

Truck-Drone Collaborative Delivery Strategies in Rural Last-Mile Logistics: A Constraint Theory and Contingency Theory Review

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Abstract

Compared with urban regions, rural last-mile logistics faces special delivery conditions, including scattered delivery points, sparse road infrastructure and low customer demand density. Currently, truck-drone collaborative delivery has emerged as a promising solution to this issue. But strategy selection across varying rural factors remains unexplored. This review aims to examine how collaborative delivery strategies perform under distinct types of rural bottlenecks through integrating Constraint Theory and Contingency Theory. Existing literature identifies that rural last-mile delivery is primarily confronted with four bottleneck types. They include road-network-driven, demand-driven, structure-driven and hybrid. Using this classification, this study compares the performance of two-stage and integrated optimization methods across categories. Findings reveal that integrated strategies are superior under road-network and structure bottlenecks, whereas two-stage strategies suffice under demand bottlenecks. A bottleneck-oriented strategy selection framework is constructed. The review delivers a theoretical framework by integrating two management theories into collaborative delivery research, practically providing valuable decision-making guidance for logistics enterprises and policy-makers.

Keywords

truck-drone collaborative delivery, rural last-mile logistics, constraint theory, contingency theory, two-stage and integrated optimization

1. Introduction

In recent years, rural last-mile logistics has attracted widespread attention. As e-commerce continues to extend into remote areas, the demand for expeditious rural delivery has grown considerably. When the State Post Bureau first put forward a proposal to “guide logistics enterprises to use drones for mail and express delivery in rural areas”, it signified the official adoption of drone delivery into rural logistics [1]. However, rural regions have unique environmental factors that need to be considered in delivery, including complex terrain [2], scattered delivery points [3], sparse road networks [4] and low demand density [5]. A collaborative

truck-drone delivery model, in which a truck serves as a mobile depot carrying multiple drones for last-mile delivery, can precisely offer a promising solution to break this bottleneck.

Existing modeling studies for truck-drone collaborative delivery can be clearly categorized into two approaches: Two-stage methods first cluster delivery demand points into zones and then adjusts the coordinated routes of trucks and drones within each zone separately. It reduces computational complexity and shows superior performance when dealing with large-scale distribution problems [6]. Integrated optimization methods solve partitioning decisions and routing decisions simultaneously, typically achieving better overall solution quality. But this model features a high degree of complexity, and computation time rises rapidly as problem size grows [7]. In terms of optimization objectives, multi-objective optimization methods have been widely studied in urban logistics distribution. Pareto frontier analysis is adopted to show the trade-offs among objectives such as cost, time and carbon emissions [8].

However, multi-objective optimization frameworks for this collaborative delivery mostly focus on urban scenarios, meaning that it has rarely been applied to rural last-mile logistics [9]. Besides, most current delivery models focus on improving single approaches or applying them in specific scenarios, lacking a systematic comparison between the two model methods in rural regions [10]. No prior review has applied Constraint Theory and Contingency Theory to examine collaborative delivery strategy selection in varying rural conditions [11, 12].

The aim of this literature review is to address these problems. Firstly, the study is to classify bottleneck types and their formation conditions in rural truck-drone collaborative delivery, drawing on Constraint Theory. It proceeds to compare the performance of two-stage methods and integrated optimization methods under different bottleneck types using Constraint Theory and construct a bottleneck-oriented strategy selection framework using Contingency Theory. Theoretically, this review applies two management theories to collaborative truck-drone delivery research. Practically, it provides reliable guidance for logistics enterprises and policy makers in selecting proper collaborative strategies for different specific rural scenarios.

2. Theoretical Background

2.1 Constraint Theory

Goldratt was the first to propose the Constraint Theory [11]. Its core viewpoint is that any system's performance is intrinsically limited by its bottleneck—the weakest link in the chain, and posits that identifying and systematically tackling the bottleneck is the major principle lever for improving overall system performance, rather than merely optimizing non-constraint components. Mabin and Balderstone documented successful applications of Constraint Theory in operations management and tracked bottleneck-focused adjustments [13]. These changes brought disproportionate performance benefits than generalized improvement efforts. One critical conclusion of theory is that adjustments to non-bottleneck links barely lift overall system performance. This principle can steer strategy selections for rural delivery optimization.

This study examines rural truck-drone collaborative delivery work. The theory explains varied strategy requires across different settings. Rural terminal delivery faces multiple potential constraints. Customer orders are sparse. Road coverage is insufficient. Delivery points stretch over wide areas. These constraints exert disparate effects across diverse rural scenarios. Deficient road conditions block efficiency in some rural areas. Low aggregate order volumes constitute the key bottleneck and create sluggish operational throughput elsewhere. Constraint Theory points out one plain fact. The effectiveness of a given collaborative delivery strategy depends on whether it targets the system's actual dominant bottleneck.

2.2 Contingency Theory

Lawrence and Lorsch put forward Contingency Theory. No single organizational setup or management plan works perfectly in every situation [12]. A management plan shows value only under its own surrounding conditions. Donaldson refined this theoretical structure. His study showed organizational performance hits its highest level [14]. Matching chosen strategies to local environmental features creates this result. The theory holds one key finding. Good matches between strategies and local conditions beat the inherent strengths of any single fixed plan.

This paper uses Contingency Theory to select varied delivery strategies. The theory supports a clear viewpoint. Two-stage optimization and integrated optimization do not stay superior in every case. Their real efficiency shifts with rural delivery features. These features include terrain difficulty, road density and order trends. Wong et al. shared similar results in their published work [15]. Their study marked shifting impacts from unstable environmental factors. These factors change supply chain strategy performance.

2.3 Framework Integration

Combining the two theoretical systems forms a clear analysis structure for follow-up research. Constraint Theory pinpoints the core problem to resolve. This core problem is the system bottleneck. Contingency Theory outlines pathway to address this problem. Operators shall align chosen tactics with local real conditions. This combined thinking supports the current review. The review investigates real results of collaborative delivery strategies under different rural bottleneck situations.

3. Literature Review

3.1 Truck-Drone Collaborative Delivery Routing Optimization

Murray and Chu [16] launched early research on truck-drone collaborative delivery. The team defined the Flying Sidekick Traveling Salesman Problem (FSTSP). Existing research methods fall into two major types. Each type follows different theoretical logic. The logic focuses on how researchers handle partitioning and routing decisions.

Two-stage methods rely on the principle of problem decomposition. Complex optimization tasks can be split into several simple sub-tasks. These smaller tasks can be solved one after another. Calculation difficulty becomes much easier to manage. The method divides delivery points into separate areas first. Route optimization is completed separately within each zone. Agatz et al. [6] constructed a classic partition-based analysis framework. Boysen et al. [17] adopted similar ideas for multi-drone scheduling work. Moshref-Javadi et al. [18] expanded this method to multi-truck and multi-drone systems. Carlsson and Song [19] provided theoretical support for the above research.

This method brings obvious computational advantages. Separate decision processing lowers overall problem scale. Large-scale rural delivery cases can be calculated within acceptable time. Rural logistics usually involve widely scattered delivery points. Field operation equipment also faces limited computing capacity. The method also carries obvious inherent defects. Partition work and route planning work are treated as two independent steps. Related delivery points may be divided into different areas. Potential coordination benefits across different zones cannot be fully used. The degree of optimization loss changes with zone connection conditions. Rural landforms and road conditions lead to unstable connection degrees between adjacent service areas. Mountain terrain forms clear natural boundaries. Two-stage methods work efficiently in such regions. Flat countryside areas contain dense residential spots and connected roads. Zone division cuts internal connection relations and raises overall operational costs.

Integrated optimization methods focus on overall solution optimality. Mutual influence exists between partitioning and routing variables. Synchronous optimization produces better global results. All partitioning work and routing work is finished in one unified model. Yurek and Ozmutlu [7] established an integer programming model for integrated calculation. Jeong et al. [20] incorporated flight distance and payload constraints. A local iterative search algorithm was designed by Marinelli et al. [21]. Salama and Srinivas [22] proposed a joint clustering and routing model.

Integrated methods show unique advantages in result quality. The model keeps all internal connections between partitioning and routing decisions. All truck-drone cooperation modes are considered in the calculation process. The structural defects caused by step-by-step decomposition can be avoided. Complex rural terrain and road distribution make regional connection relations more complicated. Integrated methods show theoretical strengths in rural scenarios. The method faces obvious technical bottlenecks in computing efficiency. Solution ranges expand rapidly with more delivery nodes. Truck stop arrangements produce massive combinatorial possibilities. Drone distribution choices further multiply the overall calculation amount. Most practical applications rely on heuristic optimization algorithms. Such algorithms shorten calculation time

effectively, but strict global optimal results cannot be guaranteed. Different degrees of calculation errors will appear. Large-scale rural delivery scenarios contain numerous demand points. Integrated models often face excessive calculation pressure in such cases. Two-stage decomposition methods show more practical advantages in large-scale rural scenes.

Differences between the two methods reflect a common trade-off in optimization research. Though Cheng et al. [10] compared sequential and synchronous approaches, research is limited to urban instant delivery with single-objective optimization. The literature fails to systematically compare the two methods under rural settings, where the degree of coupling between partitioning and routing changes with terrain, road network, and demand characteristics.

3.2 Multi-Objective Optimization in Logistics Distribution

Logistics distribution problems naturally contain several conflicting optimization objectives. Multi-objective optimization theory supports the solution of such problems. The theory defines Pareto-optimal solutions where no objective can be improved without weakening other indicators.

Deb et al. [8] created the NSGA-II algorithm in relevant algorithm research. Fast non-dominated sorting and elite retention form its core design. The tool maintains solution diversity and guarantees accurate convergence to the standard Pareto frontier. Zhang and Li [23] established the MOEA/D algorithm. The design logic breaks multi-objective problems into multiple single sub-problems. These divided units gain optimal results through coordinated calculation.

Urban logistics practice proves the usability of these algorithms. Wang et al. [24] adjusted overall cost and carbon emission indicators. The study confirmed existing trade-off relations between economic and environmental benefits. Zhou et al. [25] balanced operating costs and consumer satisfaction, uncovering marginal effects in service quality improvement. Chen et al. [26] designed a three-goal model incorporating travel distance, operating time and energy consumption.

Related research on truck-drone delivery still lacks sufficient exploration. Most existing studies focus on fixed urban scenarios. Coelho et al. [9] optimized cost and waiting time for single-truck and single-drone configurations. Ham [27] analyzed the balance between operating cost and service quality. Moshref-Javadi et al. [28] expanded multi-objective analysis to multi-device systems. The study took delivery efficiency and drone usage rate as conflicting optimization goals. While these studies verify the feasibility of multi-objective optimization in hybrid delivery work, all research targets urban areas with concentrated orders and complete road systems, which do not match rural logistics features. Rural sparse road networks and scattered customer distribution reshape the Pareto frontier. Urban trade-off relations are affected by traffic congestion. Rural optimization differences come from road detours, customer needs and scattered demand layouts. Few academic works have discussed this theoretical difference.

3.3 Characteristics of Rural Last-Mile Logistics

Rural last-mile delivery systems possess features fundamentally different from urban logistics. Such features greatly affect the practical performance of collaborative delivery models. Dispersed customer demands and scattered village layouts constitute the major operational difficulties in rural areas. He and Wang [3] identified low order density would trigger diseconomies of scale. Boyer et al. [5] further proved sparse demand raises single-parcel delivery costs significantly.

Sparse road structures worsen rural delivery conditions. Liu and Zhang [4] regarded insufficient road facilities as a key factor limiting logistics efficiency. Tan et al. [2] recognized road constraints as the main barrier to timely rural distribution. Hu et al. [29] emphasized drones have unique practical value in such contexts. Straight flight paths cut delivery length greatly when trucks face long road detours.

High demand fluctuation is also typical. Cardenas et al. [30] recorded obvious seasonal changes and small individual orders in rural markets. Li and Zhao [31] summarized the common efficiency problems of rural last-mile service. Although current studies acknowledge rural logistics uniqueness, most truck-drone delivery studies still adopt urban parameters and rarely integrate real rural operational characteristics into the model comparison framework.

4. Key Finding

4.1 Theoretical Contributions

This review makes three primary theoretical contributions to the literature on truck-drone collaborative delivery and rural logistics optimization.

First, this study applies Constraint Theory to truck-drone collaborative delivery and argues that bottleneck type is a meaningful variable for explaining and predicting strategy effectiveness. It develops a diagnostic framework that moves beyond urban-focused optimization studies by grouping rural delivery constraints into four types: road-network-driven, demand-driven, structure-driven, and hybrid. This point fits with Mabin and Balderstone's [13] meta-analytic finding that identifying the constraint is a necessary early step in systematic performance improvement, while showing how that idea works in rural collaborative delivery. The four types do not limit performance in the same way. Road-network bottlenecks arise from physical infrastructure limits, whereas demand bottlenecks work through economic conditions that routing algorithm choice may not change much. By connecting each bottleneck type to the mechanism that restricts performance, the framework offers a clearer causal explanation.

Second, this review uses Contingency Theory to justify selecting different strategies for different rural conditions. No single strategy is optimal across all rural bottleneck types. Here, the data points in one direction. This claim follows the core position of contingency theorists [11, 12] that effectiveness depends on how well the chosen approach fits its context. The review brings that logic into a domain where it has not been applied in a systematic way and supports Wong et al.'s [15] contingency framework. More specifically, it suggests that the contingency principle matters at the operational level of algorithm selection, not only at the broader strategic level of supply chain design.

Third, bringing Constraint Theory and Contingency Theory together in one analytical framework adds a theoretically new “diagnose-then-match” logic. Constraint Theory identifies what is limiting performance, while Contingency Theory guides the choice of approach once that constraint profile has been identified. This helps address a long-standing weakness in optimization research. Many studies compare methods in abstract computational terms, but do not clearly connect method characteristics to the conditions of the problem being solved.

4.2 Review Insight

The findings of this review connect with several strands of earlier research, but they do not fit them in exactly the same way.

One clear extension of Cheng et al.'s [10] comparative analysis appears in two areas. Cheng et al. compare two-stage and integrated approaches in urban instant delivery using single-objective optimization. Here, the comparison is widened to rural settings, where the geographic and economic conditions differ in ways that affect system performance. More specifically, this review points to bottleneck types that are distinctive to rural areas, especially the road-network-driven bottleneck. That issue has little real urban equivalent, because urban areas rarely show detour coefficients close to those reported in rural settings [4].

The multi-objective findings also connect with the studies by Coelho et al. [9], Ham [27], and Moshref-Javadi et al. [18], who confirmed the feasibility of multi-objective optimization in collaborative delivery but kept their analysis within urban contexts. This review takes that discussion into rural conditions by examining how multi-objective trade-offs may vary across different rural bottlenecks. The main argument is specific: bottleneck type may shape the geometry of the Pareto frontier. This point comes from bringing together the literature on rural logistics characteristics and the logic of multi-objective optimization. It matters here.

Besides, this review adds analytical specificity to He and Wang's [3] findings on rural logistics scale diseconomies. Instead of treating scale diseconomies as one general condition, it separates cases where collaborative strategies may partly reduce them from cases where they are less likely to help. For example, drone straight-line flight may offset some disadvantages under road-network bottlenecks. Under an economic constraint, however, that benefit may not solve the underlying problem. The result is a clearer account of when technological solutions can ease rural logistics difficulties and when they cannot.

5. Discussion

5.1 Practical Implications

The bottleneck-oriented framework gives logistics enterprises practical guidance. In regions where sparse road networks are the main constraint, enterprises should give priority to integrated optimization strategies because synchronized decision-making makes better use of drones' straight-line flight advantage when trucks must take long detours. Where demand density is the main constraint, two-stage decomposition strategies appear to deliver enough performance at a lower computational cost. For these cases, the trade-off is clearer.

The findings also support different infrastructure investments for policy-makers. In road-network-bottlenecked areas, policy should prioritize the construction of drone launch and recovery stations, because drones have the greatest relative advantage in these settings. In demand-bottlenecked areas, the first priority should be demand aggregation to increase order density before more complex collaborative delivery systems are introduced. These recommendations provide a theoretical basis for advancing the “express delivery to every village” initiative and respond directly to the policy context set out in the introduction [1].

5.2 Limitations and Future Research

Using these two theories as a combined analytical lens, this review classifies bottleneck types, compares strategy performance, and develops a selection framework. There are, however, several limitations. Because this is a literature-based synthesis, the findings have not been tested empirically. I did not examine simulation results or operational data from a specific rural delivery case, so the framework should be treated as provisional rather than confirmed. Future research could test the proposed strategy selection framework through simulation experiments, add real rural delivery case studies, and extend the analysis to dynamic factors such as weather conditions, seasonal demand fluctuations, and other environmental variables that may affect truck-drone system delivery performance.

6. Conclusion

This review applies the integrated perspective of Constraint Theory and Contingency Theory to examine truck-drone collaborative delivery strategy selection in rural last-mile logistics. Based on the above studies, there are three main conclusions.

Rural truck-drone collaborative delivery systems are confronted with four distinct types of bottleneck. These categories cover road-network, demand, structure and hybrid types. Village scattering, road coverage levels and demand concentration decide each respective bottleneck group. This typology provides a structured diagnostic framework for characterizing rural delivery environmental conditions in terms relevant to optimization strategy selection.

Two-stage and integrated methods reveal different performance under different bottleneck types. Integrated strategies outperform under road and structural bottlenecks. Strong coupling between partitioning and routing makes cross-boundary coordination valuable. Two-stage strategies offer sufficient viability with lower computational cost under demand bottlenecks. The binding constraint is economic rather than algorithmic.

Strategy selection must be bottleneck-contingent. Consistent with Contingency Theory, no single strategy is universally optimal. Sound strategy selection hinges on systematic diagnosis of the dominant bottleneck, with subsequent calibration of optimization solutions to match the characterized constraints.

This study merges two classic management theories into joint delivery research and offers decision-making guidance for logistics companies and policy makers via the practical contribution. Future research could conduct empirical verification of the proposed framework through simulation or field studies. Seasonal order shifts and other dynamic factors can be considered to analyze. And innovative hybrid methods combining decomposition and integrated logic also deserve further exploration.

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Conflicts of Interest

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