}_f \subseteq \mathbf{P}$, which represents all probability combinations for which a strategy $f \in \{1,\dots,d\}$ is optimal. Probabilities $p_j^i, i \in \{1,\dots,n\}, j \in \{1,\dots,m^i\}$ create the subspace W_f, where the following condition is satisfied for a given *f*:

$$f = \arg\min_d \left\{\sum_{j=1}^{m^i} p_j^i \, c_{j,d}^i\right\} \quad (1)$$

The condition depicted by Equation 1 is based on the COM [1] and states that a distribution strategy Z_f yields the lowest expected distribution network operating costs at the company node A^i given the probability combination p_j^i and the costs $c_{j,d}^i$ associated to each business scenario a_j^i and each distribution strategy Z_d.

Finally, we want to estimate the size of the subspace $\boldsymbol{W_f}$. Let us first denote the size as $S \in [0,1]$, $S(W_f) = 0$ implies that the strategy is never optimal in the subspace. The size *S* of the strategy *f* is then the integral of the (*r* − 1)th order over this subspace. *r* is the number of states a_j^i which a company node A^i can have. One integral dimension is subtracted due to the logical restriction $\sum_j p\left(a_j^i\right) = 1$.

[3] Consultancy company in the domain of supply chain management - www.logio.cz

$$S(\boldsymbol{W_f}) = \int_{W_f}^{(r-1)} 1 dW_f \tag{2}$$

In case any user-defined restrictions are placed on the probability space **P**, the $\sum_{f=1}^{d} S(W_f) \neq 1$. Therefore, the values $S(W_f)$ are normalized to

$$\mathrm{S}'(\mathrm{Wf}) = 1 \tag{3}$$

for better interpretation. The resulting $S'(\mathbf{W}_f)$ then represents the percentage share of the cases when the strategy *f* is optimal in the user-restricted probability space **P**.

4. CASE STUDY

In a case study involving a last-mile delivery company[4] operating in Prague, we applied the methodology presented in Section 3 to explore the probability of three distinct distribution networks being optimal under the impact of three possible traffic restriction policies. The prospective analysis extended to six years, divided into three distinct time frames: 2024, 2026, and 2028. As distribution network changes take time to implement, it is reasonable to use two-year intervals. These intervals can be modified to any necessary length if needed. For this analysis, we project a steady volume of deliveries over the outlook.

4.1 Background

The company provides a same-day delivery service to its extensive clientele, with the ability to deliver a package within four hours of ordering. It operates a distribution center located on the outskirts of Prague. All deliveries are made from this distribution center to customers using compact vehicles (less than 3.5 tons), each of which can accommodate 15 shipments at a time. We have modeled three types of traffic restriction policies inspired by those in other cities. The first scenario, based on Rotterdam's Zero-Emission-Zone, limits city center access to only zero-emission vehicles, specifically defining the restricted area to align with Prague's previous vehicle ban. The second scenario, based on Ghent's car-free zone, proposes banning vehicles in the city center and the third and most stringent scenario, inspired by Milano and Oslo, imposes a flat fee of 250 CZK for each entry into the city. We propose two distribution strategies in addition to the existing one. The current strategy uses one distribution center to facilitate same-day delivery within four hours via sub-3.5-ton vehicles. The first new strategy suggests two smart pickup boxes in the city center, served by sub-3.5-ton vehicles from the main warehouse, and cargo bicycles for final delivery, extending delivery times to eight hours. The second strategy proposes 22 smart pickup boxes throughout Prague, served by sub-6.5-ton vehicles, with cargo bicycles responsible for final delivery. Both alternatives aim to adapt to the proposed restrictions while considering operational costs and service levels.

4.2 Modeling

Using historical order data, we simulated a month of network operations for each distribution strategy and traffic restriction scenario. For realistic modeling, we employed Logio's Distribution Wizard software, which utilizes the Jsprit[5] engine to solve complex Vehicle Routing Problems (VRP). Customized OpenStreetMap layers were adjusted for specific scenarios like city center car bans. Our simulations produced various routing examples and were summarized in a results table. As can be seen in **Table 1**, the cost variations were highest in the pay-to-enter scenario, and depending on the restriction type, the optimal distribution strategy varied.

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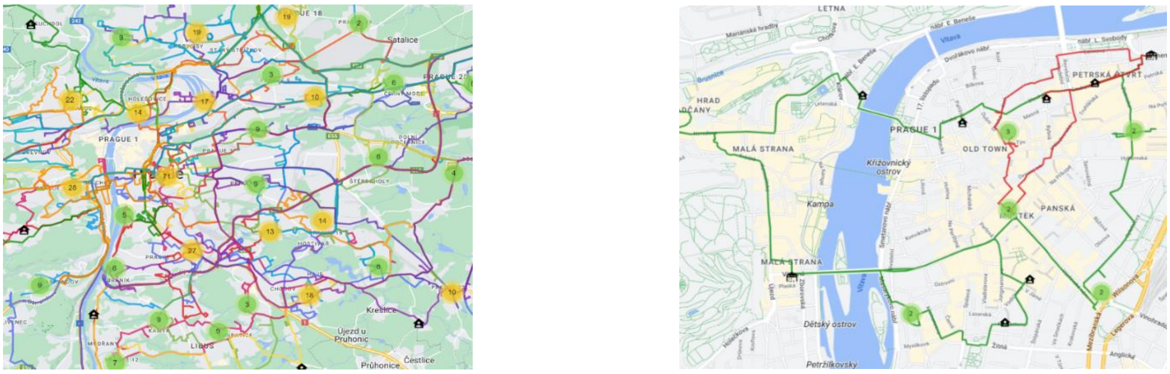
[4] As per the company's request, the name will remain undisclosed, and any other facts according to which it could be decisively identified. Consequently, all prices are always listed in units, corresponding to CZK*coefficient and, therefore, the conclusions are expressed in relative terms which remain accurate.

[5] https://github.com/graphhopper/jsprit

Table 1 Comparison of the operating cost of each scenario and each strategy

	Scenario			
Strategy	**No restrictions**	**EV in the city center**	**Pay-to-enter city**	**Bikes in the city center**
Current	100.0%	100.1%	116.1%	104.0%
2-boxes	101.7%	101.7%	118.0%	101.7%
22-boxes	106.6%	106.6%	110.0%	106.6%

The current strategy was optimal under the no restrictions and the EV in the city center scenarios; for a pay-to-enter scenario, the 22-box strategy was optimal; and for a bikes-only city center, the 2-box strategy proved most economical. The example of outputs from DW can be seen in **Figures 1**. Each line in the figures represents a route designed by DW to deliver orders to the given customers.



a) Distribution outside of the city center　　**b)** Distribution by bikes in the city center

Figure 1 Examples of simulated routes

4.3 Finding the probabilistically optimal strategy for each year

After obtaining the expected costs for each strategy under different scenarios, we applied our methodology, initially limiting the probability space for the pay-to-enter and no-restrictions scenarios. For example, the probability of a pay-to-enter scenario by 2024 was set to be at least 10%, while the likelihood of no restrictions would not exceed 75% by 2026. We then identified the optimal subspace for each distribution strategy by discretizing the full probability space, choosing a granularity of 5%. Using this framework, we calculated the expected utility for each strategy under various probability combinations, subsequently identifying the strategy with the lowest expected cost. Our results, depicted in **Figure 2**, show the optimal strategy for each modeled year, based on our probability constraints. In 2024, the current strategy dominates with a 60% share, followed by the 22-depots strategy at 27%. However, as the minimum probability for the pay-to-enter scenario rises and the maximum for no-restrictions decreases, we observe a shift in optimal strategies, primarily toward the 22-depots strategy.

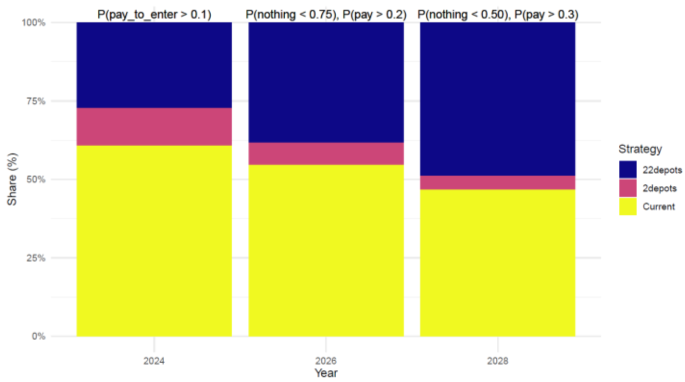


Figure 2 Shares of optimal distribution strategies each year

5. CONCLUSION

This article addresses the gap in strategic distribution network planning by introducing a methodology that replaces specific future expectations with more manageable probability intervals. Our approach simplifies the planning process without sacrificing the quality of insights. However, it still relies on accurately defined development scenarios and it is best suited for contexts where these can be estimated. The methodology's efficiency was validated using data from a Prague-based delivery company, demonstrating its adaptability to different scenarios, including evolving urban policies like a pay-to-enter regulation. Our findings show a shift in optimal strategies over time, with a 22-depot model gaining prominence as policy constraints tighten. This equips decision-makers with critical insights for long-term planning in uncertain environments. However, we should note that our method's effectiveness depends on accurately defining future scenarios and assessing strategy performance within these contexts. This dependency is a limitation, as inaccuracies can significantly affect the reliability of our conclusions. Future work aims to reintroduce causal relationships between company states, adding complexity but also enriching the model's applicability to a broader range of situations.

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