Unified Rural Logistics Delivery Model Based on Sustainability and Reliability

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1. Introduction

The development of e-commerce is closely linked to the development of logistics, which represents the key physical connection between digital purchasing and end customers. Efficient logistics is a key to successful e-commerce; otherwise, higher costs and longer delivery times are inevitable.

This paper focuses on the problem of rural logistics, specifically on delivery in rural areas. In regions with low population density, the issue of economic feasibility of parcel delivery arises. Logistics companies face the challenge of justifying delivery costs for a small number of customers spread across a relatively large area.

The paper proposes a model based on dynamic pricing, with the idea that customers voluntarily opt for later delivery, leading to the consolidation of shipments and resulting in lower delivery costs. The outcome is a delivery model that ensures sustainability and reliability of delivery in rural areas.

2. Rural logistics challenges

In urban areas, delivery is facilitated by high demand density, whereas rural areas face challenges related to low and spatially dispersed demand. E-commerce enables rural residents to access a wider range of products, lower prices, and goods that are not locally available, while providing local producers with access to broader markets.

From an economic and social perspective, e-commerce and logistics contribute to rural development by creating new jobs, reducing isolation and migration to urban areas, and improving quality of life, particularly for elderly and less mobile populations.

Rural logistics requires specific models such as shipment consolidation, flexible routing, a combination of professional and local delivery, and the use of consolidation centers, micro-hubs, and dynamic pricing in order to achieve long-term sustainability.

Delivery in rural areas is far less profitable compared to delivery in urban zones and is therefore not of interest to private courier operators. National postal operators carry out delivery in rural areas in accordance with their social function. However, national operators use a delivery approach based on a uniform pricing policy and variable delivery frequency depending on the delivery zone to which the user belongs.

Thus, the delivery zone is divided into inner, intermediate, and outer delivery zones, with deliveries carried out at different frequencies.

3. Rural logistics model with dynamic pricing and planned demand management

The proposed rural logistics model addresses the problem of high delivery costs and operational inefficiency through planned demand management rather than relying on fast but expensive delivery. The system integrates order buffering by service zones, periodic route optimization, dynamic pricing, and use of parcel lockers, with the aim of executing deliveries only when they are economically justified while remaining reliable.

The model consists of the following steps:

- Order accumulation and buffering
- User choice and demand shaping
- Economic threshold
- Route optimization.

Orders are grouped into service zones that cover multiple rural areas, representing the minimum economic unit for delivery.

Delivery pricing acts as a signaling mechanism. Users are offered clearly differentiated delivery options—ranging from faster and more expensive to slower but more affordable—thereby encouraging voluntary consolidation of shipments without degrading the perceived quality of service. Users can choose a time window during which their delivery is expected, shifting from a speed-oriented logic to a reliability-oriented logic.

Orders are temporarily held in a buffer, and at the end of predefined cycles, route activation is evaluated based on whether accumulated demand satisfies the economic threshold.

Waiting is not imposed on customers but transformed into a voluntary choice. Customers trade delivery speed for cost savings according to their preferences.

The model is further enhanced with the introduction of parcel lockers, which serve as intermediate nodes, reducing the number of home deliveries and shortening route lengths. This reduces cost, increases system flexibility and improves service perception.

The model operates through two parallel delivery channels: locker routes are activated earlier and more frequently, while home delivery is reserved for consolidated or time-sensitive shipments. Dynamic pricing further guides demand without compromising the user experience—users perceive savings and control rather than system limitations.

The result is lower cost per shipment, more frequent and reliable deliveries, stable user satisfaction, and long-term sustainable rural logistics.

At the core of the model lies the economic threshold for route formation—the minimum number of shipments or revenue required for a route to become financially viable. This threshold can be defined either by a maximum allowed cost per shipment (cost-based) or by the condition that total revenue covers route costs (profit-based). Since route costs depend on fixed vehicle and driver costs, variable per-kilometer costs, route length, and service level requirements, the economic threshold naturally increases with distance, route complexity, and service level.

This threshold is not static: dynamic pricing can raise or lower it, service level constraints may force route activation or price adjustments, alternative vehicle usage affects the threshold level, and geographic dispersion further increases required mileage. With the introduction of parcel lockers, route length and total cost are significantly reduced, allowing the economic threshold to decrease substantially.

The result is a rural logistics model that simultaneously ensures lower costs, high reliability, a clear user experience, and long-term system sustainability.

3.1 Mathematical Model

The mathematical model is based on the principle described in the text. Before defining the model itself, it is necessary to identify the following sets:

- Set of service zones $i \in Z$
- Set of time cycles $t \in T$
- Set of orders in individual service zones $j \in N_i$

The total cost of a delivery route in a rural area can be represented by the following formula:

$$C_{it} = F_i + c_d \cdot D_i + c_s \cdot q_{it} \cdot h_{it}$$

The total delivery cost consists of fixed and variable costs, where:

- F_i— fixed cost (vehicle and driver),

while the variable cost depends on the route length and the delivery structure (i.e., the share of deliveries redirected to parcel lockers);

- D_i— route length;
- c_d— cost per kilometer traveled;
- c_s— last-mile delivery cost per order;
- q_{it}— number of orders in zone *i* at cycle *t*;
- $h_{it} = 1 - l_{it}$— share of home deliveries;
- p_{it}— delivery price in zone *i* during cycle *t*;
- $x_{it} \in \{0,1\}$— decision variable indicating whether the route is activated or not;
- $l_{it} \in [0,1]$— share of deliveries via parcel lockers.

Costs can be reduced by lowering either fixed or variable components. The fixed component of costs can primarily be reduced through the use of green vehicles, which not only impacts costs but also increases the level of environmental protection.

On the other hand, variable costs can be reduced in several ways:

- The model enables an indirect reduction in route length by shifting deliveries to micro-hubs, i.e., parcel lockers, within the network.
- The cost per kilometer depends not only on the route length but also on the number of shipments on the route. The model allows customers to choose waiting-time-based options, thereby contributing to the formation of more profitable cycles in which the cost per kilometer is lower.

The revenue generated on a route is calculated as the product of the delivery price in zone *i* during cycle *t* and the number of orders in that zone and cycle.

$$R_{it} = p_{it} \cdot q_{it}$$

The key element of the model is the economic threshold, which can be represented as follows:

$$R_{it} \geq C_{it}$$

It is economically justified to establish a route and carry out delivery when the revenue generated on the observed route exceeds the costs incurred during the delivery phase.

Or expressed as:

$$p_{it} \cdot q_{it} \geq F_i + c_d \cdot D_i + c_s \cdot q_{it} \cdot h_{it}$$

From this, it is possible to calculate the minimum number of shipments required for the application of the model, i.e., for the defined route to be economically justified.

$$q_{it} \geq \frac{F_i + c_d \cdot D_i}{p_{it} - c_s \cdot h_{it}}$$

Orders are accumulated according to the following pattern:

$$q_{i,t+1} = q_{it}(1 - x_{it}) + d_{i,t+1}$$

The number of shipments in the next period is determined as the sum of newly arrived shipments and those remaining undelivered from previous cycles.

- $d_{i,t+1}$ represents new orders at time *t+1*.

When the route is not formed, all orders are carried over to the next cycle.

Route optimization is carried out based on cost minimization:

$$minC_{it} = F_i + c_d \cdot D_i + c_s \cdot q_{it} \cdot h_{it}$$

$$0 < l_{it} < 1$$

- D_i decreases as the use of parcel locker delivery increases.
- Route length is assumed to be a decreasing function of parcel locker share $D_i = f(l_{it})$, reflecting reduced delivery stops.

It should be noted that both capacity constraints and time constraints must be considered.

The objective function of the model is to maximize profit, i.e.

$$max \sum_{i,t} (R_{it} - C_{it})$$

Or:

$$max \sum_{i,t} (p_{it} \cdot q_{it} - C_{it})$$

Where:

- $p_{it} = f(\tau)$;
- $q_{it} = f(p, \tau)$;
- $C_{it} = f(l_{it})$;

The model shifts the control of delivery timing from the operator to the users, while preserving system-level efficiency through pricing and threshold constraints.

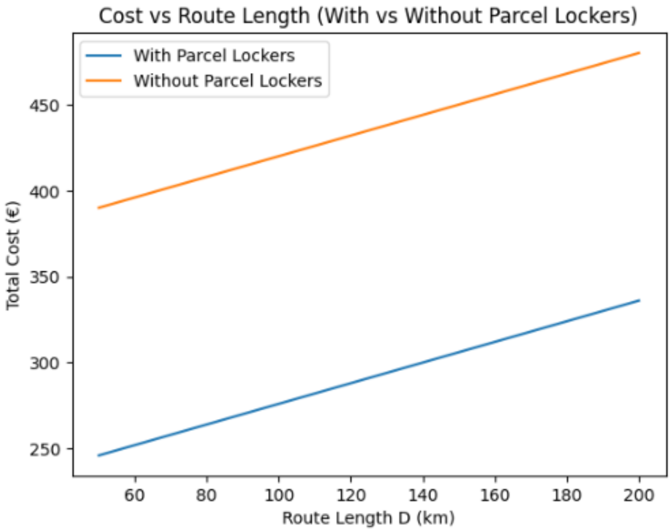

Figure 1. Cost vs Route length function (with and without parcel lockers)-example

The Figure 1. shows that the introduction of parcel lockers leads to a significant downward shift in the cost function. This reduction is driven by both shorter effective route lengths and a lower share of home deliveries. Consequently, parcel lockers play a crucial role in improving the economic efficiency of rural delivery systems.

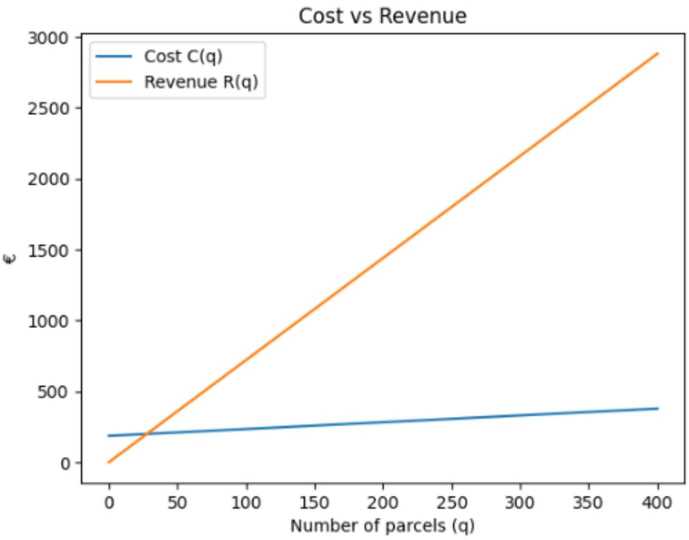

Figure 2. Cost vs Revenue function (example)

The cost function exhibits a relatively low slope due to the dominance of fixed costs and reduced last-mile delivery intensity, while the revenue function increases proportionally with demand. The intersection of revenue and cost curves determines the break-even point q^*, indicating the minimum demand required for profitability. Beyond this threshold, the system operates in a highly profitable regime, demonstrating strong economies of scale.

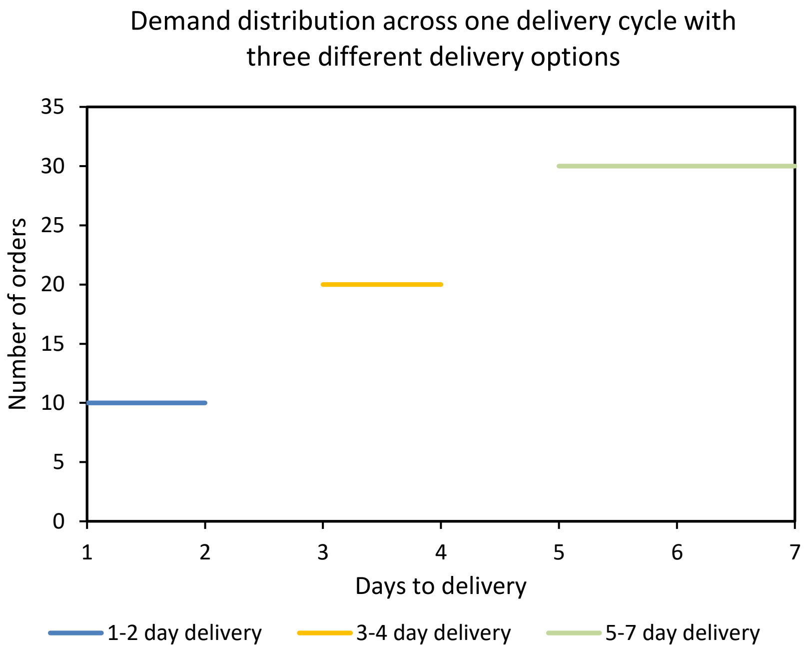

Figure 3. Example of demand distribution across one delivery cycle with three different delivery options

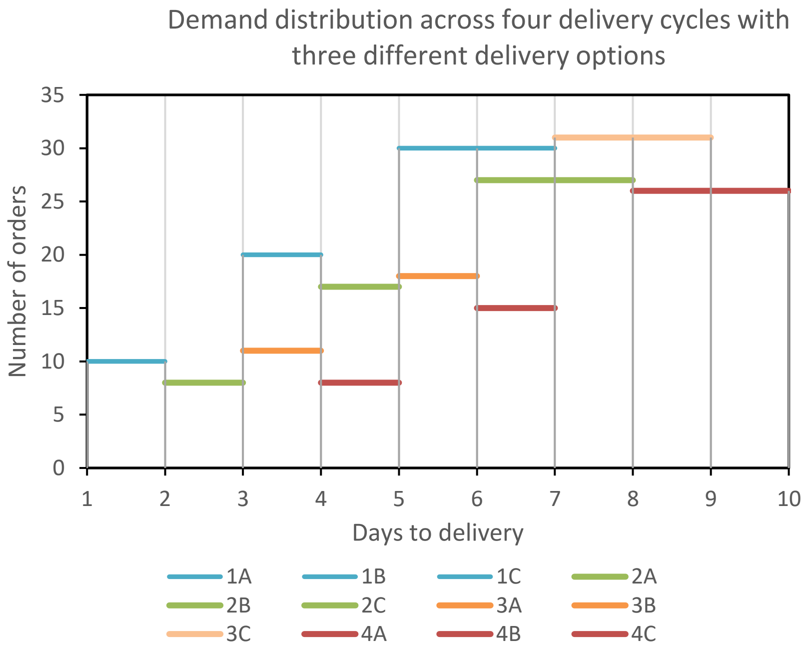

Figure 4. Example of demand distribution across four delivery cycle with three different delivery options (1A-first cycle fast delivery, 2C second cycle slowest delivery)

The figure illustrates the overlapping structure of demand across consecutive ordering cycles. Each day generates a new distribution of delivery preferences, which then extends over future time periods depending on the selected delivery speed. As a result, deliveries from different cycles overlap in time, leading to cumulative demand peaks. This effect is particularly pronounced for slower delivery options, where orders from multiple days are consolidated into a single delivery window. The model thus naturally creates demand waves, enabling higher shipment consolidation and more efficient route activation without requiring centralized scheduling decisions.

3.2 Dynamic pricing function

The model is based on the principle that a fixed delivery price is replaced by a price that depends on the amount of time the user is willing to sacrifice in the form of waiting. The user is not penalized for waiting; instead, waiting is treated as customers' willingness to trade longer delivery time for a lower price. The model can therefore be considered as a tool for demand management.

A higher number of parcels in delivery leads to a lower cost per shipment. The use of parcel lockers positioned at strategic locations reduces the number of home deliveries and, consequently, shortens the total route length. Parcel lockers are also important for the perceived quality of service. Longer waiting times lead to greater shipment consolidation, which reduces the delivery cost per shipment. On the other hand, lower prices encourage users to opt for later delivery. This effect facilitates reaching the price threshold at which delivery becomes economically justified.

One possible form of dynamic pricing function is:

$$p(\tau) \ = p_0 + \alpha \frac{1}{\tau}$$

where:

$p(\tau)$ - delivery price in zone for time delay τ

τ - waiting time

p_0 - minimum price (baseline price)

α - price sensitivity to delivery speed (how much the speed is penalized)

For low values of τ (corresponding to fast delivery), the price is relatively high. As τ increases, the price approaches p_0. The curve decreases rapidly and then stabilizes.

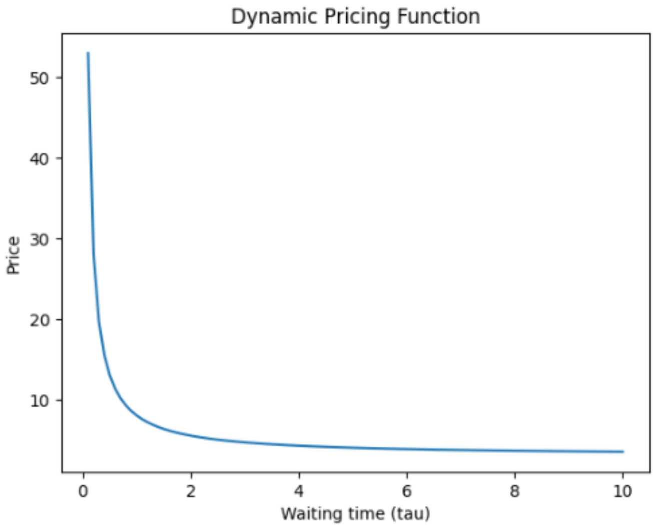

Figure 5. Dynamic Pricing function - example

Figure 6. illustrates the pricing function for different values of the parameter α. Higher values of α lead to steeper curves, indicating a stronger price premium for faster delivery. In all cases, the price asymptotically converges to the minimum price p_0 as the waiting time increases.

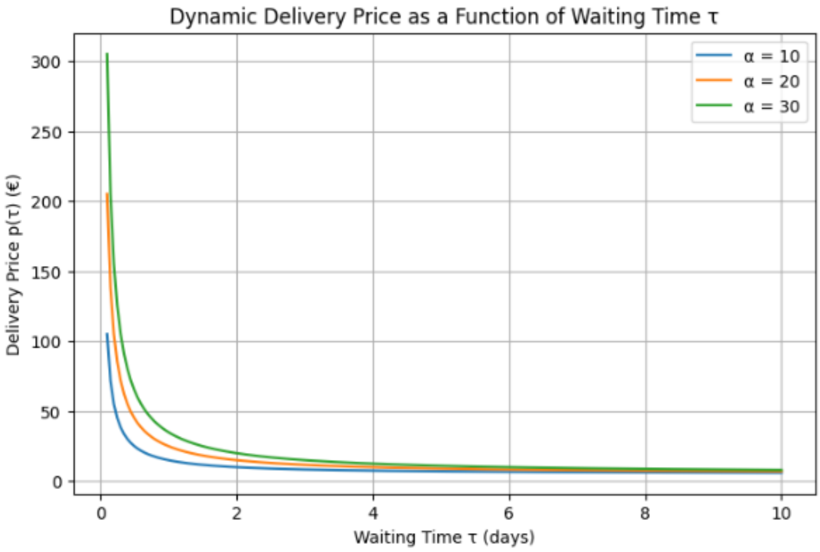

Figure 6. Dynamic pricing function for different values of the parameter α (example)

The model essentially performs three actions:

1. It segments users into those who require fast delivery and are willing to pay more, and a second category of flexible users who are willing to wait in exchange for a lower price.
2. It increases consolidation. The assumption is that more users will choose the slower delivery option, which results in a larger number of parcels being grouped into a single route, thereby reducing overall costs.

3. It stabilizes the system. The model leads to demand stabilization, meaning there are no chaotic requests for instant delivery. The idea is to spread demand over time.

The logistics operator does not directly determine delivery times. Instead, users influence operational decisions through their choices. In this way, the system balances price, delivery time, and operational efficiency.

User choice is modeled as a function of price and waiting time, where lower prices increase the probability of selecting delayed delivery options.

This mechanism operates so that lower-priced options attract a larger number of users, enabling faster accumulation of demand and quicker activation of delivery routes, and higher-priced options help cover operational costs when demand is low.

As it is said earlier, the minimum number of parcels required to activate a delivery route is given by $q*$:

$$q^* = \frac{F + c_d D}{p - c_s h}$$

It can be concluded that as the price p increases, the break-even threshold q^*decreases, making route activation easier, also lower prices require a higher number of parcels to achieve profitability.

Conversely, a higher price option lowers the threshold, allowing the route to be activated with fewer parcels, which ensures system reliability.

3.3 User Choice Modeling

Understanding the relationship between pricing (p), waiting time (τ), and actual user behaviour is key to accurately capturing system performance and validating the proposed pricing mechanism.

\Each customer chooses between following options: fast delivery option which is expensive and has shorter waiting time and slow delivery option which is cheaper and requires longer waiting time.

The utility functions are defined as:

$$U_F = \beta_p p_F - \beta_\tau \tau_F$$
$$U_E = \beta_p p_E - \beta_\tau \tau_E$$

Where:

- p — delivery price (p_F fast delivery price, p_E economy delivery price)
- τ — waiting time (τ_F waiting time for fast delivery, τ_E waiting time for economy delivery)

- βp — price sensitivity parameter
- $\beta \tau$ — time sensitivity parameter

Choice probabilities are given as:

$$P_F = \frac{e^{U_F}}{e^{U_F} + e^{U_E}}$$

$$P_E = \frac{e^{U_E}}{e^{U_F} + e^{U_E}}$$

Indicating that a higher P_F reduces the probability of choosing the fast delivery option also a higher τ_E reduces the probability of choosing the economy delivery option. Price-sensitive users are more likely to choose the economy option and time-sensitive users are more likely to choose the fast delivery option.

4. Conclusion

The problem of rural logistics is less presented in the literature. This paper presents an example of a model that directs attention to shipment consolidation in rural logistics.

The benefit of the model lies in the way consolidation is performed. The user selects a time interval allocated for delivery. In exchange for a lower price, the user agrees to a longer waiting time. The model generates a route only if the planned delivery structure is economically justified. Delivery costs may vary depending on multiple factors, thereby influencing the economic threshold.

Shipment consolidation provides multiple benefits for both users and logistics operators. Users benefit from improved delivery reliability, while logistics operators achieve lower costs. One of the key factors of consolidation is the reduction of exhaust emissions, which is an important contributor to sustainable transport.

The proposed rural logistics model achieves a balance between cost efficiency, service reliability, and user satisfaction. By integrating dynamic pricing, parcel lockers, route optimization, and economic thresholds, the model enables sustainable rural delivery operations, supports demand management, and ensures predictable service schedules.

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