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Assessment of Risk Factors and Improvement of Transportation Technology for Temperature-Sensitive Cargo in Refrigerated Containers

The article identifies risk factors associated with the transportation of temperature-sensitive cargo in refrigerated containers within the cold supply chain system using different modes of transport and their interaction, which can be taken into account when organizing intermodal, multimodal, and combined transportation. Based on the identified risk factors, hazardous situations characteristic of road transportation of such cargo are determined. The assessment of their criticality is carried out using the FMEA/FMECA methods.
temperature-sensitive cargo, refrigerated containers, cold chain, cold chain logistics, interaction of transport modes. intermodal, multimodal and combined transportation, risk factors, risk assessment method, hazardous situations, road transportation

Problem statement. The modern development of global logistics is characterized by a steady growth in the transportation of temperature-sensitive cargo (TSC), which increases the importance of the cold chain (CC) in supply systems.

TSC includes a wide range of products for which the stability of the temperature regime is a key factor in maintaining quality. This category includes food products (meat, fish, seafood, dairy products, vegetables, fruits, and frozen semi-finished products), pharmaceutical products, vaccines, biological materials, certain types of chemical reagents, and cosmetic products. For most such cargo, even a short-term deviation of temperature from the specified limits may lead to the loss of consumer properties or complete spoilage of the products.

According to analytical studies, in 2024 the global cold chain logistics (CCL) market amounted to USD 316.34 billion, and by 2033 its volume may reach USD 1,611 billion, with an average annual growth rate exceeding 20% [1]. Such dynamics are associated with the increasing international transportation of food products, pharmaceutical products, and biological materials that require continuous maintenance of specified temperature conditions.

One of the key elements of the CC is the transportation of TSC in refrigerated containers (RC). At the same time, this segment is characterized by higher costs compared to conventional container transportation. In particular, according to APD Ukraine (2024) [2], the cost of transporting one refrigerated container by road from Ukraine to the Port of Constanța is approximately EUR 1,900, whereas the transportation of grain or oil amounts to about EUR 1,324; for rail transport, the corresponding costs are EUR 1,024 and EUR 768, respectively. The increase in costs is associated with the need to ensure uninterrupted operation of refrigeration equipment, the use of autonomous power supply systems such as Generator Set (GenSet), continuous monitoring of environmental parameters, and the minimization of the risk of cargo spoilage.

The provisions of the National Transport Strategy of Ukraine until 2030 [3] are focused on the development of containerization of cargo flows, multimodal and combined transportation, and the improvement of transport process safety. At the same time, the document identifies a number of issues that create additional risks, including technological inconsistencies at the interfaces of different transport modes, delays at border crossing points, an insufficient level of digital monitoring, and uneven organization of logistics flows.

Currently, ensuring the integrity of TSC in RC has become a critical factor in transportation efficiency. Even short-term temperature deviations, interruptions in power supply, or delays during transshipment may result in significant economic losses. This necessitates a comprehensive risk assessment of refrigerated container transportation and the development of a set of measures aimed at improving technological processes.

Analysis of recent research and publications. According to DSTU ISO 1496-2:2013 [4] and ISO 1496-2:2018 [5], RC belong to the class of insulated containers characterized by enhanced thermal insulation properties. Unlike passive insulated structures, modern RC are equipped with a refrigeration unit that ensures the maintenance of a specified temperature regime within the range from –25 °C to +25 °C, and in some modifications down to –35 °C. RC represent a standardized transport unit [4, 5], which allows transportation without cargo transshipment between different modes of transport. Such structural versatility enables the integration of RC into intermodal, multimodal, and combined transport systems. The standardization of dimensions (20 ft, 40 ft, 40 ft High Cube, 45 ft High Cube) ensures compatibility with road, rail, and maritime transport, as well as with terminal infrastructure.

A specific feature of RC operation is the combination of stationary and autonomous power supply. In ports, terminals, and storage yards, containers are connected to stationary electrical outlets, whereas during road or rail transportation their autonomy is ensured by diesel generator units of the GenSet type in clip-on or underslung configurations.

Currently, the development of the CC is characterized by the active implementation of smart technologies and digital solutions corresponding to the concept of Industry 4.0 [6]. RC are equipped with sensor systems for monitoring temperature, humidity, and vibration, GPS tracking modules, as well as digital technologies for monitoring and managing the CC, including Internet of Things (IoT) and blockchain-based solutions [7, 8], which enable real-time data transmission.

In particular, study [8] investigates the application of IoT technologies for managing the energy consumption of RC at port terminals. Studies [9, 10] examine a cyber-physical approach to the problems of transport systems and technologies. In addition, [8] proposes a cyber-physical system that enables the interaction of containers with power supply systems and energy consumption planning platforms. The proposed mathematical models make it possible to optimize the power supply regimes of RC, taking into account variable electricity prices, environmental parameters, and the specific features of their operation.

Maintaining a stable temperature regime is a key condition for the functioning of the CC. As noted in study [11], temperature monitoring during transportation is necessary to ensure the integrity of TSC and to prevent economic losses.

At the same time, transport systems face a number of risks associated with the human factor in the organization of transportation and the influence of external environmental conditions [12]. Study [13] proposes an approach to risk assessment in the transportation of dangerous goods based on the analysis of potential hazardous situations and the application of the expert evaluation method, which makes it possible to determine the probability of their occurrence and the potential consequences.

Methods for the implementation and improvement of smart technologies in transport, taking into account expert recommendations, are considered an effective tool for improving the quality of the transportation process [14] and cargo operations as its component [15]; however, they require further adaptation to the specific features of CCL. At the same time, it is necessary to consider the design features and technical characteristics of specialized vehicles used for the transportation of TSC, as well as their refrigeration units [16].

Modern research pays considerable attention to the environmental aspects of the CC and the improvement of the energy efficiency of refrigeration equipment, which correspond to the general European trends in the development of environmentally oriented transport systems and are consistent with the integration of the transport system of Ukraine into the European transport space. In particular, study [17] examines modern technical solutions in the transportation of RC aimed at reducing energy consumption and negative environmental impact, as well as the use of passive insulated transport units that allow a partial reduction in the need for active cooling.

In the near future, in the field of TSC transportation, it is advisable to implement the principles of risk management in the organization of the transportation process [18], as well as to consider the development of transport corridors oriented toward consumer needs and their logistics demands [3]. Under these conditions, conducting research aimed at identifying critical risk factors and improving transportation processes for TSC, particularly in RC, becomes relevant, as they have significant economic potential in CCL [19, 20].

The aim of the study is to assess hazardous situations and risk factors arising during the transportation of temperature-sensitive cargo in refrigerated containers by road transport and to develop recommendations for improving transportation technology within the cold chain supply system.

To achieve this aim, the following tasks are addressed in the study:

– to classify risk factors associated with the transportation of temperature-sensitive cargo in refrigerated containers by different modes of transport and in their interaction;

– to identify hazardous situations corresponding to the risk factors in the transportation of temperature-sensitive cargo in refrigerated containers by road transport;

– to assess the criticality of hazardous situations in the transportation process of refrigerated containers based on the FMEA (FMECA) method and expert evaluation;

– to develop recommendations for risk reduction and improvement of the technology for transporting temperature-sensitive cargo.

Presentation of the main material. The technology of RC transportation has a multi-stage nature and differs significantly from the transportation of standard containers. The first stage is the Pre-trip Inspection (PTI), which includes diagnostics of the refrigeration unit, verification of tightness, assessment of the condition of thermal insulation, calibration of sensors, and verification of the correct setting of the temperature regime.

Before loading, pre-cooling of the container is carried out to stabilize the internal microclimate and prevent temperature shock. The loading process requires strict compliance with the temperature compatibility of the cargo and proper organization of air circulation inside the container.

A critical stage of the technological process is the transshipment of the container between different modes of transport, as it is at this moment that operating conditions and power supply sources change. Even a short-term disconnection from the power supply under unfavorable climatic conditions may lead to fluctuations in internal temperature parameters. Temporary storage is carried out at specialized sites (reefer racks) equipped with power supply systems and technical monitoring facilities. At the same time, during periods of transshipment and waiting, the process becomes more dependent on organizational factors and compliance with established procedures.

The final stage is unloading and recording the actual temperature parameters, after which the container is either sent for re-inspection or introduced into a new transportation cycle.

The complexity and multi-component nature of this process determine the presence of factors that affect the stability of its functioning. Considering their origin, the risks can be divided into three main categories: human-related risk factors (HRF), technical and technological risk factors (TTRF), and natural and climatic risk factors (NCRF).

Risk factors of the transportation process may be classified according to various criteria, in particular by the stages of the transportation process or by the nature of their impact on the functioning of the transport system. However, for the purposes of this study, their systematization according to the origin of risks is considered appropriate, as it allows the main sources of risk occurrence to be clearly identified.

The identified groups of factors reflect the main directions of potential deviations in the process of transporting refrigerated containers (RC). Their specific manifestations depend on the mode of transport and operating conditions. Typical examples of possible incidents in different modes of transport are summarized in Table 1.

Table 1 – Examples of hazardous situations in the transportation of refrigerated containers by different modes of transport and their interaction

Mode of transport	Risk factors	Hazardous situation	Consequences
Maritime transport	HRE	Dropping of the container from the spreader during vessel unloading at the port	– complete or partial loss of TSC; – damage to the RC; – damage to the berth or adjacent containers.
	TTRF	Failure of the vessel's electrical power system during the voyage	– complete or partial loss of TSC; – costs for repair of the electrical power system.
	NCRF	Strong storm leading to the container falling overboard	– complete loss of TSC; – damage to RC; – costs associated with raising the container from the water.
Rail transport	HRE	The container was not connected to the power supply at the terminal or during train formation	– partial or complete loss of TSC.
	TTRF	Refrigerant leakage in the refrigeration unit	– complete or partial loss of TSC; – repair of the refrigeration unit.
	NCRF	Short circuit in the electrical system due to water ingress	– complete or partial loss of TSC; – damage to the unit; – delays in train traffic and increased logistics costs.
Road transport	HRE	Unauthorized access to the container during parking	– loss of TSC; – possible damage to RC; – penalties for the carrier.
	TTRF	Shutdown or malfunction of the GenSet during transportation	– partial or complete loss of TSC; – costs for generator repair.
	NCRF	A tree falling onto the container due to weather conditions	– complete or partial loss of TSC; – damage to RC; – risks to the driver's health.
Interaction of transport modes	HRE	Violation of technological procedures during transshipment and changes in container operating conditions	– partial or complete loss of TSC; – increase in idle time; – penalties and additional logistics costs.
	TTRF	Interruption of power supply during the transition between transportation segments	– partial or complete loss of TSC; – damage to the refrigeration unit; – delays in transportation and increased costs.
	NCRF	Exposure to open environmental conditions during waiting for transshipment	– partial or complete loss of TSC; – damage to RC or electrical equipment; – delays in subsequent transportation.

Source: developed by the authors

The road transport component of CCL is characterized by increased sensitivity to external influences, as it operates mainly outside controlled terminal infrastructure. The operating conditions of RC in this segment are determined by the variability of the road environment, climatic factors, and the stability of autonomous power supply, which creates an additional level of operational uncertainty. In intermodal, multimodal, and combined transportation systems, road transport usually integrates the container into the logistics chain at the initial and final stages of transportation. It is at these stages that direct contact with the consignor and consignee occurs, which increases the importance of the road segment for ensuring the integrity of TSC and the stability of the entire transportation process.

Taking into account the previous systematization of risk factors (Table 1) makes it possible to form an extended list of hazardous situations characteristic specifically of road transport and to proceed to their assessment using the selected methodology. A generalized list of such hazardous situations is presented in Table 2.

Table 2 – Main hazardous situations in the road transportation of refrigerated containers

Hazardous situations Risk factor group	Risk factor group
Violation of the temperature regime due to power supply failures during idle periods	TTRF
Failure of the refrigeration unit or GenSet during transportation	TTRF
Personnel errors when setting temperature or ventilation parameters	HRF
Violation of loading technology causing blockage of air circulation channels	HRF
Mechanical damage to RC during maneuvering or transshipment between different modes of transport	HRF/TTRF
Unauthorized interference during parking (intrusion by unauthorized persons, attempts to open the container)	TTRF/NCRF
Damage to RC due to adverse weather conditions (strong wind, precipitation, hail)	NCRF

Source: developed by the authors

One of the methods for risk assessment described in [21] is Failure Mode and Effects Analysis (FMEA), as well as its extended modification – Failure Mode, Effects, and Criticality Analysis (FMECA). These methods are widely used for the study of technical and organizational-technological processes, which makes them suitable for risk assessment during road transportation of refrigerated containers (RC).

The application of FMEA makes it possible to:

– systematize potential failures (hazardous situations) of refrigeration equipment, power supply systems, and container components;

– take into account the influence of the human factor;

– determine the priority of hazardous situations.

The quantitative determination of the criticality of a hazardous situation is carried out using the Risk Priority Number (RPN), which is defined as:

$$RPN = S \cdot O \cdot D, \quad (1)$$

where S (Severity) – the severity rating of the consequences of a failure for the integrity of the cargo and the technical condition of the RC; O (Occurrence) – the rating of the probability of occurrence of the corresponding type of failure; D (Detection) – the rating of the ability to detect a deviation before the occurrence of its critical consequences.

The D indicator is ranked in reverse order: the more difficult it is to detect a deviation, the higher the score assigned.

In order to increase the objectivity of the assessment of the parameters S, O, and D, the expert evaluation method was applied. A group of specialists in the field of road transportation organization and RC operation was involved in the assessment. Each expert was asked to rank the identified hazardous situations according to the three FMEA components using a ten-point scale.

The calculation of the average values of the parameters for each hazardous situation is determined as follows:

$$\overline{S}_i = \frac{1}{m}\sum_{j=1}^{m} S_{ij}, \tag{2}$$

where $i = 1, 2, ..., n$ – the number of the hazardous situation; $j = 1, 2, ..., m$ – the number of the expert; S_{ij} – the severity rating of the consequences of the *i*-th hazardous situation assigned by the *j*-th expert.

Similarly, the average values of the parameters of the probability of occurrence O_{ij} and detectability D_{ij} are determined as follows:

$$\overline{O}_i = \frac{1}{m}\sum_{j=1}^{m} O_{ij}, \tag{3}$$

where O_{ij} – the probability of occurrence rating of the *i*-th hazardous situation assigned by the *j*-th expert.

$$\overline{D}_i = \frac{1}{m}\sum_{j=1}^{m} D_{ij}, \tag{4}$$

where D_{ij} – the detectability rating of the *i*-th hazardous situation assigned by the *j*-th expert.

The obtained average ratings were used to determine the RPN:

$$RPN_i = \overline{S}_i \cdot \overline{O}_i \cdot \overline{D}_i. \tag{5}$$

Thus, the RPN_i indicator reflects the integral assessment of the criticality of the *i*-th hazardous situation, taking into account the severity of its consequences, the probability of occurrence, and the difficulty of detection under the conditions of the road transport segment of CCL.

The hazardous situations were ranked in descending order of the RPN_i value (Table 3), which makes it possible to identify the most critical stages of the transportation process and to establish priorities for the implementation of preventive measures.

Table 3 – Ranking-based assessment of main hazardous situations in the road transportation of refrigerated containers

Hazardous situations	S	O	D	RPN
Failure of the refrigeration unit or GenSet during transportation	8	8	6	384
Violation of the temperature regime due to power supply failures during idle periods	9	8	4	288
Personnel errors when setting temperature or ventilation parameters	7	5	7	245
Mechanical damage to RC during maneuvering or transshipment between different modes of transport	9	6	4	216
Violation of loading technology causing blockage of air circulation channels	5	4	8	160
Unauthorized interference during parking (intrusion by unauthorized persons, attempts to open the container)	6	5	5	150
Damage to RC due to adverse weather conditions (strong wind, precipitation, hail)	7	7	3	147

Source: developed by the authors

Overall, the assessment results demonstrate that the greatest risk is associated with situations directly related to violations of the temperature regime, regardless of their root cause – technical, organizational, or related to the human factor. In this regard, it is advisable to develop and implement a set of organizational and technical measures aimed at minimizing these risks.

To reduce the risk of refrigeration equipment failure, it is advisable to carry out regular maintenance and diagnostics of the units before the start of transportation. The use of remote monitoring systems for refrigeration equipment operation is also important, as it allows deviations in its functioning to be detected promptly. An additional measure is the use of backup power sources or the possibility of connecting the container to alternative power supply systems.

Minimizing violations of the temperature regime caused by failures in power supply during idle periods requires ensuring continuous power supply for RC during stops, in particular through the use of stationary power supply points at terminals or backup generators. It is also advisable to implement automated temperature control systems with real-time data transmission.

Reducing the risk of personnel errors can be achieved through the implementation of standardized procedures for configuring container operating parameters, the use of automated systems for input and verification of parameters, as well as regular training and instruction of personnel.

To prevent mechanical damage to RC during maneuvering or transshipment between different modes of transport, it is necessary to ensure compliance with the technology of cargo handling operations, the use of certified handling equipment, and regular technical inspection of containers. An important measure is also the improvement of the qualifications of operators performing cargo operations.

Minimizing the risk of violations in loading technology that may lead to blockage of air circulation channels requires compliance with established cargo placement schemes within the container that ensure free circulation of cold air. In addition, the use of instructions and visual loading schemes for personnel is advisable.

To prevent such situations as unauthorized interference during stops (intrusion by unauthorized persons or attempts to open the container), it is necessary to apply physical and electronic security measures, including container sealing, the use of electronic seals, video surveillance systems, and GPS monitoring. It is also important to ensure access control at terminal areas and parking sites.

Reducing the impact of weather-related factors can be achieved through the selection of safe locations for container parking, the use of protective structures at terminals, and consideration of weather forecasts during transportation planning.

The implementation of the proposed measures will contribute to ensuring the integrity of TSC, reducing economic losses, and improving the efficiency of transport process organization during the transportation of RC.

Conclusions: 1. The specific features of the organization of temperature-sensitive cargo transportation in refrigerated containers within the cold chain supply system were identified. It was established that the stability of the temperature regime is a key factor in ensuring cargo integrity and the efficient functioning of cold chain logistics.

2. A classification of risk factors arising during the transportation of refrigerated containers by different modes of transport and in their interaction was carried out. Three main groups of factors were identified: human, technical and technological, and natural and climatic, which made it possible to systematize the main hazardous situations of the transportation process.

3. A list of hazardous situations characteristic of the road transportation of refrigerated containers was identified. Their criticality was assessed on the basis of the methods of Failure Mode and Effects Analysis and Failure Mode, Effects, and Criticality Analysis (FMEA/FMECA) using expert evaluation of the parameters of severity of consequences,

probability of occurrence, and the possibility of timely detection of deviations. Based on expert ranking, the corresponding indicator ratings were determined and the Risk Priority Number (RPN) was calculated, which made it possible to rank hazardous situations according to their level of criticality and to identify priority directions for the implementation of preventive measures.

4. Based on the results of the assessment, a set of organizational and technical recommendations aimed at reducing risks during the transportation of refrigerated containers was developed. These include the implementation of remote monitoring systems for temperature parameters, ensuring uninterrupted power supply for refrigeration equipment, improvement of loading procedures, and strengthening control over cargo handling operations. The implementation of the proposed measures will contribute to improving the reliability of the functioning of cold chain logistics and ensuring the integrity of temperature-sensitive cargo.

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Оцінювання факторів ризику та удосконалення технології перевезення температурно чутливих вантажів у рефрижераторних контейнерах

Анотація. У статті розглянуто питання оцінювання небезпечних ситуацій та факторів ризику під час перевезення температурно чутливих вантажів у рефрижераторних контейнерах автомобільним транспортом, а також розроблення рекомендацій щодо удосконалення технології перевезення у системі холодового ланцюга постачання.

Визначено фактори ризику перевезення температурно чутливих вантажів у рефрижераторних контейнерах у системі холодового ланцюга постачання різними видами транспорту та при їх взаємодії, що може бути враховано під час організації інтермодальних, мультимодальних і комбінованих перевезень. Проведено класифікацію факторів ризику за характером їх походження та виділено три основні групи: людські, техніко-технологічні та природно-кліматичні. На основі виділених факторів визначено перелік небезпечних ситуацій, характерних для автомобільного транспортування рефрижераторних контейнерів. Оцінювання їх критичності виконано із застосуванням методів аналізу видів і наслідків відмов та їх критичності (FMEA/FMECA) із використанням експертного оцінювання параметрів тяжкості наслідків, імовірності виникнення та можливості своєчасного виявлення відхилень. На основі експертного ранжування розраховано пріоритетне число ризику (RPN), що дозволило здійснити упорядкування небезпечних ситуацій за рівнем їх критичності.

За результатами дослідження розроблено комплекс організаційних та технічних рекомендацій, спрямованих на зниження ризиків під час перевезення рефрижераторних контейнерів. Зокрема, запропоновано впровадження систем дистанційного моніторингу температурних параметрів, забезпечення безперервного енергоживлення холодильного обладнання, удосконалення процедур завантаження та підвищення контролю за технологією вантажних операцій. Реалізація запропонованих заходів сприятиме підвищенню надійності функціонування cold chain logistics та забезпеченню схоронності температурно чутливих вантажів.

температурно чутливі вантажі, рефрижераторні контейнери, логістика холодового ланцюга, взаємодія видів транспорту, інтермодальні, мультимодвльні та комбіновані перевезення, фактори ризику, метод оцінювання ризику, небезпечні ситуації, автомобільні перевезення

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