A Network-Based Model of Transport Vehicle Movement in Petroleum Product Logistics

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Abstract. This study develops a network-based model for transport vehicle movement in petroleum product logistics under market economy conditions. Simulation-based approaches are commonly employed to distribute various types of petroleum products from supply facilities over a specified period in accordance with demand. However, these methods do not adequately address key issues such as route selection under multiple scenarios, minimization of transportation costs across regions, inventory estimation, and the coordination of vehicle movements. Existing inventory management approaches rely on diverse modeling techniques, while logistics algorithms typically assume that different types of petroleum products can be transported by a single vehicle. Furthermore, most simulation models focus on the interaction between oil refineries and oil depots, without fully incorporating the broader distribution network that includes fuel filling stations. In addition, they do not account for the relocation of vehicles between depots and stations across different regions. As a result, the vehicle fleet is not explicitly represented as a parameter in logistics models, despite its direct role in transportation processes.

To overcome these limitations, an extended Colored Petri Net-based model for transport vehicle movement in petroleum product logistics is proposed. The model is formally defined using sets of places and transitions, with input, output, and incidence functions represented in matrix form. The structural properties of the model are analyzed, the sequence of admissible transitions from the initial state is determined, and a rule base describing causal relationships is constructed. In addition, a graph-based representation of vehicle movement is developed.

Keywords: network model, petroleum product logistics, petroleum products, Colored Petri nets, transport vehicles, oil depots

1. Introduction

Under market economy conditions, meeting consumer demand for petroleum products in a wide assortment, in required quantities, with safety and minimal cost, necessitates the development of efficient and competitive logistics systems. Petroleum product logistics represents a complex hierarchical network that integrates financial, material, and information flows. Recent studies on petroleum product distribution and supply chain optimization highlight the importance of integrated modeling approaches in complex logistics systems [1, 12]. This system comprises oil companies, refineries, petroleum product supply facilities (oil depots), their associated fuel filling stations, and other related infrastructures.

Oil depots are enterprises consisting of a complex of facilities and structures designed for the reception, storage, transportation, and servicing of consumers with crude oil and petroleum products [2]. The primary function of oil depots is to ensure the uninterrupted supply of petroleum and petroleum products, in the required quantities and assortments, to industrial enterprises, transport systems, agricultural sectors, and other consumers. In addition, they aim to minimize losses occurring during the processes of receiving, storing, and transporting petroleum products.

Distribution oil depots are intended to supply consumers with crude oil and petroleum products. Compared to transshipment (loading-unloading) oil depots, distribution depots are smaller in scale and are established to serve specific regions. In general, they perform loading and unloading operations and provide short-term storage of petroleum products. Typically, the volume of petroleum products received by distribution oil depots within a day is approximately equal to the volume distributed during the same period. These depots receive petroleum products via tankers, pipelines, and rail transport, and distribute them using rail transport, small barges, small-capacity containers, and road transport vehicles [18].

According to the nature of their operations, distribution oil depots are classified into regional and district depots, as well as rail, water-rail, and water-based facilities. In order to ensure high-quality service to consumers, their location must comply with sanitary and fire safety regulations. Furthermore, it is essential to minimize the transportation routes of road vehicles between consumers and the oil depot.

Distribution oil depots also include deep depots and facilities connected to trunk pipelines. The first type of depots is located at a considerable distance from railway and water transport systems; therefore, the transportation of petroleum products is mainly carried out by road vehicles. The second type of depots is situated in proximity to trunk pipelines [12]. In this case, petroleum products are supplied periodically through pipelines, while their distribution to consumers is performed by road transport [13].

The integration of innovative technologies enables the effective coordination of logistics processes. Computerized management systems allow real-time regulation of vehicle routes, reducing time losses and ensuring the timely delivery of products to their destinations. This contributes to improved cost efficiency and operational performance. Consequently, modeling the movement of transport vehicles constitutes a key strategic task in petroleum product logistics.

Simulation modeling methods are widely used to distribute various types of petroleum products from supply facilities over a specified period in accordance with the demand of fuel filling stations [16, 15]. However, these approaches do not adequately address issues such as the determination of distribution routes under different scenarios, minimization of transportation costs across regions, inventory estimation, and the

coordinated movement of transport vehicles. In many studies, inventory management is modeled using different approaches, while logistics algorithms often assume that multiple types of petroleum products can be transported by the same vehicle [11, 17].
In practice, most simulation models focus on the "oil refinery-oil depot" chain and do not fully incorporate the "oil depot-fuel filling station" distribution network [6, 8, 9]. Moreover, they do not consider the relocation of transport vehicles between depots and stations across different regions. As a result, the vehicle fleet is not explicitly included as a parameter in logistics models, although vehicle movement along the "oil depot-fuel filling station" route is considered. These limitations highlight the need for the development of new logistics models based on systematic representation and dynamic modeling tools [7, 11, 20].
To address these challenges, a transport vehicle movement model for petroleum product logistics has been developed.

2 Transport Vehicle Movement Model in Petroleum Product Logistics

The transport vehicle movement model in petroleum product logistics is designed to ensure the efficient transfer of products between different points of the supply chain. The model aims to reduce logistics costs, minimize product losses, and maintain high safety standards by organizing vehicle operations, including routing, speed, and loading-unloading processes [3].
The model is developed by considering multiple operational factors. At the initial stage, transportation routes and scheduling conditions are defined. These routes determine the most efficient paths for delivering products from supply sources to customers or storage facilities. During route planning, factors such as weather conditions, road quality, traffic intensity, and other external influences are taken into account, as they may significantly affect transportation performance [22, 25].
Particular attention is given to the regulation of vehicle speed and handling times. Vehicles are dispatched in a manner that ensures timely arrival at their destinations, while loading and unloading operations are organized to achieve efficient utilization of available resources. These processes are structured to be carried out with minimal time and resource consumption, even under time-critical conditions.
The system also incorporates safety requirements into the organization of vehicle movement. Loading and unloading processes are managed with due consideration of fire safety and other potential hazards. In addition, automated monitoring and response mechanisms are introduced to address incidents such as product leakage and other emergency situations. The model is supported by digital control tools, including GPS-based tracking systems that enable real-time monitoring of vehicle routes and movements [9, 12]. Continuous data transmission to a centralized control system allows deviations and anomalies in logistics operations to be promptly identified, supporting timely decision-making.
Another important factor in reducing logistics costs is the loading efficiency of transport vehicles [6, 21]. Higher loading levels enable vehicles to travel longer distances while carrying sufficient quantities of products, thereby improving overall operational performance. This approach ensures both efficient use of resources and safe

cargo transportation. In addition, transport vehicles should be insured against potential risks, which enhances the reliability and cost-effectiveness of transportation operations. Overall, the proposed model represents a comprehensive approach that enables faster, safer, and more cost-efficient logistics operations. Its implementation leads to reduced transportation costs, minimized product losses, and improved operational efficiency. The automation of the model also supports environmental protection and promotes the rational use of available resources, contributing to more stable and sustainable transportation processes.

The model constitutes a strategic framework aimed at optimizing and effectively managing the transportation of petroleum products. It incorporates vehicle types, loading and unloading locations, and route selection. In developing the model, the characteristics, volume, and safety requirements of the transported products are taken into account. The primary objective is to minimize transportation costs, preserve product quality, and ensure reliable supply to consumers.

The selection of optimal routes contributes to reduced fuel consumption and lower carbon emissions, thereby supporting environmental sustainability. Furthermore, the integration of artificial intelligence and big data analytics enhances forecasting and decision-making processes [12, 24]. In addition, the technical condition of transport vehicles is continuously monitored to ensure operational reliability.

The petroleum product logistics model considers several possible scenarios for the movement of transport vehicles (TV):

1. Initial movement of a transport vehicle (TV) from the vehicle fleet (VF) to an oil depot (OD). In this case, an empty-capacity TV is dispatched from its assigned VF to an OD in order to serve the fuel filling stations (FFS) associated with that depot.
2. Reciprocal movement between the oil depot (OD) and fuel filling stations (FFS). In this case, a predefined number of movements between the OD and the FFSs is performed.
3. Movement of a transport vehicle (TV) from one oil depot (OD) to another via fuel filling stations (FFS). In this scenario, the TV operates through FFSs while relocating to another OD, without returning to the previously assigned OD.
4. Return of a transport vehicle (TV) from a fuel filling station (FFS) directly to the vehicle fleet (VF) after completion of service. In this case, after servicing the final FFS, the TV returns empty to its assigned VF. In the transport vehicle (TV) movement model, the following constraints are considered:

A TV cannot leave the vehicle fleet (VF) more than once; each TV must be assigned to a specific VF; a TV cannot enter an oil depot (OD) to which it is not assigned more than once; a TV that enters another OD must return to its assigned OD; each TV must satisfy the demand of every fuel filling station (FFS); and each TV must meet the maximum service demand within a single working day.

For modeling petroleum product logistics, the following requirements should be considered:

1. Costs associated with planned consumption or demand.
2. Inventory levels maintained at the oil depot (OD).
3. Tariffs, penalties, and other costs defined by contractual agreements.

The possible movement routes of a transport vehicle (TV)-namely, from the vehicle fleet (VF) to OD-1, from OD-1 to its assigned fuel filling stations FFS-1 and FFS-2 and back to OD-1, then from OD-1 to another oil depot OD-2 and its associated fuel filling stations FFS-3 and FFS-4, as well as movements to fuel filling stations assigned to other depots-are structurally represented as shown in Fig. 1.

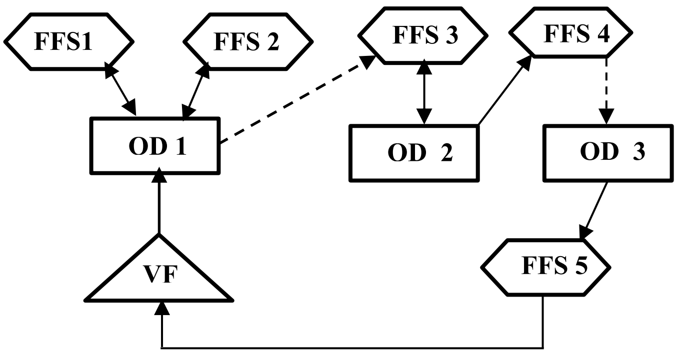

Fig. 1. Structural diagram of possible movement scenarios of a transport vehicle (TV)

The movement model of the transport vehicle is represented in the form of an extended Colored Petri Net (CPN) [5, 11]. Petri Net-based approaches have been widely applied for modeling complex discrete-event systems and logistics processes [4, 5].

The extended CPN is formally defined as $N = (P, T, \Omega, F, H, \lambda, \varphi, \psi, \mu_0, R)$. The extended Colored Petri Net is formally defined by sets of places and transitions, together with input, output, and incidence functions, which provide a rigorous mathematical framework for modeling system dynamics [5].

where

$P = \{p\}$ - a non-empty finite set of places;

$T = \{t\}$ - a non-empty finite set of transitions;

$\Omega = \{\omega\}$ - a non-empty finite set of colors of places and tokens;

$F: P \times T \to \{0,1,2, \dots\}$ and

$H: P \times T \to \{0,1,2, \dots\}$ - are the incidence matrices of the sets of places and transitions, respectively;

$\lambda : P \times \Omega \to \{0,1\}$ - the function of color distribution over the places of the net;

$\varphi : (P \times \Omega) \times T \to \{0,1, \dots\}$ - the function of distributing the colors of tokens over the input places of transitions;

$\psi : T \times (P \times \Omega) \to \{0,1, \dots\}$ - the function of distributing the colors of tokens over the output places of transitions;

$\mu_0 : P \times \Omega \to \{0,1,2, \dots\}$ - the initial marking of the net.

The functions φ and ψ define the firing rules of transitions and determine the distribution of token colors over places during the operation of the net. The functions defining the distribution of token colors over input and output places determine the firing conditions of transitions and the evolution of the system state [5, 10].

R - is a rule base consisting of production rules expressed in the form of IF-THEN. The marking elements of places are represented in matrix form of dimension $| P | \times | \Omega |$, where each element corresponds to the number of tokens of color ωin place p [5].

As a result of firing any transition t, the marking $\mu_i(p, \omega)$is replaced by the marking $\mu_{i+1}(p, \omega)$according to the following expression:

$$\mu_{i+1}(p,\omega) = \mu_i(p,\omega) - \delta_i(p,\omega) * F(p,t) + \gamma_t(p,\omega) * H(t,p),$$

where

$$\delta_i(p,\omega) = \begin{cases} 1, if \ \ (p,\omega) \in I(p,t); \\ 0, otherwise. \end{cases}$$

$$\gamma_t(p,\omega) = \begin{cases} 1, if \ (p,\omega) \in O(p,t); \\ 0, otherwise. \end{cases}$$

In the developed model, the movement states of the transport vehicle are described by the following set of places. The set of places:
p_1 - there is an empty transport vehicle in the vehicle fleet that meets the standard requirements;
p_2 - there is an empty transport vehicle at the oil depot that meets the standard requirements;
p_3 - the storage tank of the oil depot is in the mode of filling the transport vehicle with petrole
um products;
p_4 - there is a transport vehicle loaded with petroleum products at the oil depot;
p_5 - the fuel filling station is in the mode of receiving petroleum products;
p_6 - there is a transport vehicle loaded with petroleum products at the fuel filling station;
p_7 - petroleum products have been unloaded into the storage system of the fuel filling station;
p_8 - there is an empty transport vehicle at the fuel filling station;
p_9 - the service life of the transport vehicle has not expired;
p_{10} - the service life of the transport vehicle has expired;
p_{11} - there is a demand for petroleum products at the fuel filling station.
Possible events in the movement model are described by the following set of transitions. The set of transitions:
t_1 - the process of transferring an empty transport vehicle that meets the standard requirements to the oil depot is carried out;
t_2 - the process of loading petroleum products from the storage tank into an empty transport vehicle that meets the standard requirements is carried out;
t_3 - the process of receiving the transport vehicle loaded with petroleum products at the fuel filling station is carried out;
t_4 - the process of unloading petroleum products from the vehicle tank into the storage tank of the fuel filling station is carried out;
t_5 - the process of regulating the operating mode of the empty transport vehicle at the fuel filling station is carried out;
t_6 - the process of determining the demand for petroleum products at the fuel filling station is carried out;
t_7 - the process of returning the empty transport vehicle to the oil depot is carried out;

t_8 - the process of returning the empty transport vehicle to the vehicle fleet is carried out.
In the studied model, four colors are defined as $W = (w_1, w_2, w_3, w_4)$:
w_1 - an empty transport vehicle (TV) that meets the standard requirements;
w_2 - the storage tank of the oil depot (OD);
w_3 - a transport vehicle (TV) loaded with petroleum products;
w_4 - a fuel filling station (FFS) with demand.
Fig. 2 shows the graph diagram of the transport vehicle movement model.

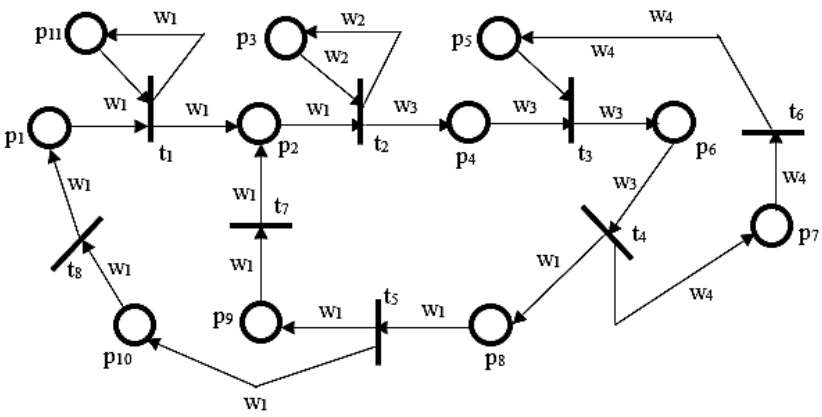

Fig. 2. Graph-based representation of the transport vehicle movement model

The input and output incidence matrices of the set of places with dimension $(8 \times 11), F\ (8 \times 11)$, and of the set of transitions with dimension $(11 \times 8), H\ (11 \times 8)$, are represented as follows [14, 23]:

$$F(8 \times 11) = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{vmatrix}$$

$$
\mathrm{H}\ (11 \times 8) = \begin{vmatrix}
0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{vmatrix}
$$

$$
D\ (8 \times\ 11)\ = \begin{vmatrix}
-1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0
\end{vmatrix}
$$

The color distribution functions over the input and output places of transitions are represented by the matrices $\Phi\ (8 \times\ 4)\ and\ \Psi\ (8 \times\ 4)$, respectively.

$$
\Phi(8 \times 4) = \begin{vmatrix}
1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{vmatrix}
\qquad
\Psi(8 \times 4) = \begin{vmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0
\end{vmatrix}
$$

The distribution of colors over places and the initial marking are represented by the matrices $\lambda\ (11 \times\ 4)\ and\ \mu^0\ (11 \times 4)$, respectively, as follows:

$$\lambda(11\times 4)=\begin{vmatrix}1&0&0&0\\1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&1&0\\0&0&0&1\\1&0&0&0\\1&0&0&0\\1&0&0&0\\1&0&0&0\end{vmatrix}\quad \mu^0(11\times 4)=\begin{vmatrix}1&0&0&0\\0&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&1\\0&0&1&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}$$

Based on the initial data, a computational experiment was conducted, and the following results were obtained:

$$\mu^1(11\times 4)=\begin{vmatrix}0&0&0&0\\1&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&1\\0&0&1&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}\quad \mu^2(11\times 4)=\begin{vmatrix}0&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&1&0\\0&0&0&1\\0&0&1&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}$$

$$\mu^3(11\times 4)=\begin{vmatrix}0&0&0&0\\0&0&0&0\\0&1&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\\0&0&0&1\\1&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}\quad \mu^4(11\times 4)=\begin{vmatrix}0&0&0&0\\0&0&0&0\\0&1&0&0\\0&0&1&0\\1&0&0&0\\0&0&1&0\\0&0&0&1\\1&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}$$

$$\mu^5(11\times 4)=\begin{vmatrix}0&0&0&0\\0&0&0&0\\0&1&0&0\\0&0&1&0\\1&0&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\\1&0&0&0\\1&0&0&0\\1&0&0&0\end{vmatrix}\qquad \mu^6(11\times 4)=\begin{vmatrix}0&0&0&0\\0&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\\0&0&0&1\\0&0&0&0\\1&0&0&0\\1&0&0&0\\1&0&0&0\end{vmatrix}$$

$$\mu^7(11\times 4)=\begin{vmatrix}0&0&0&0\\0&1&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\\0&0&0&1\\0&0&0&0\\0&0&0&0\\1&0&0&0\\1&0&0&0\end{vmatrix}\qquad \mu^8(11\times 4)=\begin{vmatrix}1&0&0&0\\0&1&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\\0&0&0&0\\0&0&0&1\\0&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\end{vmatrix}$$

The use of input and output incidence matrices allows the analysis of structural relationships between places and transitions, as well as the evaluation of system state changes [10, 22].

The obtained markings at different stages of the computational experiment reflect the dynamic evolution of the system and confirm the correctness of the proposed model [22].

Taking into account the input and output functions of transitions in the Colored Petri Net, the rule base in the form of **IF-THEN**conditions is defined as follows:

Rule 1. IF there is an empty transport vehicle in the vehicle fleet that meets the standard requirements **AND** there is a demand for petroleum products at the fuel filling station, **THEN** the process of transferring the empty transport vehicle to the oil depot is carried out.

Rule 2. IF there is an empty transport vehicle at the oil depot that meets the standard requirements **AND** the storage tank of the oil depot is in the mode of filling the vehicle with petroleum products, **THEN** the process of loading petroleum products from the storage tank into the transport vehicle is carried out.

Rule 3. IF there is a transport vehicle loaded with petroleum products at the oil depot **AND** the fuel filling station is in the receiving mode, **THEN** the process of delivering the loaded transport vehicle to the fuel filling station is carried out.

Rule 4. IF there is a transport vehicle loaded with petroleum products at the fuel filling station, **THEN** the process of unloading petroleum products from the vehicle tank into the storage tank of the fuel filling station is carried out.

Rule 5. IF there is an empty transport vehicle at the fuel filling station, **THEN** the process of regulating the operating mode of the empty transport vehicle at the fuel filling station is carried out.
Rule 6. IF petroleum products have been unloaded into the storage system of the fuel filling station, **THEN** the process of determining the demand for petroleum products at the fuel filling station is carried out.
Rule 7. IF the service life of the transport vehicle has not expired, **THEN** the process of returning the empty transport vehicle to the oil depot is carried out.
Rule 8. IF the service life of the transport vehicle has expired, **THEN** the process of returning the empty transport vehicle to the vehicle fleet is carried out.
The rule base defined in the form of IF–THEN conditions enables the formal representation of system behavior and supports decision-making processes in the logistics system [9, 10].

Through computer simulation, the structural elements of the transport vehicle (TV) movement model, represented in the form of colored and timed Petri nets, have been described using matrix representations. The problem of executing enabled transitions under conflict conditions has been resolved, resulting in a reduction in the number of places and transitions within the network. Consequently, the modeling process has been simplified and accelerated. Furthermore, software has been developed within the MATLAB and CPN Tools modeling environments, enabling the solution of problems involving relatively large-scale matrices. This approach fully satisfies the requirements for modeling complex distributed systems.

Conclusion. This study has examined the methods of transportation of petroleum products, their operational characteristics, and the functioning of distribution oil depots, thereby identifying the key advantages and limitations of existing logistics approaches. Based on this analysis, a structural scheme representing possible variants of transport vehicle (TV) movements in petroleum product logistics has been developed. In accordance with this scheme, a formal model of TV movement has been constructed using the Colored Petri Net (CPN) framework.
The structure of the proposed CPN model, including its places, transitions, and color sets, has been systematically defined. The rules governing transition execution have been formulated on the basis of the color distribution function, ensuring a consistent and mathematically grounded representation of system dynamics. Computer simulation has been performed to determine the trajectory of transition sequences within the TV movement model, enabling the analysis of its dynamic behavior. In addition, a graph-based representation of the model has been developed to enhance interpretability and structural clarity.
Furthermore, a production rule base has been established to support the operation and adaptability of petroleum product logistics models. The proposed approach contributes to improving the coordination of transport processes and provides a flexible foundation for modeling and analyzing complex logistics systems under varying operational conditions.

References

1. Acosta-Amado, R. J., et al. Optimization of petroleum products distribution via pipeline systems: Modeling and computational challenges. *Heliyon*. (2024).
2. Amen, S. A., Prokhorov, A. V., & Fedorovich, O. E. Coordination of agent interaction in modeling petroleum product supply processes. *Radioelectronics and Computer Systems*, 4(56), 185–192. (2012).
3. Atazhakhov, Z. D. Logistic foundations of petroleum product supply. Rostov-on-Don: RSEU. (2004).
4. Baptista, G., Vieira, M., & Pinto, T. An exact approach to the multi-compartment vehicle routing problem: The case of a fuel distribution company. *Mathematics*, 12(4), 527. (2024).
5. Bashkin, V. A., & Lomazova, N. A. *Resource equivalence in Petri nets*. Moscow: Nauchny Mir. (2008).
6. Boev, V. D. *System modeling: GPSS World tools*. Saint Petersburg: BHV. (2004).
7. Indrianti, N., et al. Green vehicle routing problem optimization for LPG distribution: Genetic algorithms for complex constraints and emission reduction. *Sustainability*, 17(3), 1144. (2025).
8. Jaffal, M. S., Abdulghafour, A. B., Ayadi, O., & Masmoudi, F. Optimizing petroleum products distribution centers using GFA and AnyLogistix simulation: A case study. *Logistics*, 9(2), 63. (2025).
9. Kaiyandra, D. R., et al. Colored Petri nets for modeling and simulation of a green supply chain system. *IFAC-PapersOnLine*, 57, 130–135. (2024).
10. Liu, Y., et al. Efficient feasibility checks and adaptive large neighborhood search for time-dependent green vehicle routing problems. *European Journal of Operational Research*, 310(1), 133–155. (2023).
11. Lomazova, N. A. Object-oriented Petri nets: Formal semantics and analysis of systems with object structure. *Siberian Branch of RAS Proceedings*. (2004).
12. Mogale, D. G., et al. Modelling and optimizing a multi-depot vehicle routing problem for freight distribution. *Computers & Operations Research*. (2025).
13. Mohammad, N. *Modeling and simulation in SIMULINK for engineers and scientists*. (2005).
14. Mustafayev, V. A., & Huseynzade, S. S. Development of a control model using colored Petri nets. *Herald of Computer and Information Technologies*, 3(155), 36–44. (2018).
15. Nguyen, V. S., Pham, Q. D., Nguyen, T. H., & Bui, Q. T. Modeling and solving a multi-trip multi-distribution center vehicle routing problem. *Computers & Industrial Engineering*, 172, 108597. (2022).
16. Redutskiy, Y., et al. Energy efficiency in petroleum supply chain optimization. *Energies*, 17(2), 388. (2024).
17. Sabet, S., & Farooq, B. Green vehicle routing problem: State of the art and future directions. *IEEE Access*, 10, 101622–101642. (2022).
18. Sadeghi, N. (2017). *Petroleum logistics and supply chain management*. CRC Press.
19. Sherif, S. U., et al. (2021). Integrated optimization of transportation and inventory in green supply chains. *Journal of Cleaner Production*, 287, 125434.
20. Su, Y., Zhang, S., & Zhang, C. Genetic algorithm with variable neighborhood search for vehicle routing. *Applied Soft Computing*, 161, 111789. (2024).
21. Wang, S., et al. Reducing carbon emissions in vehicle routing problems using multiple depots. *Sustainability*, 14(3). (2022).
22. Wen, M., et al. Adaptive large neighborhood search for large-scale vehicle routing problems. *Journal of Cleaner Production*, 374, 133916. (2022).
23. Reisig, W*Understanding Petri nets: Modeling techniques, analysis methods, case studies*. Springer. . (2013).

24. Zhang, H., et al. Optimizing speed in green truckload pickup and delivery routing. *Computers & Industrial Engineering*, 198, 110736. (2024).
25. Zhou, Z., Ha, M., Hu, H., & Ma, H. Multi-depot heterogeneous vehicle routing problem for hazardous materials transportation. *Sustainability*, 13(3), 1262. (2021).