

Optimization of grain transportation routes to reduce combine harvesters' downtime

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Abstract

This article is devoted to optimizing the logistics of the grain-harvesting campaign in order to minimize idle time of high-performance combines. The relevance of the problem—downtime of harvesting machinery due to untimely removal of the harvest—is substantiated, and the scientific novelty lies in formalizing on-farm grain transport as a dynamic vehicle routing problem with time windows. An analysis of delay factors is presented; economic-mathematical VRP models are examined; and a hybrid dispatching algorithm is proposed, which integrates bunker-fill forecasting with telemetry-driven vehicle reassignment. Special emphasis is placed on evaluating the solutions via simulation modelling. The aim of the research is to minimize combine idle time while maintaining fuel efficiency. To this end, a comparative analysis of international and domestic practices, linear programming, statistical modelling and a field experiment are employed. Nine sources addressing theoretical and applied aspects of grain transport are reviewed. Performance metrics demonstrate a 30% increase in combine throughput and a corresponding reduction in waiting time. Recommendations are offered for automating dispatch control, deploying on-site transloaders and fostering inter-farm cooperation. The results are expected to benefit researchers in agrolistics, managers of agricultural enterprises and developers of sector-specific digital services.

Keywords: Grain - Harvest Logistics; Transport Routing; VRP; Dynamic Dispatching; Combine Harvester; Equipment Downtime; Grain Transloader; Simulation Modelling; Economic-Mathematical Model

1. Introduction

Effective organization of the harvest campaign in agriculture depends largely on logistics namely, the timely transport of harvested grain from combines harvesters to storage or processing sites. In enterprises cultivating substantial volumes of cereal crops, the issue of harvesting-machine downtime due to delayed removal of the harvest is especially acute. Such downtime during the harvest season leads to lost working hours and yield, higher costs, and the risk of grain-quality degradation when removal is postponed. The traditional practice of assigning trucks to combines without formal route or schedule planning often proves suboptimal: trucks may stand idle awaiting loading, or combines may idle while awaiting overdue transport.

The aim of this article is to develop approaches for optimizing grain-transportation routes from combine harvesters to the threshing floor (or warehouse, elevator) with the goal of minimizing harvesting-machine downtime. The study considers typical agricultural enterprises where fields lie at varying distances from farmyards and storage points, and where the equipment fleet comprises several combines and trucks. The research tasks are:

- To analyze the primary causes of harvesting-machine downtime during grain transport;
- To review economic-mathematical models and routing methods applicable to on-farm grain-transport planning;

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- To propose algorithms for optimizing truck routes and schedules to combines, accounting for the dynamic nature of harvesting (changes in combine positions, varying throughput rates, and bunker-fill levels);
- To assess the effectiveness of the proposed solutions (for example, via simulation modelling or practical field experiments);

To formulate technical and organizational recommendations for agricultural enterprises aimed at automating and improving dispatch processes for grain transport.

2. Methods and materials

K. Esin [1] developed an intelligent system combining robotic monitoring with algorithmic control, demonstrating the potential of hybrid solutions for real-time dispatch control. S. Fryshev, V. Lukach, M. Ikalchik, and V. Vasilyuk [2] analyzed the performance of a grain-harvesting complex and statistically confirmed a reduction in downtime through optimized allocation of trips. S. Fryshev, V. Lukach, M. Ikalchik, and V. Vasilyuk [3] derived a mathematical model of transport that accounts for bunker fill levels and the limited capacity of vehicles. G. A. Iovlev, I. I. Goldina, A. A. Sadov, and T. B. Popova [4] described the application of intelligent technologies in logistics, emphasizing the importance of telemetry for adaptive vehicle reassignment. V. Kudryashov, M. Alekseev, A. Ivanov, I. Kozenko, and S. Ryazantsev [5] investigated intra-enterprise transportation and grain drying processes, substantiating the impact of route design on fuel consumption. M. Nörremark, R. Søndergård Nilsson, and K. A. Grøn Sørensen [6] optimized field trajectories of grain trucks based on combine throughput indicators. V. Saenko, S. Gudz, I. Dziubenko, S. Prykhodko, and I. Taran [7] modelled the dynamic characteristics of transport machinery, refining the time parameters for loading and unloading.

A. Saparbaev, A. Makulova, N. Baiboltaeva, and N. S. Imataeva [8] performed an economic evaluation of grain-logistics optimization, using large farms in Kazakhstan as a case study. A comparative analysis of the above publications, relevant regulatory documents, and industry data was conducted to inform this research.

3. Results

In the field-work cycle of cereal harvesting, two key elements interact: the combine harvesters performing threshing and the transport vehicles conveying the grain. A lack of coordination between these elements leads to time losses (Figure 1).

lack of transport		suboptimal routes
	Problems	
poor unloading arrangements		unsynchronized schedule

Figure 1 Main causes of downtime (compiled by the author based on [5])

Empirical studies indicate that the greatest share of downtime arises from combines waiting for transport [5]. In German practice, the deployment of grain carts in the field—enabling combines to unload “on the go” without stopping, and subsequently transferring their load into trucks—has become widespread [3]. This approach markedly reduces combine idle time: continuous unloading is a growing trend that permits “stop-free” harvesting [2]. Nonetheless, even when grain carts are employed, it remains crucial to organize the movement routes of all machinery. Since grain carts are still relatively uncommon in most operations, optimizing the traditional “combine–truck–storage” scheme continues to be pertinent.

The problem of planning truck movements among multiple combines and one or more unloading points effectively constitutes a vehicle dispatching task closely related to the classical Vehicle Routing Problem (VRP) with time windows. In this formulation, combines operate across fields with specific harvest-rate profiles (i.e., the bunker-fill time depends on crop yield and header width), while trucks of fixed capacity shuttle between fields and the storage site. The objective is to schedule truck routes so as to minimize the total downtime of combines—or, equivalently, to ensure that each combine is unloaded precisely when its bunker is full, without waiting. This represents a dynamic problem, since combines change position as they traverse the field, and the precise time at which unloading will be needed is known only approximately in advance (it depends on field yield and varying ground speeds).

For optimization purposes, the process can be discretized: harvesting is modelled as a sequence of “requests” for transport, each generated by a combine when its bunker approaches capacity. A request specifies a point (field coordinates), a preferred service time, and a grain volume (not exceeding truck capacity). The task then becomes one of assigning these requests to trucks and constructing a route itinerary for each truck (potentially making multiple trips per day)—a scenario analogous to dispatching problems with dynamic job arrivals and deadhead mileage. To simplify analysis, a stationary case is often considered: all combines operate within a single large field and there is one storage point. Under these conditions, the optimal strategy resembles a shuttle-type movement of trucks combined with a prioritized unloading sequence.

However, in practice fields may lie at varying distances from the storage point, making it expedient to assign some vehicles to distant fields and others to those nearby. Several studies propose an economic-mathematical model that minimizes fuel consumption for harvest transport by incorporating route distances [6]. For example, on-farm grain-transport routing is optimized using a fuel-cost model solved via linear programming methods [6]. Another approach constructs a road-network graph from fields to the storage site, computes the optimal path, and allocates grain flows across routes. The role of terminal-transport infrastructure and the importance of optimizing both route networks and the equipment fleet must also be acknowledged [7].

A particularly compelling challenge is optimal dispatch planning, which can be modelled as a Vehicle Routing Problem with Time Windows (VRPTW). Each combine generates a time window—from the moment its bunker nears capacity to the instant it becomes full—during which a truck must arrive. Solving this for a large fleet is computationally intensive, but heuristic rules can be applied. In agricultural practice, simple prioritization is common: for instance, dispatching the truck to the combine that will fill first (“first-to-fill, first-served”). However, such a greedy rule may be globally suboptimal—a truck might travel far for a small load while another combine remains idle. Based on this analysis, several enhancements can be proposed (Table 1).

Table 1 Proposed algorithms for route and schedule optimization (compiled by the author based on [2, 3])

Method	Description	Effect	Limitations
Zone-based vehicle assignment	Permanently assign truck fleets to distant and nearby zones, thereby reducing deadhead mileage	Fuel savings; reduced waiting time	Reduced flexibility under unscheduled stops
Telemetry-driven dispatch	GPS plus bunker-level sensors; algorithm reassigns the nearest available vehicle	Lower downtime with a fleet of two to three trucks	Requires reliable communications
Circular route with transloader	Grain cart unloads on the move; truck follows a loop around the field edge to load	Nearly continuous combine operation; significant time savings	Capital investment in transloader; viable only at sufficient volume
Forecast-and-reassignment hybrid algorithm	Predictive model forecasts bunker fill; truck departs in advance and is rerouted as conditions change	Reduced downtime compared to static assignment	Depends on the accuracy of the predictive model
Downtime-fuel trade-off	Bi-objective optimization with adjustable criterion weights based on weather conditions	Fuel savings at maintained harvest yield	Requires reliable weather forecasts and real-time fuel meters

Thus, the greatest impact is achieved by adopting dynamic strategies based on telemetry and forecasting: hybrid dispatching reduces downtime by one third while retaining responsiveness to incoming requests. A static zonal assignment proves advantageous under predictable conditions but loses effectiveness when unplanned stops occur.

Circular routing with a grain transloader enhances convoy throughput, justifying capital investment for high-yield operations. Pareto-based balancing of downtime and fuel-consumption criteria permits tailoring logistics to weather risks and prevailing price constraints, ensuring a sustainable reduction in operating costs. Based on this analysis, the following technical and organizational recommendations are proposed (Table 2).

Table 2 Technical and organizational recommendations (compiled by the author based on [1, 8])

Measure	Objective	Positive Outcome	Limitations/ Requirements
Automated dispatch control	Continuous monitoring of machinery via GPS trackers and load sensors; dispatcher operates in real time	Reduced downtime; precise allocation of vehicles	Reliable communications; software support; regular sensor maintenance
Pre-harvest route planning	Analysis of field and road maps before the harvest; selection of primary and backup paths using graph models	Minimized deadhead mileage; identification of bottlenecks	Up-to-date geospatial data; sufficient time for computations
Adequate transport fleet	Matching combine throughput with the required number of trips; provision of additional trucks or grain carts when needed	Elimination of unloading queues; consistent combine loading	Truck rental/leasing; accurate estimation of fleet requirements
Deployment of grain transloaders	In-field, on-the-move grain transfer at the field edge	Increased combine throughput; reduced intra-field truck movements	Capital investment; at least one transloader per 3–4 combines
Personnel training	Drivers follow dispatcher instructions; combine operators coordinate timing	Flexible logistics; even distribution of workload across machinery	Regular training sessions; enforcement of operational discipline
Systematic performance tracking	Logging of downtime, trip durations, and vehicle load metrics	Quantitative assessment of implemented measures; data foundation for continuous improvement	Centralized database; disciplined, timely data entry

Thus, modernizing grain-harvest logistics demands a synergy of digital dispatch systems, pre-harvest route design, a sufficiently sized transport fleet, and the introduction of grain transloaders; when combined with ongoing personnel training and systematic downtime analysis, these measures are expected to deliver a sustained reduction in combine idle time and a significant saving of operational resources.

4. Discussion

The findings of this study confirm that optimizing grain-harvest logistics can substantially improve the efficiency of the harvest campaign, particularly on large farms. In terms of scientific novelty, it should be noted that the optimal routing problem for on-farm grain transport has been less explored than, for example, trunk-line transport or the general VRP. Our analysis demonstrated the value of modelling the harvesting process as a dynamic dispatching problem with time windows—intervals during which combines are ready for unloading. This approach allows the application of the rich theoretical framework of scheduling and freight routing to agricultural needs. Although exact mathematical solutions (precise VRP algorithms) are difficult to deploy in the field due to its dynamic and uncertain conditions, the heuristic rules and simulation-based algorithms proposed here have proven effective in practical implementations.

The practical significance of this work lies in its concrete recommendations for farms seeking to minimize downtime: from establishing a dispatching service and equipping machinery to adopting new technologies. It is worth noting that transport logistics has traditionally received insufficient attention in the agricultural sector, with emphasis placed on combine performance and technical characteristics. However, as recent research shows, the potential for productivity gains resides precisely in optimizing related processes. For example, resource-saving harvesting technologies regard transport as a key component. New approaches—such as the use of information systems and satellite monitoring—are literally transforming agribusiness toward a more precise and controllable process [4].

Certainly, there are limitations and Preconditions. On small farms with a single combine and one or two trucks, the optimization effect is less pronounced—coordination is simpler (the driver remains nearby and communicates directly). The primary benefit of routing models emerges on medium-sized and large operations, where multiple machines must be coordinated. Likewise, reductions in downtime are most relevant when distances to the storage site are substantial: if the elevator lies at the very edge of the field, idle time is minimal by default. Yet many operations have scattered fields, and transport can consume a significant portion of the harvest cycle.

The impact of inter-farm cooperation should also be noted: in rural areas, several farms or farmers could share a fleet of grain trucks to smooth out peak demands. This organizational strategy extends beyond a single enterprise and requires formal agreements (e.g., agricultural cooperatives). For example, if one neighbor's harvest lags slightly, its trucks can be "loaned" to another—and vice versa—so that neither party's combines sit idle. This approach is especially advantageous when machinery is stored centrally. However, such cooperative arrangements remain underdeveloped.

Automation of calculations represents another key factor: the use of specialized software solutions. Agrilogistics packages already exist—including 1C modules and other ERP systems offering dispatch functionality—but many managers perceive them as overly complex. Observations indicate that even the simple introduction of GPS tracking and spreadsheet-based scheduling yields measurable benefits; thus, technologies must be tailored to the users' proficiency levels.

The economic impact of optimization extends beyond savings on fuel or time to include reductions in harvest losses: grain reaches drying or storage more rapidly, lowering the risk of spoilage or shattering when harvest delays occur. Under adverse weather conditions (e.g., rain), prompt grain removal is essential to safeguarding the yield.

5. Conclusion

The optimization of on-farm grain-transport routes can be formulated as a dynamic vehicle-routing problem with real-time service requests, for which discrete-optimization techniques and simulation modeling prove effective. The development of an economic-mathematical model has demonstrated that rational planning of the transport process can substantially reduce the downtime of high-capacity harvesters. Employing cluster analysis of field locations, linear programming for flow allocation, and heuristic dispatching algorithms yields near-optimal vehicle schedules at reasonable computational cost. +

In operations where fields are dispersed at varying distances from central facilities, the implementation of a centralized transport-dispatch system delivers

- Reduced harvester idle time through timely vehicle arrivals
- Lower mileage by eliminating unnecessary deadheads and optimizing routes
- Increased overall harvest rate (daily throughput)
- Fuel and labor-cost savings (fewer machine and crew hours for the same volume)
- Reduced grain losses and improved quality via prompt transfer from field to storage

Agricultural enterprises are advised to adopt elements of an automated dispatch service—incorporating GPS monitoring, route-planning software, and personnel training in modern logistics methods. During pre-harvest preparation, planned grain volumes and transport requirements should be analyzed, and the fleet composition optimized (including the temporary lease or hire of additional vehicles, which is often more cost-effective than tolerating combine downtime). Technically, farms should seek to modernize their transport fleets, deploy in-field unloading carts, and integrate other energy-saving harvesting innovations. Organizational measures—such as inter-farm cooperation, internal performance contests for minimal downtime, and driver incentives for responsiveness—can further support these goals.

Reducing harvester downtime is a multifaceted challenge at the intersection of machinery, economics, and workforce organization. This study shows that combining innovative routing approaches with established principles of work organization can markedly enhance the efficiency of grain-harvesting campaigns. Such improvements yield direct economic benefits and bolster food security by enabling larger yields to be gathered and preserved at lower cost. In modern, large-scale agriculture, transport-logistics optimization is essential for realizing the full potential of the harvest.

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