

Optimizing Cold Chain Logistics for Meat Product Distribution: Technological, Environmental, and Operational Perspectives

Dmytro Burko^{a1}, Pavlo Vakulenko^a, Denys Ponkratov^a

^aO. M. Beketov National University of Urban Economy in Kharkiv, 17, Chornoglazivska Str., Kharkiv, 61002, Ukraine

Abstract

Climate change driven by global warming imposes increased requirements on the preservation of food products, including meat products, which are highly sensitive to variations in ambient temperature. This impact can be mitigated by maintaining appropriate temperature ranges for each type of meat product within the cargo compartment of freight vehicles during transportation. Ensuring these temperature ranges requires continuous temperature monitoring using sensors and maintaining cooling through the operation of vehicle engines during delivery routes and engine idling. In cold supply chains for meat products, two cooling options may be applied: the use of the vehicle engine for cooling the cargo compartment or the operation of an autonomous refrigeration unit with an independent engine. In both cases, a non-operational engine results in an increase in cargo compartment temperature, leading to near-continuous engine operation to maintain the required thermal conditions. The duration of engine idling is directly related to the time required for loading and unloading operations during meat product distribution and is associated with increased emissions of harmful substances into the atmosphere. Classical approaches to evaluating distribution technologies in freight transport systems, including cold chains, are based on objective functions that minimize transport work, delivery costs, and time. This study proposes a comparison between the classical approach to meat product distribution and an approach based on achieving sustainable development goals. Additionally, various technological aspects of freight vehicle operation during meat product delivery are assessed, and potential reserves for reducing loading and unloading times are identified in order to improve transport process efficiency, reduce engine idling time, and decrease environmental impact while ensuring optimal temperature conditions in the cargo compartment to preserve the consumer properties of meat products for end users. Consequently, the study is relevant in the context of achieving sustainable development goals related to food security, healthy lifestyles, rational consumption patterns, and climate change mitigation.

Keywords: Freight Transportation; Sustainability; Cold Chain Logistics; Meat Product; Environmental Protection.

1 Introduction

Modern urban transport systems ensure the movement of material flows with a sufficient level of efficiency, considering the technological features of transportation. Road transport plays one of the leading roles in this process. Material flows in the form of finished products are consumed by the urban population, which places certain demands on them. Products must be delivered to the consumer in the proper quantity and quality, i.e., with their marketable appearance preserved. Particular attention is paid to food products. Special transport conditions are required for food products for which it is important to maintain a certain temperature range. In case of temperature deviations during transportation and storage, this type of product quickly loses its consumer properties and becomes unfit for consumption, i.e. it is considered perishable. In the European Council, the circulation of such products (Directive (EU) 2019/633, 2019), general provisions (Regulation (EU) No 1169/2011, 2011), transport (Agreement on the International Carriage of Perishable Foodstuffs, 2016), labelling (Labelling and nutrition) are regulated by special directives and rules. One type of perishable product is meat products, which must be delivered to consumers as quickly as possible in order to maintain the appropriate level of quality. The transport component of delivering such products consists of maintaining the appropriate temperature in the cargo compartment by using refrigeration equipment, i.e. transporting goods using specialised freight vehicles. In addition, transport technology, as is well known, must be based on the use of vehicles with rational load capacity, which reduces transport costs and affects the cost of production, which correlates with the price of the final product. Therefore, researching ways to optimise the delivery of meat products in cold chains and its impact on

¹ Corresponding author. tel.: +380-67-948-94-49; e-mail address: dburko81@gmail.com

technological, environmental and operational prospects is a current task in the distribution of goods in transport systems and ensuring their sustainability.

2 Literature review

Numerous studies have been conducted with the aim of developing methods for preserving the consumer properties of perishable products. One approach is to analyse the models of distribution networks presented (Rodriguez, 2020). The research optimizes the modern distribution network to preserve the shelf life of perishable products. A comparison of the operating models of optimized distribution networks was carried out to find the best method for improving distribution networks and extending the maximum shelf life of perishable products during transportation. Cross-docking technology is currently widely used to ensure the freshness and quality of perishable products. In particular, the paper (Wang et al., 2026) considered the formation of a cross-docking network in cold supply chains to reduce transport costs, carbon emissions and ensure the freshness of perishable products. As a result, adaptive delivery options are formed that reduce losses from product spoilage and transport costs while ensuring a stable and efficient delivery system for perishable goods in cold supply chains. The research (Pan et al., 2021) developed an integer mathematical model for planning the loading of vehicles at a cross-docking centre for fresh produce, taking into account the reloading mode, where the objective function minimizes the total loss of product quality based on an exponential spoilage model. The proposed reloading mode provides a statistically significant reduction in total product spoilage compared to the traditional mode. Parametric analysis has established that reducing the size of the loading batch and the time required to change trucks non-linearly reduces the overall spoilage of products, confirming the increased efficiency of flexible reloading in conditions where fresh products are highly sensitive to the duration of logistics operations. The paper (Theophilus et al., 2021) presents the problem of forming and optimizing truck schedules at a cold chain cross-docking terminal, considering the rate of product spoilage. A mathematical model is presented that minimizes the total costs associated with servicing all trucks arriving at the cold chain. The main cost components included in the mathematical model are: total waiting cost, total service cost, total product storage cost, total shipment delay cost, and total product spoilage cost. The patterns of change in the total waiting time of a truck, the total storage time of products, and the total delay time of a truck's departure are obtained, considering the number of platforms in the cross-docking centre and the arrival patterns of freight vehicles. The research (Liang et al., 2024) investigates the vehicle routing problem faced by a supplier delivering perishable goods to customers. It proposes the introduction of flexibility in the supplier's services, offering customers different delivery methods associated with differentiated time windows. The supplier strives to maximize both its profit and customer satisfaction, which is measured by the weighted average loss of quality of perishable products during delivery. The paper (Maiorino et al., 2021) provides an overview of refrigeration systems used in the transport of perishable goods, alternative technologies that can reduce the environmental impact of road refrigerated transport, optimization models and methods used to minimize fuel consumption and greenhouse gas emissions, with a focus on both reducing thermal loads and solving the problem of routing refrigerated freight vehicles.

The problem of multi-criteria optimization of perishable cargo transportation is solved in (Anufriyeva et al., 2023) considering the minimization of delivery time with restrictions on the rational use of transport vehicles. The simulation model developed for this purpose considering factors characterising the distribution network and the size of the cargo batch, and allows the formation of dynamic delivery routes for perishable goods.

The movement of freight vehicles has a significant impact on traffic flow characteristics, in particular traffic speed, and determines the conditions for the functioning of transport networks in cities during the day (Burko et al., 2020). An increase in the proportion of freight vehicles in traffic flows changes traffic safety indicators related to driver qualifications, speed limits, and the difficulty of manoeuvring in traffic (Prasolenko, et al., 2019; Prasolenko, et al., 2023). The trend towards an increase in such vehicles also affects the environmental performance of transport systems in the context of sustainability. In such conditions, the planning of freight transport in the context of ensuring the sustainability of freight transport systems becomes a current issue.

3 Conceptual framework

The conceptual framework for this study is based on a combination of two approaches to the organisation of meat product transportation technology. According to the first – classical approach to the organisation of transport technology, at any stage of transport, the minimum amount of transport work must be ensured, provided that the load capacity of the vehicle is used rationally, depending on the volume of orders from end consumers (retail stores) and determining the order of delivery points, with the unloading of the maximum possible amount of cargo (Fig. 1), which accordingly ensures the minimum transportation costs.

Compared to the classic approach, an alternative approach, that can be used when planning routes is based on the physical properties of meat products and the ability of the refrigerated truck to maintain a certain temperature range without turning on the compressor of the refrigeration unit. Thus, under certain weather conditions and with a certain load, it becomes possible to use an alternative route for delivering meat products, which involves keeping as much chilled product as possible in the cargo compartment of the vehicle and unloading small batches of meat

products first. An important condition here is to ensure that the transport work is close to optimal within a certain range, i.e. it does not exceed it by more than 5-10%. It is assumed that the use of an alternative approach to determining the order of arrival to meat product delivery points may, in the long term, lead to fuel savings, reducing the environmental impact of transport systems and improving the sustainability of freight transport systems and the cold chain for meat product distribution.

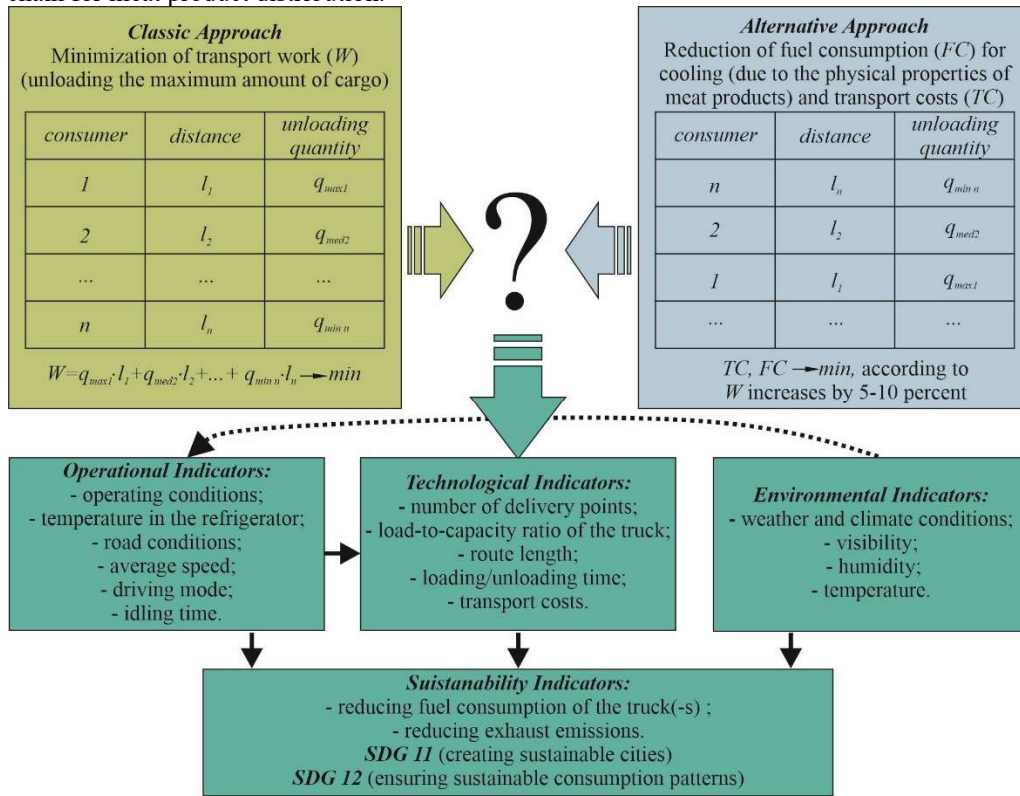


Fig. 1. Conceptual framework of the research.

Improving the sustainability of freight transport systems and the cold chain distribution of meat products is consistent with SDG 11 on creating sustainable cities and ensuring sustainable consumption patterns SDG 12 (Sustainable Development Goals).

Based on the above, a working hypothesis for the study can be formulated, which consists in the existence of a certain combination of weather and climate factors, operational factors of freight vehicles of a certain load capacity, and technological factors for forming a list of delivery points, under which, taking into account the physical properties of meat products, it is possible to ensure the potential environmental efficiency of transportation in cold chains for the distribution of meat products.

4 Experimental research

Refrigerated meat products are transported using two types of freight vehicles: MAN TGL 12.180 and Hyundai EX10. The products are transported in plastic boxes formed separately for each delivery point of the retail network. The product range is as follows: refrigerated chicken, pork and beef. According to the rules for transporting meat products, the temperature requirements for transporting chicken are 0 °C to +2 °C, and for transporting pork and beef, 0 °C to +2 °C. This temperature range is ensured by the refrigeration units of the freight vehicles used. On the day before the products are transported from the distribution centre located in a suburban area, the supplier receives information about the required quantity of cargo for delivery the next day. The truck arrives for loading at night so that the loading time and travel time to the first delivery point match the arrival of employees at the store to receive the meat products. In addition, weather conditions must be taken into account, under which it may be necessary to turn on the refrigeration unit an hour before loading to ensure the required temperature range for transporting chilled meat products. According to the technical passports of the freight vehicles, the following load capacities are specified: MAN TGL 12.180 – 5500 kg. and Hyundai EX10 – 6130 kg. (fig. 2).

In accordance with the requirements of the cargo transportation process, it is necessary to comply with the requirements for loading trucks, which prohibit exceeding the loading limits specified in the technical passports of vehicles. The MAN TGL 12.180 vehicle has autonomous refrigeration equipment. The equipment has a separate diesel engine that powers the compressor. This equipment operates completely independently of whether the truck is running or not. The system automatically maintains the set temperature with high accuracy. The Hyundai EX10

vehicle has engine-driven refrigerators. In this case, the compressor of the refrigeration unit is connected by a belt drive directly to the engine of the vehicle itself. The unit cools the cargo compartment of the vehicle only when the truck's engine is running. The cooling capacity depends largely on the engine speed. Engine-driven refrigerators differ in that they only work when the engine is running. This means that they are completely dependent on the vehicle: if the engine is turned off or breaks down, the temperature in the cargo compartment begins to rise. In city traffic jams, when the engine is idling, the cooling efficiency will drop, forcing the driver to keep the vehicle's engine revs high while idling. This type of refrigeration unit creates a constant additional load on the truck's main engine and generator, which slightly accelerates their wear and tear. The refrigeration unit itself has a long service life, but it is strictly tied to the service life of the vehicle.



Fig. 2. (a) freight vehicle MAN TGL 12.180; (b) freight vehicle Hyundai EX10.

The vehicles operate on delivery routes for chilled meat products from the agricultural company to a retail chain of stores located in Khmelnytskyi city (Ukraine) – fig. 3. The retail chain has 46 permanently operating stores in Khmelnytskyi city.

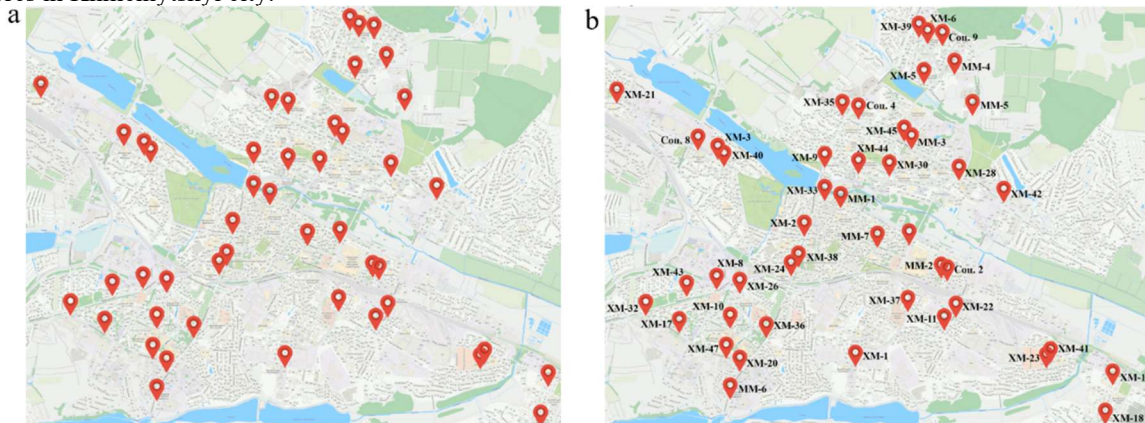


Fig. 3. (a) location of delivery points in the city; (b) delivery point numbers.

The study of vehicle traffic indicators on routes was carried out while servicing part of the store network, consisting of seventeen delivery points, i.e. about one third of the total number of delivery points.

Each vehicle is equipped with GPS sensors, which allow tracking the date, time of transportation, temperature in the cargo compartment, instantaneous speed of the vehicle, and the position of the vehicle (active links allow you to immediately display the location of the vehicle on Google Maps - fig. 4).

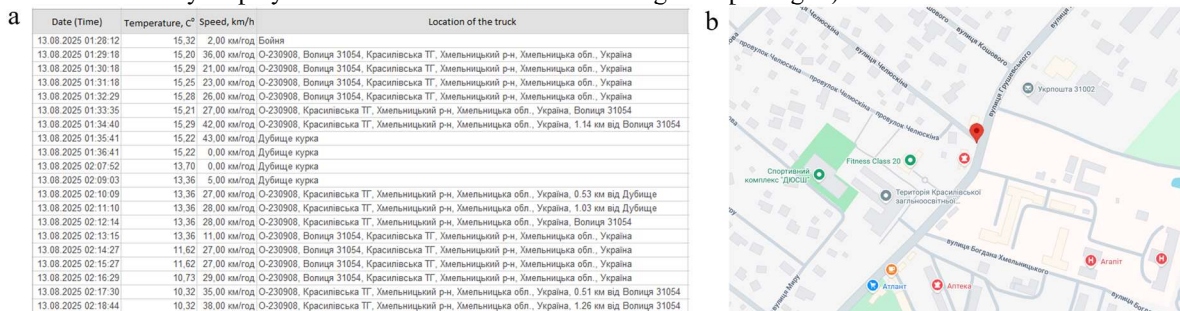


Fig. 4. (a) transportation timing data; (b) location of the freight vehicle on Google Maps.

As a result of processing the data on the timing of refrigerated meat product deliveries on distribution routes (Fig. 4a), arrays of raw data were obtained for MAN TGL 12.180 and Hyundai EX10 freight vehicles, which can be statistically processed using a statistical software (Fig. 5). As a result of processing the timing data, a sample of twenty experiments was obtained for MAN TGL 12.180 and twenty experiments for Hyundai EX10.

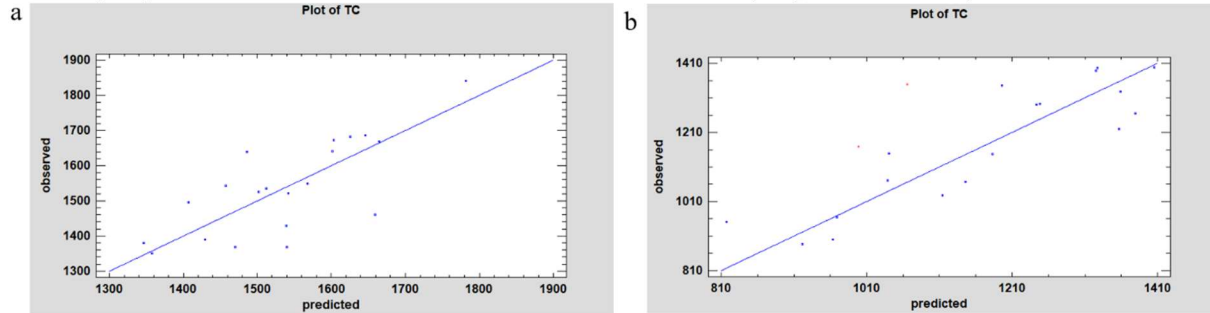


Fig. 5. (a) multiple regression graph for a truck MAN TGL 12.180; (b) multiple regression graph for a truck Hyundai EX10.

A model for changes in transportation costs for a truck MAN TGL 12.180 has been defined:

$$TC_{MAN} = 1590,67 \cdot \frac{t_{mov}}{t_{tot}} + 3566,83 \cdot q_{nc} \cdot \gamma - 36,62 \cdot t_{ref} \quad (1)$$

where t_{mov} – route travel time, min.;

t_{tot} – total time spent by the truck on the route, min.;

q_{nc} – nominal load capacity of the truck, kg.;

γ – load capacity factor;

t_{ref} - temperature in the refrigerator, C°.

A model for changes in transportation costs for a truck Hyundai EX10 has been defined:

$$TC_{Hyun} = 1277,05 \cdot \frac{t_{mov}}{t_{tot}} + 1135,51 \cdot q_{nc} \cdot \gamma + 56,76 \cdot t_{ref} \quad (2)$$

For the models obtained, the mean approximation error is determined, which indicates the possibility of using the models in the specified ranges of independent variables, as well as for short-term forecasting of transportation costs for the presented trucks. The mean approximation error for model (1) is 4.46%, and for model (2) – 5.98%.

Statistical estimates of the obtained models (1, 2) are presented in Table 1.

Table 1. Statistical estimates of models for changes in transport costs.		
Statistical indicator	Model TC_{MAN}	Model TC_{Hyun}
F-Ratio	1803.76	1054.35
Model coefficients T Statistic/ P-Value:		
t_{mov}/t_{tot}	6.63/0.0000	8.28/0.0000
$q_{nc} \cdot \gamma$	8.65/0.0000	2.44/0.0278
t_{ref}	-4.99/0.0001	5.25/0.0001
R-squared, %	99.6868	99.528
Correlation coefficient	0.998433	0.997637
Mean approximation error, %	4.46	5.98

The resulting models of transportation cost changes for both freight vehicles are adequate according to the calculated F -Ratio values. The tabulated F -Ratio value for MAN TGL 12.180 is 2.08 and the F -Ratio for Hyundai EX10 is 2.15. The models obtained are adequate with 95% reliability, since F -Ratio > F -Ratio for both vehicles, or $1803.76 > 2.08$ and $1054.35 > 2.15$. The model coefficients for T Statistic and P -Value are also significant, which for any of the coefficients does not exceed 0.05. Since the P -value is less than 0.05, that term is statistically significant at the 95.0% confidence level. Additionally, it is necessary to analyse the impact of each factor on the value of transport costs to ensure the corresponding physics of the process of the phenomenon under study – the

change in the resulting feature depending on the factors presented. In models (1) and (2), the ratio of travel time to total time spent on the route increases transport costs. This effect is explained by the fact that the greater the proportion of technological operations related to vehicle movement in the total time spent on the route, the greater the fuel consumption on the route and the higher the transport costs. In models (1, 2), the result of multiplying of the nominal load capacity of the vehicle and the load capacity factor characterizes the average amount of meat products in the refrigerated truck at each stage of the route when travelling between retail chain stores. The result of multiplying the nominal load capacity of a vehicle by the load capacity coefficient increases transport costs because a heavier load on the vehicle leads to higher fuel consumption and, consequently, higher transport costs. In models (1) and (2), the temperature in the refrigerated truck has a mixed effect on the value of transport costs: in model (1), this factor reduces the value of transport costs, while in model (2), the value of transport costs increases with an increase in the temperature in the refrigerated truck. This effect can be explained by the fact that the refrigerator works both to heat chilled meat products at low temperatures and to cool them at high temperatures. This effect can also arise due to different vehicle loads and types of refrigeration units, as noted in the paper above.

Optimization of cold chain logistics in the distribution of meat products is directly related to the cost of diesel fuel used in the technological process of delivering chilled meat products to the retail network in Khmelnytskyi city. Further research indicates the need to model diesel fuel consumption by MAN TGL 12.180 and Hyundai EX10 trucks when operating on routes, since fuel consumption is an indicator of the rationality of route formation, vehicle driving modes, and the duration of product cooling or heating under certain weather and climatic conditions to maintain its optimal quality during transportation to retail stores.

A model for changes in diesel fuel consumption for truck MAN TGL 12.180 has been defined:

$$DiesF_{MAN} = 0,0633922 \cdot t_{mov} + 0,0735307 \cdot t_{l/u} \quad (3)$$

where t_{mov} – route travel time, min.;

$t_{l/u}$ – loading/unloading time of the truck, min.

A model for changes in diesel fuel consumption for truck Hyundai EX10 has been defined:

$$DiesF_{Hyun} = 0,0658795 \cdot t_{mov} + 0,867864 \cdot t_{l/u}^{0,5} \quad (4)$$

For the models obtained, the mean approximation error is determined, which indicates the possibility of using the models in the specified ranges of independent variables, as well as for short-term forecasting of diesel fuel consumption for the presented trucks. The mean approximation error for model (3) is 5.48%, and for model (4) – 9.48%.

Statistical estimates of the obtained models (3, 4) are presented in Table 2.

Statistical indicator	Model $DiesF_{MAN}$	Model $DiesF_{Hyun}$
F-Ratio	1837.61	497.04
Model coefficients T Statistic/ P-Value:		
t_{mov}	6.072/0.0000	2.379/0.0286
$t_{l/u}$	6.229/0.0000	2.510/0.0218
R-squared, %	99.5126	99.528
Correlation coefficient	0.99756	0.99107
Mean approximation error, %	5.48	9.48

The obtained diesel fuel consumption models for both freight vehicles are adequate according to the calculated F-Ratio values. The tabulated F_r -Ratio value for MAN TGL 12.180 is 2.08 and the F_r -Ratio for Hyundai EX10 is 2.15. The models obtained are adequate with 95% reliability, since F -Ratio > F_r -Ratio for both vehicles, or $1837.61 > 2.08$ and $497.04 > 2.15$. The model coefficients for T Statistic and P-Value are also significant, which for any of the coefficients does not exceed 0.05. Since the P-value is less than 0.05, that term is statistically significant at the 95.0% confidence level. Additionally, it is necessary to analyse the impact of each factor on the value of diesel fuel consumption in models (3, 4). In the presented models, the travel time along the route increases diesel fuel consumption. According to (3, 4), the loading/unloading time of the vehicle increases fuel consumption due to the fact that during loading/unloading, the refrigerator doors are opened and the refrigerator at this time equalises the set temperature in the cargo compartment to preserve the consumer properties of chilled meat products.

5 Conclusions

The study attempts to determine the impact of the parameters of the meat product distribution logistics chain on operational, technological and environmental indicators. Models of changes in transport costs related to the technological indicators of refrigerated meat product transportation by road freight vehicles are presented. The models include three factors that characterise the transport route, cargo and cargo transportation conditions. The models are adequate, the model coefficients are significant, and the approximation errors do not exceed the permissible values. Given the importance of taking into account the environmental component when organising the technology of meat product transportation, models of changes in diesel fuel consumption for two freight vehicles are presented. The models of changes in diesel fuel consumption are based on two factors that directly characterise the technology of transportation and the performance of loading and unloading operations. These models, like the models of changes in transport costs, are adequate, the model coefficients are significant, and the approximation errors do not exceed the permissible values. The technological prospects for further research are in increasing the load capacity when transporting meat products and determining the limit characteristics of meat products for the application of an alternative approach to route formation. The operational prospects are in studying the load capacity of vehicles and their load levels in relation to the fuel consumption of trucks. Research into the impact of environmental conditions involves determining the impact of weather and climatic conditions on the operating conditions of refrigeration units and studying the impact of the operating conditions of refrigeration units on the physical characteristics of meat products.

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