OPTIMIZATION OF TRANSPORT ACTIVITIES IN THE SUGAR BEET HARVESTING CAMPAIGN

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A B S T R A C T

This paper explores the optimization of sugar beet transport from loading points to processing plants throughout the harvest campaign. An optimization model was developed to address the key logistical aspects of this process. The approach was applied to data from a company that encompasses 50% of Serbia's sugar beet processing, with operations across three sugar factories. The results include an evaluation of the current operating method and the analysis of two alternative scenarios that present further opportunities to reduce logistical costs. These savings not only lower company expenses but also contribute to reduced greenhouse gas emissions, underscoring both economic and environmental benefits.

Introduction

Production and processing of sugar beet in the European Union (EU) play a significant role in the European agribusiness complex. Over the past decade, sugar beet has been cultivated in the EU on approximately 1.5 million hectares, accounting for about 2% of the total temporary crops. With relatively high average yields (around 70 tons/ha), the total annual production of sugar beet exceeds 100 million tons, while sugar

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production reaches around 18 million tons. Depending on the year, sugar beet in Serbia is cultivated on over 40.000 hectares, which, with somewhat lower yields (around 50 tons/ha), results in an annual production of just over 2 million tons of sugar beet and over 300.000 tons of sugar (FAOSTAT, 2024).

Transporting sugar beet to processing facilities, i.e., sugar factories, represents a complex logistical campaign process that encompasses the logistics of harvesting, storage, and transportation. The specific characteristics of sugar beet, including its high-water content (about 75%) and rapid sugar loss after harvest, make this logistics chain particularly challenging. To reduce economic and environmental costs, sugar factories have been strategically located near production fields for more than two centuries, enabling efficient transport of sugar beets to process plants. However, with changes in industry structure and factory closures, the need for continuous optimization has become more pronounced. The average distance between fields and sugar factories in the EU-27 was only 44 kilometers in 2009 (van Campen, Marihart, 2010).

In recent decades, the EU sugar industry has faced increasingly stringent environmental requirements while maintaining a focus on cost rationalization. In many countries, efforts are being made to streamline sugar beet transport costs by employing larger vehicles or even using rail transport, which can contribute to significant cost reduction and lower greenhouse gas emissions.

Optimization of transport costs is also significant from the point of view of impact on the environment. One of the objectives of the Farm to Fork strategy is to ensure that the food chain, covering food production, transport, distribution, marketing, and consumption, has a neutral or positive environmental impact. This indicates that the EU is focused on reducing the harmful environmental effects of food production along the entire chain (European Commission, 2020). In the same document, it is emphasized that the manufacturing, processing, retailing, packaging, and transportation of food significantly contribute to air, soil, and water pollution and GHG emissions and profoundly impact biodiversity.

The primary goal of the research in this paper is to develop a mathematical model for optimizing sugar beet transport costs, specifically to reduce travel distance and, consequently, the transport costs of sugar beet from loading sites to processing facilities. The main research hypothesis is that applying a transport optimization model can achieve significant savings in travel distance, and thus in transport costs. After a literature review and problem description, an optimization model is presented that covers transport activities in the process of collecting sugar beets from fields to sugar factories. The model is applied to the Sunoko d.o.o. that accounts for approximately 50% of sugar beet processing in Serbia through its ownership of three sugar factories: “Bačka” in Vrbas, “Donji Srem” in Pećinci, and “Jedinstvo” in Kovačica. Options for optimizing transport routes to maximize efficiency are analyzed. The results of applying the model are presented through an analysis of the current operations, as well as two additional scenarios that provide insight into potential additional savings in the sugar beet supply chain.

The literature on optimization of sugarcane and sugar beet supply chains covers many aspects, from transport scheduling and synchronization to risk management and strategic decision-making, the complexity of these supply chains demands robust models capable of addressing both operational and long-term planning needs.

Sugar beets contain around 75% water, which constitutes a significant portion of their weight, creating a considerable impact on transport costs and efficiency. Due to these challenges, sugar processing factories in Europe have been strategically located close to sugar beet fields for more than 200 years, predominantly in rural areas with a goal to reduce transport costs and harmful gas emissions.

The European sugar industry continuously strives to reduce both the environmental and economic impact of transport through process optimization. In the UK, although the number of factories has decreased from 17 to 4, increasing the average transport distance from 29 km to 45 km, the total distance traveled by vehicles has been halved due to larger vehicles, improved crop quality, and a reduction in soil content during transport. Similarly, in Italy, the introduction of new machinery has reduced soil content by 50% over the past ten years, while Austria transports approximately 50% of its sugar beet by rail, significantly lowering emissions. In Germany, Denmark, and Sweden, systematic sugar beet cleaning in the fields has drastically reduced the amount of soil transported to factories, optimizing costs and lessening the environmental impact (van Campen, Milojević et al., 2020; Marihart, 2010).

Transportation costs represent a substantial component of total production expenses within the global sugar industry. In Australia, for instance, the transportation of sugarcane constitutes approximately 15% of overall production costs, equating to AU$4.00 per ton (Higgins, 2006). Efficient scheduling of transport, particularly when synchronized with harvesting activities, is essential for cost minimization. This review explores various optimization models developed to tackle the complexities of agricultural supply chains, focusing on strategies to enhance logistical efficiency and reduce costs. Higgins (1999) introduced a large-scale integer programming model to optimize cane supply decisions, aiming to maximize profitability across entire mill regions. The model incorporated multiple constraints related to milling capacity, transportation logistics, and equitable distribution, and it was solved using a heuristic approach. The process began with a linear programming approximation, followed by a novel local search technique incorporating dynamic oscillation to explore both feasible and infeasible solutions. This dynamic oscillation approach can also be applied to other heuristic methods, such as tabu search and simulated annealing, making it a versatile tool for complex supply chain problems. Fikry (2021) proposed a comprehensive model addressing the integrated challenges of production, logistics, and crop rotation within the sugar beet supply chain. This mathematical model sought to minimize total transportation and storage costs while accounting for the unique characteristics of agro-food production. A key innovation was the inclusion of a time dimension, which enabled the model to accommodate multiple cropping seasons, thereby increasing its relevance over extended planning horizons. Similarly, Paiva & Morabito (2009) developed an optimization model to support decision-making in the aggregate production planning of sugar and ethanol milling companies. The mixed-integer programming model facilitated decisions on industrial process selection, sugarcane quantities to be processed, supplier choices, and inventory strategies for final products. The planning horizon encompassed the entire sugarcane harvesting season, with decisions made at discrete intervals, thereby ensuring comprehensive coverage of operational processes.

Effective transport mode selection is critical to managing costs and reducing environmental impact. Lopez-Milan (2006) highlighted the importance of carefully planning the allocation of road and rail transport based on availability and cost. Road transport, often more expensive due to fuel consumption, must be balanced against the cost-effectiveness of rail. His model optimized the capacities of road and rail systems to ensure a steady supply to processing mills while streamlining daily transport operations. In Austria, for example, approximately 50% of sugar beet is transported by train, resulting in significant emissions reductions (van Campen, Marihart, 2010).

Synchronization between harvesting and transport is another critical component of logistical efficiency. Gvozdenović & Brcanov (2018) developed a model to synchronize large fleets of vehicles and loading machines during the harvest, aiming to minimize waiting times and maximize operational efficiency. Their approach demonstrated that effective synchronization could significantly reduce delays and improve resource utilization (Literature review 3). Similar principles were observed in other logistics sectors by Bala et al. (2010) and Bala et al. (2017), who demonstrated that synchronization is crucial across various logistical problems, from newspaper delivery to multi-echelon distribution, and highlighted the parallels with agricultural supply chains.

Agricultural supply chains are inherently exposed to risks arising from unpredictable weather patterns and long supply lead times. Behzadi (2018) explored these vulnerabilities, noting that such factors complicate post-harvest activities like packing, processing, and transport. Supply spikes can overwhelm logistics systems, while resource degradation over time exacerbates these challenges. The work of Rong et al. (2011) and van der Vorst et al. (2009) further underscored the need for robust logistics planning to mitigate these risks.

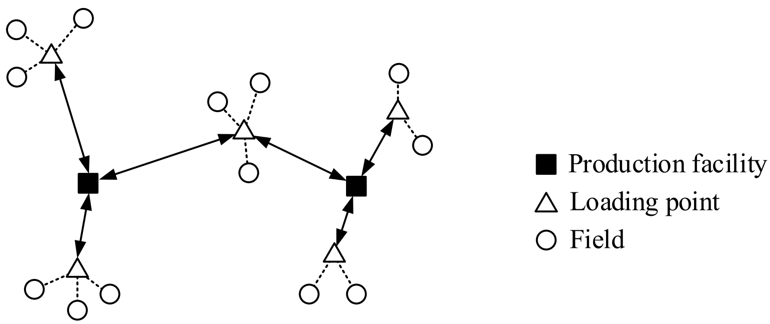
Harvest planning in the sugar industry is constrained not only by logistical and resource limitations but also by the need to maintain a consistent supply to processing facilities. Jena (2013) examined the difficulties of maximizing profitability while adhering to industrial, social, and environmental constraints. He highlighted the challenge of harvesting each field at its optimal maturity due to logistical constraints and limited capacity, which often results in suboptimal yields. In a related field, Ali et al. (2009) studied path planning for agricultural vehicles and robotics to identify optimal routes for crop harvesting. The limited bin capacity of combine harvesters, which necessitates frequent grain unloading, presented a major challenge. The problem was initially modeled as a vehicle routing problem with turn penalty constraints, producing feasible routes for harvest and grain transfer. However, as problem instances grew larger, solution times increased dramatically. To overcome this, the model was reformulated as a minimum-cost network flow problem, enabling more efficient solutions for medium-sized fields.

Materials and methods

Harvest planning for sugar beet is conducted in a way that enables optimal profit, considering the impact of numerous factors. Profit directly depends on variables such as fuel prices, availability of labor and fleet, available machinery for sugar beet harvesting and loading onto transport vehicles, as well as the maturity and quality of the sugar beet. On the other hand, continuous operation of production capacities is one of the most important factors, which allows for some deviation from optimal behavior. Specifically, the biggest issue in this chain is the lack of raw material in production facilities. Therefore, ensuring an uninterrupted processing flow can be viewed in two ways: either as the ultimate goal or as a constraint in the optimization process.

The focus of the research is not on decision-making regarding the timing of sugar beet harvesting or decisions about storing it at loading points, but rather on the process of transporting sugar beet to the factory. Sugar beet is collected from multiple fields, and sugar beet piles are placed at convenient locations near paved roads. At these locations, loading machines transfer the sugar beets into transport vehicles, so it is essential to have adequate maneuvering space to carry out these operations effectively. The sugar beets are then transported by trucks to processing facilities. Given that multiple production facilities are involved, a key question arises: which production facility should each truckload of raw material be directed to?

Figure 1. Typical transportation scheme



Source: Authors

Figure 1 provides an illustration of sugar beet transport involving two production facilities and five loading points. All sugar beet from the fields is transported along routes marked by dashed lines to the loading points, while the transport analyzed in this study focuses on the routes between loading points and production facilities, shown with solid lines. Although the allocation of two left and two right loading points seems straightforward, the position of the central loading point raises the question of which production facility, left or right, it should be assigned to.

Since the locations of production facilities are fixed and cannot be changed without significant investment, the positions of fields and loading points greatly impact overall transport costs. Additionally, road quality can significantly affect the situation, as transport on paved roads often consumes less time and fuel compared to movement on dirt roads between fields. Furthermore, weather conditions can influence transport efficiency; vehicle capacities can be fully utilized when trucks travel on asphalt, whereas traveling on dirt roads may reduce load capacity due to poor conditions. All these specific factors must be considered when the dispatcher decides on the optimal truck route.

Additionally, the transport process is directly linked to optimizing the operation of production capacities, as a continuous inflow of raw materials ensures maximum utilization of facilities, thereby increasing profitability. However, improper planning or transport delays can cause production stoppages, leading to unused capacity and potential losses. The key challenge, therefore, lies in balancing the dynamics of harvesting, the location of loading points (piles of sugar beet), available routes, and production facility capacities to minimize transport costs and ensure uninterrupted production.

Beyond geographic factors, such as the distance between fields and facilities and road quality, weather conditions and the seasonal nature of harvesting and production further complicate decision-making. Taking all these factors into account, the manager must carefully plan each step to minimize costs, optimize transport time, and ensure a steady supply of raw materials to production facilities.

To define a model, let I represent the set of indices corresponding to the loading points. For each $i \in I$, let q_i denote the quantity of sugar beet at loading point i. Let J be the set of indices representing the factories or production facilities. We denote by d_{ij} the distance between each loading point $i \in I$ and factory $j \in J$. Without loss of generality, we assume the distance matrix is symmetric, meaning $d_{ij} = d_{ji}$.

The transport cost between two locations is denoted by c_{ij}. These costs are expressed as cost per kilometer and are directly related to the distance between locations d_{ij}. Additionally, we assume that the capacity of each production facility is given as the maximum quantity of sugar beet that can be delivered, including storage space within the facility. This capacity is denoted by C_j, for each $j \in J$.

Let's define a binary variable x_{ij} as follows:

$$x_{ij} = \begin{cases} 1, & \text{if the sugar beet from loading point } i \text{ is transported to factory } j \\ 0, & \text{otherwise} \end{cases}$$

This variable will help in formulating the optimization model by indicating whether a specific transport route from loading point $i \in I$ to factory $j \in J$ is selected (when $x_{ij} = 1$) or not (when $x_{ij} = 0$).

With the proposed notation, the optimal costs can be determined by solving the following model:

$$\min \sum_{i \in I} \sum_{j \in J} d_{ij} c_{ij} q_i x_{ij} \tag{1}$$

$$\sum_{i \in I} q_i x_{ij} \leq C_j, \text{for each } j \in J. \tag{2}$$

$$\sum_{j \in J} x_{ij} = 1, \text{for each } i \in I. \tag{3}$$

$$x_{ij} \in \{0,1\}, \text{for each } i \in I, j \in J. \tag{4}$$

In equation (1), we define the optimization objective, which is to minimize the total costs. Relation (2) ensures that the factory's capacity constraint is satisfied, meaning the total amount of sugar beets collected cannot exceed the factory's total capacity. Equation (3) imposes the condition that all available sugar beets from each loading point are delivered to the factories. The constraint (4) defines the binary nature of the variable x_{ij}.

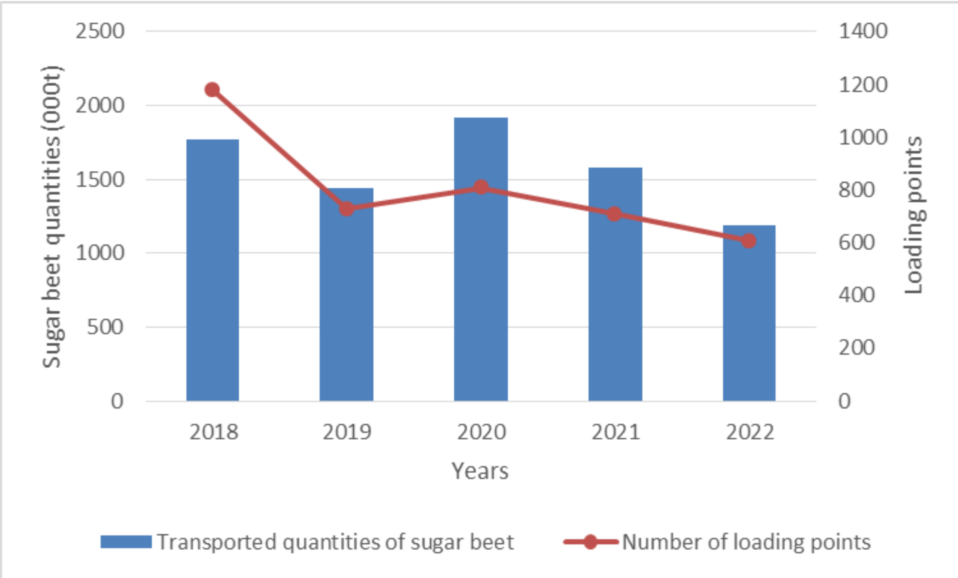
Results and discussion

The presented model is developed to optimize the transportation of sugar beets for any business system with at least two sugar factories receiving sugar beet deliveries. In this study, the model is tested on a case involving three sugar factories within the same business system. The data source is a business system Sunoko d.o.o. that owns sugar beet processing factories located in different regions of Vojvodina: central Bačka Vrbas, eastern Srem Pećinci, and southern Banat Kovačica. Collected data on sugar beet transportation covers a five-year period from 2018 to 2022, a cycle in which sugar beets reappear in crop rotation, returning to the same plot of land. The quantity of sugar beets transported to these factories between 2018 and 2022 represents about 50% of Serbia's total sugar beet production (Collected Data and SORS, 2024), suggesting that the model's application could conditionally be considered as an optimization of sugar beet transportation at a national level. Implementing the developed model is expected to lead to cost savings in transportation, significantly enhancing the operational efficiency of sugar beet production. The results review is divided into two parts: the first section describes key indicators for the current operation of the analyzed sugar production business system, while the second section outlines potential savings achieved through the application of the sugar beet transportation optimization model.

Existing Operating Method

The analyzed business system owns three sugar factories located in the Autonomous Province of Vojvodina, where nearly all of Serbia's sugar beet production takes place (SORS, 2024).

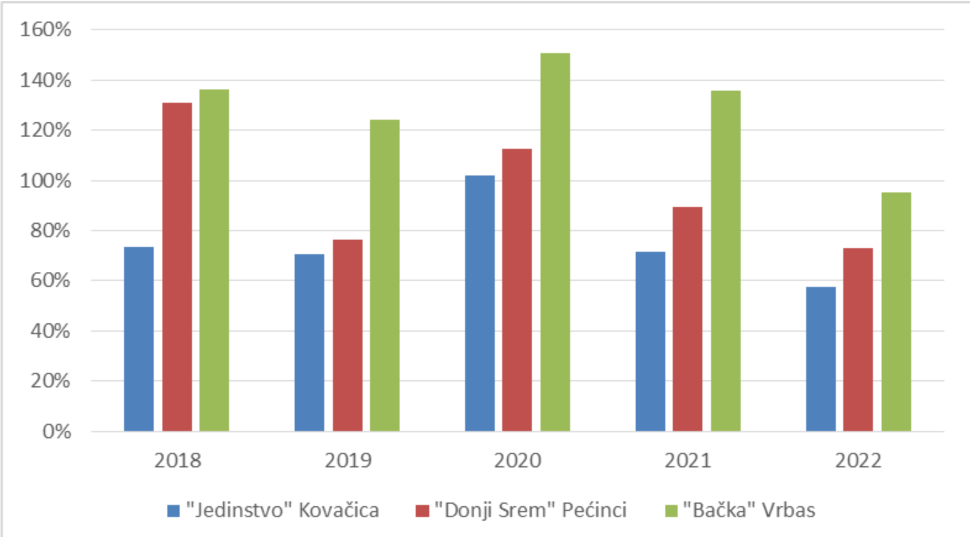
Figure 2. Transported average quantities per loading point and the number of loading points over the period 2018-2022.



Source: Authors' calculations based on collected data

The quantities of transported sugar beets during the analyzed period, along with the number of loading locations, are shown in Figure 2. Except for 2018, a certain alignment between the quantities and the number of loading locations can be observed. Throughout the entire observation period, the average quantity of sugar beets per loading location is approximately 1.960 tons. The sugar beets are processed in three factories, each differing in daily processing capacity and number of operating days. The quantities of processed sugar beets by year and production facility are shown in Figure 3, which also presents deviations from the average processed sugar beet quantity as percentages. Notably, in each of the observed years, the factory "Bačka" in Vrbas records a higher production volume than the other factories.

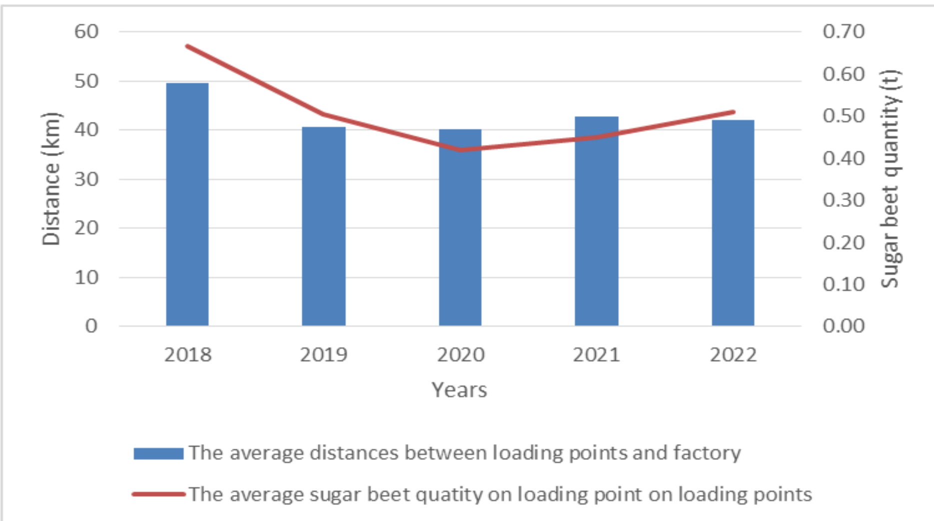
Figure 3. Percentages of working days per factory and year over the period 2018-2022.



Source: Authors' calculations based on collected data

The differences in processed quantities arise not only from production capacities but also from the duration of the processing campaign. Figure 3 illustrates this, where we can also observe greater deviations in the number of operating days at the "Bačka" factory compared to the other factories.

Figure 4. The average distances between loading points and factories and sugar beet quantities on loading points



Source: Authors' calculations based on collected data

The cost aspect can also be examined through the distance from loading locations to production facilities. Reviewing the implementation plan, Figure 4 provides a comparative overview of the average distance and average quantity of sugar beets at loading locations by year. The average distance over the observed period is approximately 43,8 km, which is comparable to the European average of 44 km (van Campen, Marihart, 2010).

Table 1 presents an overview of transportation costs, the number of truck trips, and the distance traveled by loaded trucks per year. Although transportation costs were highest in 2018, the largest quantity of transported sugar beets was recorded in 2020.

Table 1. The overview of transport activities

Year	Transportation costs (RSD)	The number of truck routes	Travelled distance (km)
2018	847.078.989	63.245	3.524.537
2019	574.285.335	51.614	2.068.339
2020	782.442.517	68.571	2.844.234
2021	670.240.120	56.299	2.481.688
2022	449.364.304	42.371	1.588.729
Total	3.323.411.264	282.099	10.707.835
Average	664.682.253	56.420	2.141.567

Source: Authors calculations based on collected data

Potential savings with model

To analyze the current performance of this production system, optimization was applied to each of the given years, with results compared after each season. The analysis assumes that each factory operates within its realized capacity, allowing for optimization through different allocations of loading locations. Thus, factory capacities are set to match the annual quantities of processed sugar beets for each observed year. Additionally, each year is treated independently, resulting in five separate sub problems to solve. Potential savings from this approach are presented in Table 2.

Table 2. The potential savings per year and in total over the period 2018-2022

Year	Transportation costs (RSD)	Travelled distance (km)
2018	789.966.697	2.963.240
2019	571.504.510	2.055.398
2020	752.493.734	2.698.181
2021	645.348.266	2.358.882
2022	437.722.661	1.534.143
Total	3.197.035.869	10.158.614
Average	639.407.174	2.031.723
Savings	-3,80%	-5,13%

Source: Authors calculations based on collected data

As shown in Table 2, savings in transportation costs vary annually, ranging from 0,48% to 6,74%. Considering the total amount of sugar beets transported over this period, the overall savings amount to 3,80%. At the same time, with similar annual variations, total distance savings reach 5,13%. Consequently, the average distance from loading locations to the sugar factories is reduced to 43,24 km, a decrease of 1,30% compared to the current implementation.

Beyond evaluating current operations, the model can also be utilized for medium-term planning. Two scenarios are presented below, outlining conditions for achieving further cost savings.

Scenario 1. Aggregate tactical planning

This approach relies on historical data and projections of future activities, encompassing all loading locations and factory capacities, and treating them as a unified, aggregated problem based on the five-year processed sugar beet quantity. Since sugar beets are not planted on the same fields each year, but typically rotate to the same sites every 3-5 years, field locations and consequently, loading locations and raw material quantities vary over time. A five-year period is considered sufficiently long to approximate these shifts in field and loading point distribution, as well as yield fluctuations, thereby enabling tactical decision-making.

The geographic aspect and density of loading locations near factories become particularly significant in this approach. Consolidating all loading sites with factory capacities adjusted to five-year demands allows for greater flexibility in resource allocation. This modification of input data, compared to the analysis of the current state, creates space for further optimization and potential savings, as shown in Table 3. Total savings in transportation costs amount to 4,67%, while distance traveled is reduced by 6,34%. The average distance between loading locations and factories decreases to 42,18 km, a reduction of 3,73%.

Scenario 2. Tactical planning with additional capacities

Sugar beets are a crop that tolerates cooler climates well, which, along with favorable weather conditions, allows the harvest and processing campaign to extend into the early winter months. Extending the campaign provides additional operational days for sugar factories, thus increasing production capacity and creating opportunities for further savings. In a scenario without capacity constraints (by removing constraint (2) from the optimization model) it becomes possible to estimate minimum costs under ideal conditions. In this case, geographic distance remains the only critical factor in optimization, allowing the model to provide insight into target costs that the system should aim to achieve.

This approach results in significant optimizations, as shown in Table 3, with the allocation of loading locations to factories optimized. Transportation cost savings reach 9,61%, while the total distance traveled by trucks carrying sugar beets is reduced by 12,70%. The average distance between loading locations and sugar factories decreases to 38,11 km, which is 13,02% less than the distance achieved in the current scenario. This model highlights the potential savings that could be realized through further optimization and adjustment of the logistical system for sugar beet processing.

Table 3. The potential savings under scenario and 2

Indicator	Scenario 1		Scenario 2	
	Value	Savings	Value	Savings
Total transport costs	3.168.297.232 RSD	-4,67%	3.003.913.537 RSD	-9,61%
Total travelled distance	10.028.790 km	-6,34%	9.347.643 km	-12,70%
Average distance between loading points to factories	42,18 km	-3,73%	38,11 km	-13,02%

Source: Authors calculations based on collected data

To implement this transportation plan, additional processing capacity is needed, which can be addressed by determining the optimal campaign duration for each factory. Considering the existing processing capacity and the allocated sugar beet quantities, we conclude that to achieve this transportation plan, the factory "Jedinstvo" in Kovačica would need to reduce its operating days during the season by approximately 10 days, the factory "Donji Srem" in Pećinci by 17 days, while the factory "Bačka" in Vrbas would need to extend its operation by 20 days. If it is technically feasible to extend the operating days of the "Bačka" factory, the potential savings in transportation costs would be substantial.

However, this raises the question of the feasibility of extending the operation of one factory and the challenges of reducing operating days for the other two, which goes beyond the scope of this study.

Conclusions

Sugar beet production and processing form an economically significant part of the agribusiness sector and are also crucial for national food security. Given that sugar beets are bulky and must be transported from the field to processing facilities within a relatively short time, the logistics of transporting sugar beets from farm to factory is highly complex. Additionally, high transportation costs impact the utilization of existing capacities, thereby influencing operational efficiency. In this context, there is a strong interest in exploring ways to optimize and reduce transportation costs. This is feasible only if the sugar-producing enterprise operates multiple processing facilities located at significant distances from each other.

This study presents a model for optimizing transportation costs from loading points to sugar factories, applied to a production entity that owns three sugar factories located in northern Serbia (Vojvodina), where nearly all of the country's sugar beet production is concentrated. The factories are located in Vrbas, Pećinci, and Kovačica, collectively transporting approximately 50% of Serbia's total sugar beet production. The study's findings demonstrate potential savings achievable through optimization methods. Assuming all three factories operate at existing capacities, the projected savings in distance traveled is 5,13%, with transportation cost savings of 3,80%. Given that these savings are relatively modest, alternative methods to reduce costs have also been explored.

The first alternative considers optimization over a five-year period during which sugar beets rotate within the crop cycle and return to the same plots. With this approach, savings are somewhat higher, resulting in a 6,34% reduction in distance traveled and a 4,67% reduction in costs. The second alternative involves optimization without capacity constraints on individual factories. Given that the factories do not operate at full capacity, this is a relatively feasible approach. This scenario yields substantial savings, with a 12,70% reduction in distance traveled and a 9,61% reduction in transportation costs. The distance from loading points to the factory decreases by as much as 13,02%, significantly more than the 3,73% reduction observed in the first alternative. This underscores that, without strategic planning, including the flexibility to adjust factory operating capacities, it is challenging to achieve substantial savings in raw material transport costs.

It is essential to note, however, that changes in operating capacity, specifically extending the operating days of individual factories, introduce other production and business challenges that fall outside the scope of this study. This limitation represents a key constraint of the research.

Reduction of transport costs by optimizing the distance traveled also reduces fuel consumption, which has a positive environmental effect. It can be concluded that this method can proportionally reduce GHG emissions approximately within a given range. Future research will focus on a more detailed analysis of environmental effects.

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Conflict of interests

The authors declare no conflict of interest.

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