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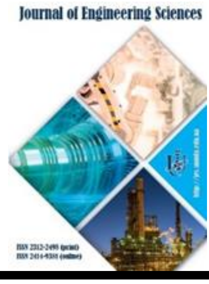

Modeling of Transportation Process in a Technological Complex of Beet Harvesting Machines

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Abstract. Based on a critical review of known research and developments in recent years, the article presents a methodology for analyzing the capacity of the sugar beet sweeping-transport complex. The research aims to find rational use of machinery resources in the technological complex. A reloading method of transportation of root crops was considered. Its peculiarity was flexibility, adaptability to weather, and climatic and economic conditions during the gathering of sugar beet. Under favorable weather conditions and the availability of a sufficient number of vehicles, dug roots, removed from the combine from the field by a tractor semi-trailer, were reloaded into the heavy trucks. They were on the road from the edge of the field and transported to the plant. In case of changing conditions (in rainy weather, when the soil was too wet, or when there were not enough vehicles), a cleaner loader was added to the machines complex. After, the production process was carried out in a transshipment or flow-transshipment way. Beet harvesting and transportation of root crops were considered as work of the technological chain, which consists of three links: "field – beet harvester", "beet harvester – tractor semi-trailer", and "tractor semi-trailer – vehicle". The basic steps of the capacity analysis allowed for determining the capacity of the 1st, 2nd, and 3rd links, their comparison, and subsequent analysis and selecting rational options to overcome the possible difference between their values.

Keywords: complex system, vehicle, row material, product innovation.

1 Introduction

In Eastern Europe, sugar beets are collected by flow, transshipment, flow-transshipment, and transshipment methods [1]. The choice of method depends on the characteristics of the soil and climatic zones of beet cutting and on the method of transporting root crops to the plant [2]. During stream harvesting, which is characteristic of zones of unstable moisture, where there is an alternation of dry and moderately wet years, root crops dug by harvesters or root-harvesting machines are loaded into vehicles moving nearby and delivered to the beet receiving points of factories [3]. This method ensures minimal labor costs and costs, lower crop losses, higher technological quality of raw materials delivered to factories, and most importantly, an increase in the gross collection of root crops due to their direct transportation to factories and avoiding temporary storage in field sugarcane [4]. Under the transshipment method, which is used mainly in areas with sufficient moisture, root crops are loaded into vehicles directly from under beet harvesters and delivered to field trucks for temporary storage and further cleaning and transportation to beet receiving points of factories [5]. This method is also used in the case of factories' limited-dose acceptance of raw materials, which factories have recently practiced, especially in Western European countries [6]. The flow-transfer method of harvesting beets combines the flow and transfer methods [7].

A critical direction to improve the efficiency of the sugar beet harvesting and transportation processes is the use of powerful harvesters with a large hopper capacity in combination with heavy-duty specialized tractor semi-trailers-loaders and powerful cargo-cleaning equipment, which provide a transshipment method or its transshipment variant [8]. This direction should be considered in close connection with the problem of reducing soil compaction during the transportation of root crops from the field [9]. The method of analyzing the throughput of the collection and transport complex proposed in the article was developed considering the deterministic approach [10].

The purpose of this study is to find ways to rationally use the resources of machines of the technological complex for harvesting and delivering beet root crops to the plant.

2 Literature Review

Effective processing of root crops at sugar factories requires managing huge product flows from the field to the receiving point [11]. In general, there are not many publications and articles from this field of research in scientometric databases [12].

The initial problem of transportation of sugar beets was presented by Ana Anokic [13]. She found optimal mathematical modeling results by establishing connections between the start-up date, the plant's operating modes, and the harvesting intensity schedule [14]. The problem of the location of field kagats was solved by hiding part of the objects in the logistics network [15]. In order to universally serve as many clients as possible, a two-stage hybrid fuzzy clustering method is developed when, after solving the input problem, the position is evaluated to solve the task of identifying one specific object [16]. The fuzzy clustering step also uses MatLab for geographic clustering based on the destination of the customer plant for raw materials when the cost incurred by the hybrid method is lower than the other methods [17]. For example, they developed a two-step method for finding a new place for biofuel [18]. Using a geographic information system at the first stage of determining possible sites, they conducted a sensitivity analysis of a location study in Michigan's Upper Peninsula [19]. Ashwani Chandel found methods for solving the seat allocation problem using a genetic algorithm [20]. They found that this problem is challenging to solve using alternative heuristics. Ming Liu and Xin Liu developed stochastic models to solve the problem of allocating docking sites with different bandwidths [21]. They also return a hybrid algorithm that includes network simplex, stochastic modeling, and genetic algorithms and verify its performance on numerical examples. Research studies an allocation problem with fuzzy requirements and models this problem in three different minimization models [22]. They return another hybrid algorithm to solve the models. Also, the research work [23] presented a detailed review of the literature on location-allocation compatible with shared complexes, stating that there are many available solutions to location-allocation problems, but there is a lack of application-based research articles. As an example, six individual cases are investigated. Yasamin Ghadbhan Abed et al. [24] changed the methodology of estimating traffic flows from fields to factories or elevators, predicting costs for improving and maintaining roads and roads [24].

A simplified consumer distribution scheme is recommended. They also develop methods for determining the duration of the journey, provide for the availability of geographic information system analysis, and consider using Dijkstra's algorithm to describe the shortest path between the points of origin and destination [25].

Consequently, using a geographic information system has proven itself well for solving positioning problems, as shown in the literature review. However, the algorithms proposed in some articles are approximate since the number of sugar beet fields is significant, and it is challenging to consider all the variables.

One of the main places in the material and technical base is given to energy resources, among which an important role belongs to transport [20]. A noticeable lack of it is manifested during mass harvesting and export of agricultural products [13]. This is especially felt when harvesting, yielding not 40–80 t/ha.

Solving this problem is related to the need to use the carrying capacity of vehicles more efficiently. The multifaceted nature of agricultural production requires constant improvement of the structure of the transport fleet and ways of organizing its use with the introduction and use of progressive methods of organizing transport [18].

Harvesting of sugar beet has three schemes of transportation: streaming, transshipment, and flow-transshipment [9]. Each of these schemes has its advantages and disadvantages.

The following factors must be considered in the selected scheme: yield, productivity of the harvester, distance of transportation to the processing plant, and availability of vehicles [11]. The essence of the streaming method is that the entire set of assembly works is performed sequentially, without a time gap between individual technological operations. The harvested crop is loaded directly from the harvester into a vehicle and taken to the receiving point of the sugar factory. Continuity of the production process is determined by the time-coordinated operation of harvesters, transport, and mechanisms for unloading beets at the sugar factory [6].

Transshipment method – the beets collected by the harvester are unloaded into tractor-trailers or dump trucks and transported to the edge of the field, placed in bins or bags, where they are stored before being sent to the sugar factory [14]. The flow-transshipment method combines flow and transshipment systems, in which part of the beet is taken directly to the receiving point of the sugar factory and part of it to the field of kagats. Each of the above methods of transporting sugar beets has its advantages and disadvantages, listed in Table 1.

Today, the flow-transshipment scheme is more favorable. This scheme will meet the requirements With high-performance harvesters with capacious hoppers and a shortage of vehicles [9]. The economic effect of the correct organization of the flow-transshipment scheme for the transportation of the crop consists of a reduction in the overall labor intensity of loading and unloading operations and a reduction in the costs of harvesting and transportation of the crop [2].

Table 1 – Advantages and disadvantages of sugar beet transportation methods

Transportation methods	Advantages	Disadvantages
Streaming	The most productive when the transportation distance is no more than 12–15 km. The highest sugar content and conditioning.	Continuous, every 10–12 min, arrival of vehicles.
Transshipment	There is no strict connection between the work of the harvester and the motor vehicles. It eliminates running motor vehicles on the field during loading, which reduces fuel consumption. The possibility of organizing two-shift and even round-the-clock operation of vehicles.	Additional transportation and unloading lead to damage, loss of mass, and decreased sugar content during cask storage. In this case, expenses are 10–15 % more than with the flow method.
Flow-transshipment	Vehicles can be maneuvered freely. If insufficient motor vehicles exist, beets are delivered to the kagats and then to sugar factories.	Additional transportation and unloading lead to damage.

The choice of the type of vehicles for sugar beet transportation is determined by their highly productive use in specific operating conditions and complete satisfaction of transportation requests [22].

The choice of the type and brand of transport depends on the technology of assembly and transport works and taking into account the fact that mass transportation is advisable to be carried out by motor vehicles of medium and heavy loads (5–10 t) and even by road trains with one or two trailers [17].

Analysis of the duration of the transport cycle of motor vehicles shows that the main reserves for increasing their productivity are the reduced time spent on loading and unloading operations. The loading time depends on the productivity of the harvester's unloading conveyor. The variable time of the harvester includes the duration of clean work, the time for making turns, and the time for technological stops to unload the hopper.

3 Research Methodology

At the Research Institute of Sugar Beet (Kyiv, Ukraine), a transshipment variant of sugar beet harvesting and transport technology was proposed. However, its production introduction at that time was complicated by the lack of development of a sufficiently high technical level of both trailers and harvesters.

Over the past ten years, the Ropa and Holmer companies have developed a new generation of self-propelled loader-cleaners of sugar beet root crops focused on high productivity and economic efficiency, with entirely new dimensions in working condition and a system for selecting root crops from 10.2 m wide field kagats (Euro-Maus 4, top) and 9.5 m (Terra Felis 3, bottom).

Their productivity reaches 600–650 t/h. The loading of the truck standing on the road is carried out from the side, located at a distance of up to 15 m from the edge of the field.

Thus, nowadays, when more advanced beet harvesters with large capacity hoppers have appeared in the EU countries – 40 m^3 (e.g., Ropa harvesters, Vervaet Beet Eater 625) or even 50 m^3, as in the 12-row Agrifac harvester Hexa 12, and RuwHawe loader trailers with a capacity of 40 m^3 in a unit with a John Deere 8400 tractor, and in Ukraine – TZP-27 "Atlant" semi-trailers, the introduction of flow-and-handover collection technology into production is actual.

The research aims to find ways to rationally use machines' resources in the technological collection and transport complex to produce sugar beets.

4 Results

According to the scientists of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Sciences of Ukraine, the most efficient way to transport sugar beet from the field to the receiving point of the plant is by flow, provided that road trains consisting of heavy trucks and trailers are used [6, 8]. Nevertheless, this method has the following significant disadvantages:

– a significant number of motor vehicles is required to operate beet harvesters without stops effectively and taking into account the long distance of transportation to sugar factories. Simultaneously, due to significant fluctuations in the turnover time of motor vehicles, the downtime of beet harvesters waiting for transport reaches 20 %;

– hitching trailers requires additional labor;

– on moistened soils, it is impossible for motor vehicles to work in the field, which leads to downtime of beet harvesters;

– heavy-duty motor vehicles significantly compact the soil, which causes its degradation and, as a result, requires additional costs for loosening;

– a significant amount of fertile soil is removed from the fields as a pile of root crops.

The first two disadvantages lead to decreased productivity of both beet harvesters and motor vehicles, prolonging the agrotechnical harvesting period and causing crop losses.

The evolution of the development of beet harvesters took place in the direction of equipping them first with hoppers-compensators with a capacity of 1.5–3.5 t, and then, with an increase in engine power to 250–300 kW, the capacity of the hopper was gradually increased from 10–12 t to 15–18 t and 20–25 t. Accordingly, the transport fleet, enriched with specialized equipment, grew significantly in carrying capacity.

As the experience of the EU countries shows, the use of the transshipment mode of transportation for the transportation of beets from beet harvesters eliminates the disadvantages mentioned above to a large extent. The basis of this method is the introduction of high-performance collection and transport complexes, which include, for example, the SF-10 Franz Kleine combine or "Holmer", a specialized TZP-27 tractor semi-trailer with a 150–200 hp tractor equipped with wide-profile low-profile tires pressure, loader-cleaner, and heavy-duty motor vehicles. It also makes it possible to significantly reduce soil compaction due to the elimination of the removal of beets from harvesters by heavy-duty motor vehicles. The beet harvester works non-stop, loading beets into a tractor semi-trailer moving nearby, with the possibility of accumulating beets in the hopper when replacing the tractor semi-trailer for further reloading into a heavy-duty vehicle or trucks. Using a large capacity hopper allows the combine to make long working passes, thus covering possible transport delays. The tractor-semi-trailer works as a mobile compensator.

An equally important advantage of a tractor semi-trailer over a truck is the reduction of the impact on the soil because when the truck enters the field, there is high pressure on the soil, which negatively affects the subsequent yield of cultivated crops. If the specific pressure of a tractor, tractor semi-trailer, or combine harvester is close to the regulatory requirements due to wide-profile tires, then in trucks, this indicator is many times higher than the permissible norm, and in rainy weather, trucks are generally inoperable in the field.

In Ukraine, the Kobzarenko plant started production of universal sliding semi-trailers of the "Atlant" series: TZP-27 with a carrying capacity of 20 t and a volume of 32 m^3; TZP-39 with a carrying capacity of 30 t and a volume of 40 m^3. The design of "Atlanta" provides for its universal use by installing a replaceable manure-spreading mechanism on a semi-trailer or a transshipment auger for grain, making it possible to use it as a mobile compensator when harvesting sugar beets or grain. Technical characteristics of semi-trailers are given in Table 2.

Table 2 – Technical characteristics of ATLANT semi-trailers

Indicators	TZP-39	TZP-27
Weight capacity, kg	30 000	20 000
Volume, m^3	40.0	32.0
Volume with patches, m^3	48.4	32.0
Required power of tractor, kW	180–220	160–180
Axes, pieces	3	2

A feature of the transshipment method of beet harvest transportation is its flexibility and adaptability to weather, climate, and economic conditions during harvesting. Under favorable weather conditions and a sufficient number of motor vehicles, the collection and transport complex carries out the flow-transshipment method of transportation. The beets, taken from the field by semi-trailer, are reloaded into heavy-duty vehicles located on the road at the edge of the field and transported to the sugar factory.

In the event of a change in conditions, namely in rainy weather, when the soil is over-moistened, or when there is an insufficient number of motor vehicles, a loader cleaner is added to the complex of machines, and the operation of the complex switches to a transshipment mode of transportation. A tractor semi-trailer unloads the produce into bins at the edge of the field, from where it is loaded with simultaneous cleaning into a vehicle after drying, or part of the beets is immediately reloaded into a vehicle for transportation. The stock of root crops created at the transshipment sites allows more rational and productive use of road transport to remove beets during the day. It is possible to deliver root crops to the sugar factory with modern separate heavy-duty vehicles and road trains KrAZ-6230C4-330 + KrAZA261C3, MAN11-224 + SZAP8357, or DAFFATCF85.430 + MAZ856103.

We consider the processes of harvesting and transporting sugar beets as a technological chain containing three links: "beet harvester – field", "tractor semi-trailer – beet harvester", and "motor vehicle – tractor semi-trailer". A condition for the continuous operation of the harvesting and transport complex is the balance of time when each semi-trailer serves one beet harvester. Then, the number of tractor semi-trailers serving a group of beet harvesters is determined as follows:

$$n_S = m_H, \tag{1}$$

where n_s and m_H – the number of tractor semi-trailers and beet harvesters in the harvesting and transport complex.

For this purpose, the duration of the working cycle of the tractor's semi-trailer t_{st} – from the moment of completion of its loading of the beet harvester to the moment of its return after unloading (to the vehicle or to the sides of the field) to the beet harvester for the next loading should be less than or equal to the time of loading the harvester's hopper t_b.

The following expression determines this condition:

$$t_{st} \leq t_b, \tag{2}$$

where

$$t_{st} = t_m W_{st} + k_m q_b \left(1 + \frac{W_{hp}}{W_{bk}}\right); \tag{3}$$

$$t_b = \frac{q_b}{W_{hp}}, \tag{4}$$

where t_m = 0.07 h – the duration of the tractor semi-trailer's stay in the field during the working cycle (driving), which consists of the time of moving and loading from the beet harvester [25]; W_{st} – the productivity of the semi-trailer unloading transporter, t/h; k_m = 1.5 – a coefficient that takes into account additional time for maneuvering a tractor's semi-trailer when loading a motor vehicle; q_b – mass of root crops contained in the hopper of the beet harvester, t; W_{hp} – productivity of the beet harvester per hour of the main time, t/h; W_{bk} – the productivity of the unloading transporter of the beet harvester, t/h.

Taking into account the obtained values (3) and (4), the condition of continuous operation of the collection and transport complex has the following form:

$$t_m W_{st} + k_m q_b \left(1 + \frac{W_{hp}}{W_{bk}}\right) \leq \frac{q_b}{W_{hp}}. \tag{5}$$

The throughput capacity of the first link of the technological chain "field – beet harvester" N_1 is the most significant number of beet bunkers that can be collected by harvesters of the harvesting and transport complex during the main working day and is defined as follows:

$$N_1 = m_c \frac{T_w}{t_s}, \tag{6}$$

where m_c – the number of combined harvesters in the complex; T_w – the main working day of the beet harvester, which depends on the organization of the interaction of the machines:

$$T_w = T_s k_z \tau, \tag{7}$$

where τ = 0.81 – shift time utilization factor; T_s – shift duration, h; k_z = 1.5–2.0 – shift factor, showing the number of shifts (T_s = 7 h), which combines performance per working day (24 h); t_s – the duration of the work cycle of the beet harvester, which takes into account the time of filling and unloading the hopper during the operation of the combine, as well as the duration of idling on turns, which corresponds to a single cycle of the combine has the following form:

$$t_s = 1.1 \cdot \frac{q_b\,(W_{bk} + W_{hp})}{W_{hp}\,W_{bk}}, \tag{8}$$

The throughput capacity of the second link "beet harvester – tractor semi-trailer" N_2 is the most significant number of combined beet bunkers during the main working day:

$$N_2 = \frac{n_S\,T_w}{t_s\,\rho}, \tag{9}$$

where n_S – the number of tractor semi-trailers in the collection and transport complex, units; ρ – the number of hoppers of the beet harvester, which are unloaded into the tractor semi-trailer, equal to 1.0.

The carrying capacity of a tractor semi-trailer q_{st}, considering the technical indicators of modern beet harvesters, will be determined as follows:

$$q_{st} = q_b \left(1 + \frac{W_{hp}}{W_{bk}}\right) = 1.08 \cdot q_b. \tag{10}$$

The throughput capacity of the third link "tractor semi-trailer – motor vehicle" N_3 is the most significant number of combined beet bunkers that can be transported by motor vehicles during the main working day and is defined as follows:

$$N_3 = \frac{n_a\,T_w}{t_{vc}}, \tag{11}$$

where n_a – the number of motor vehicles or groups of motor vehicles for the transportation of beets:

$$n_a = \frac{n_{st}\,t_{vs}}{t_{sa}\,\rho}, \tag{12}$$

t_{sa} – time of filling the tractor semi-trailer with root crops and its unloading:

$$t_{sa} = 1.08\,q_b \left(\frac{1}{W_{bk}} + \frac{k_{\mathrm{m}}}{W_{st}}\right), \tag{13}$$

t_{vs} – duration of vehicle turnover:

$$t_{vs} = \frac{k_m\,q_{st}}{W_{st}} + \frac{2\,l_{ij}}{v_t} + t_{vs}, \tag{14}$$

t_{vs} – the duration of the vehicle's stay at the unloading point; l_{ij} – the distance of transportation of beets from the field (point *i*) to the unloading point *j*; v_t – the average technical speed of the motor vehicles from the field to the unloading point and back, km/h.

The first link determines and limits the total capacity of the technological chain of the collection and transport complex during the application of transshipment technology. Simultaneously, the bandwidth of other links can be significantly (excessively) greater.

If this is the case, the circuit is operating at maximum capacity, but the bandwidth of the second or third link remains partially unused. Bandwidth is a resource that is completely unused in this case. Rational use of the resource (machines of the collection and transport complex) determines the increase in the efficiency of technologies. A significant (excessive) difference in the capacity of a separate link compared to the previous one is such a difference, the reduction of which allows for reducing the number of machines of the collection and transport complex due to rational changes in specific parameters of technological processes.

The main steps of the bandwidth analysis are the comparison of the bandwidth of the first, second, and third links and the subsequent selection and analysis of alternative options that allow overcoming the possible significant difference between their values. This can be formulated as follows:

– determine the bandwidth of individual links and compare their values with each other [26];

– analyze the possibility of reducing, and in some cases, increasing the capacity of the second and third link to the maximum possible – the capacity of the first or second link with a decrease (in some cases, with an increase) by one or more units of vehicles for the transportation of beets due to the change duration of turnover of the motor vehicle [27];

– to propose an alternative version of the operating parameters of a particular link, which allows to eliminate the significant difference in its throughput from the previous one [28];

– the obtained analytical dependencies and experimental data make it possible to calculate the rational values of the capacity of individual links of the transshipment technological chain and, if necessary, to improve the rational composition of the collection and transport complex [29].

A necessary condition for the efficient operation of the harvesting and transport complex for transshipment technology is the fulfillment of the condition under which the maximum throughput of the first link "field – beet harvester" is ensured, and its work is not inhibited from the side of the second, as well as from the side of the third link, which is reflected in the following expressions:

$$N_1 \leq N_2; \tag{15}$$

$$N_1 \leq N_3. \tag{16}$$

In this way, the absence of inhibition of the work of the first main link is achieved by a rational mode of interaction of the first and second links, the first and third links. However, if the first and second links relate to the operation of the assembly and transport complex directly in the field, where the number of aggregates is constant, then the throughput of the third link depends on both the duration of the cycle time and the number of motor vehicles.

Consider the option when the capacity of the third link, "tractor semi-trailer – motor vehicle", significantly exceeds the capacity of the second link. We will analyze the possibility of reducing the throughput capacity of the third link to the maximum possible – the throughput capacity of the first link due to the reduction of a certain number of motor vehicles for the transportation of beets. For the analysis, we accept the conditional limit of throughput for the third link:

$$N_3^* = N_1, \tag{17}$$

where N_3^* – the capacity of the third link with a decrease in the number of motor vehicles by Δn_a and a corresponding decrease in cycle time by Δt_a, h:

$$\Delta t_a = \frac{T_p \, \Delta n_a}{N_1}. \tag{18}$$

Then, a decrease in the number of motor vehicles by Δn_a requires an increase in the speed of the motor vehicle v_{t1}, km/h:

$$v_{t1} = \frac{2l_{ij}}{\frac{2l_{ij}}{v_t} - \Delta t_a}. \tag{19}$$

Another option for reducing the duration of vehicle turnover may be to reduce the time for loading and unloading the vehicle.

The following case study can be considered as a practical example. After analyzing the throughput of individual links of the technological chain, which includes:

1) three beet harvesters "Holmer" with technical and operational indicators: W_{hp}=125 t/h, q_b=20 t, W_{bk} = 1600 t/h shift time utilization factor τ = 0.81;

2) TZP-27 "Atlant" semi-trailers with a 220–250 hp tractor and the productivity of the unloading conveyor W_{bn} = 600 t/h, q_{bn} = 20 t;

3) motor vehicles with the following working conditions: beet transportation distance l_{ij} = 15 km, v_t = 40 km/h, shift time T_s = 7 h, k_z = 2.0.

As a result, the condition of the continuous operation collection and transport complex was checked:

$$t_m W_{st} + k_m q_b \left(1 + \frac{W_{hp}}{W_{bk}}\right) \leq \frac{q_b}{W_{hp}} ;$$

$$t_m W_{st} + k_m q_b \left(1 + \frac{W_{hp}}{W_{bk}}\right) = 0.12 \text{ (h)};$$

$$t_b = \frac{q_b}{W_{hp}} = 0.16 \text{ (h)}.$$

The necessary condition is fulfilled: 0.12 h < 0.16 h.

Also, an analysis of the bandwidth of individual links was conducted:

1) the capacity of the first link "field – beet harvester" is defined as follows:

$$N_1 = m_c T_w t_s^{-1} = 178 \text{ (bunkers/days)},$$

where

$$T_w = T_s k_z \tau = 11.3 \text{ (h)}.$$

The duration of the work cycle of the beet harvester:

$$t_s = 1.1 \, \frac{q_b \, (W_{bk} + W_{hp})}{W_{hp} \, W_{bk}} = 0.19 \text{ (h)}.$$

2) the throughput capacity of the second link "beet harvester – tractor semi-trailer" is defined as follows:

$$N_2 = \frac{n_S \, T_w}{t_s \, \rho} = 282 \text{ (bunkers/days)},$$

where

$$t_s = 0.07 + \frac{1.5 \cdot 20 \cdot \left(1 + \frac{125}{1600}\right)}{600} = 0.12 \text{ (h)}.$$

3) the bandwidth of the third link "tractor semi-trailer – motor vehicle" is equal to

$$N_3 = \frac{n_a \, T_w}{t_{vc}} = 288 \text{ (bunkers/days)}.$$

The number of motor vehicles or groups of motor vehicles for the transportation of grain will be determined as follows:

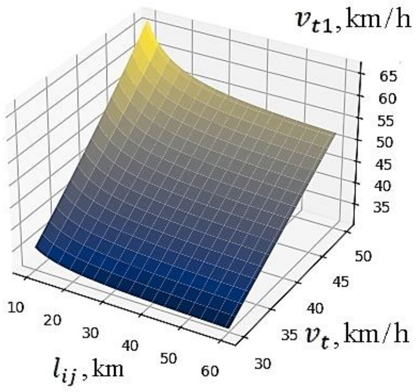
$$n_a = \frac{n_{st} \, t_{vs}}{t_{sa} \, \rho} = 23,$$

where the duration of turnover of motor vehicles:

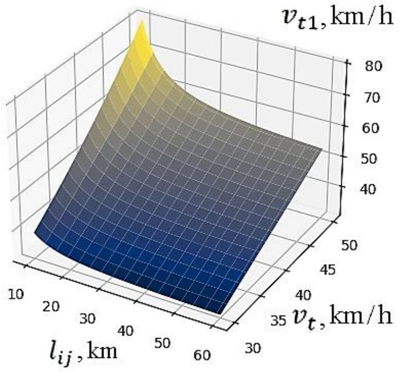
$$t_{vs} = \frac{k_m \, q_{st}}{W_{st}} + \frac{2 \, l_{ij}}{v_t} + t_{vs} = 0.9 \text{ (h)}.$$

The obtained data indicate that the collection and transport complex provides maximum throughput of the first link "field – beet harvester", because in there is no inhibition of its work on the side of the second and third links: $N_1 = 178 < N_2$; $N_1 = 178 < N_3$.

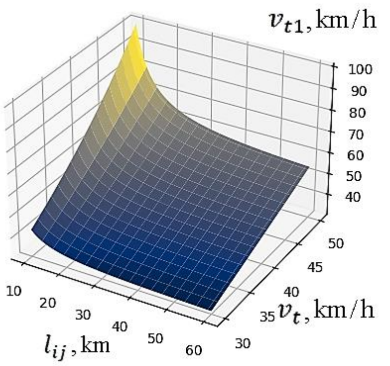
The bandwidth of the third link "tractor semi-trailer – motor vehicle", exaggerates the capacity of the first link. Therefore, an alternative transportation option with a decrease in the number of motor vehicles by Δt_a = 3 units up to Δt_{a1} = 20 units have been analyzed with a simultaneous decrease in the motor vehicles' revolution (working cycle) duration by increasing the motor speed.



a



b



c

Figure 1 – Graphical interpretation of the model (19):
a – Δt_a = 0.1 h; b – Δt_a = 0.15 h; c – Δt_a = 0.2 h

For analysis, we accept the limiting condition of bandwidth for the third link: $N_3^* = N_1$ = 178 bunkers/days.

Reduction of motor vehicles for 3 units Δn_a = 3 needs an increase in the speed of motor vehicles to

$$v_{t1} = \frac{2l_{ij}}{2l_{ij}/v_t - \Delta t_a} = \frac{2 \cdot 15}{2 \cdot 15/40 - 0.0635 \cdot 3} = 53.5 \text{ (km/h)}.$$

The methodological provisions of the model (19) with the adopted stages and numerical values allow for a graphical representation (Figure 1).

A smaller number of motor vehicles (20 units instead of 23 units) will provide the bandwidth of the third link "tractor semi-trailer – motor vehicles". The example shown is a rational alternative collection and transport complex containing 3 units of beet harvesters, 3 units of tractor semi-trailers with tractors, and 20 units of motor vehicles.

The characteristics of each harvester indicate the productivity per hour of clean work with an attachment of up to 1.0 ha and 1.5–2.0 ha. Under specific conditions, to determine the performance, it is necessary to take the speed of movement. Having at the disposal data on the productivity of the beet harvester and in order to ensure the system integrity of the harvesting and transport complex and the maximum loading of all its links, it is necessary to fulfill the condition of the flow of the technological process. This is when the total productivity of the assembly line matches that of the transport line. In this case, we cannot predict the performance and unloading time at the receiving point.

5 Discussion

The main requirement of modern approaches to the construction of current sugar beet harvesting processes is to ensure the operation of sugar beet harvesters without downtime due to the lack of vehicles [30].

Such systems are studied by modeling. In our case, simulation modeling involved the development of a modeling algorithm and using a discrete system modeling system [31].

The simulation process compares the characteristics of the object being modeled through variant calculations [32].

The ability to repeatedly reproduce the modeled processes with their subsequent statistical processing plays a special role, which allows taking into account random external influences on the object under study [33].

Based on the statistics collected during computer experiments, conclusions are drawn in favor of a particular variant of operation, the design of an actual beet harvester, or the nature of the phenomenon [34].

To evaluate the time of vehicles on the route, it is necessary to consider the state of road conditions and their length. The average speed of movement depends on this, which affects the time of rotation of the vehicle, and the latter directly affects its performance. Thus, the importance of transportation during harvesting takes on great importance as the last chain in the production of quality agricultural products.

6 Conclusions

A method of analyzing the throughput of the harvesting and transport complex for sugar beets has been developed, aimed at finding ways to use the resource of machines in the technological complex rationally.

The analysis of the throughput capacity of the collection and transport complex of beet harvesters shows ways to improve the parameters of the transport process in the technological complex of collection and transport works.

In the future, transporting beets from the harvester to the truck may be automated. However, farmers will still have to choose the machinery despite future automation. Furthermore, the quality of the obtained products and the work efficiency will depend on these decisions.

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