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FAULT TREE METHOD AS A DECISION-MAKING TOOL FOR ASSESSING THE RISKS OF TRANSPORTATION OF DANGEROUS LOADS

Summary. Improving road traffic safety on the one hand and increasing the transport of dangerous goods on the other requires searching for methods and tools for risk assessment at various levels of transport of this type of cargo. This is directly related to the disruption of the safety and efficiency of road transport systems around transporting dangerous goods. In this respect, risk assessment and its estimation method are a significant issue. The article analyzes the risk resulting from the transport of dangerous goods. Threats occurring during the organization and execution of the transport of dangerous goods were identified and risk assessment studies were carried out using the FTA method (fault tree method). The purpose of using the FTA method was to develop and graphically illustrate a set of factors that cause adverse events in the transport of dangerous goods. TopEvent FTA computer software was used to verify the proposed approach, which is used both to construct error trees and to identify and correct irregularities in existing trees.

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1. INTRODUCTION

Transport, due to its functions, is an important determinant of the socio-economic development of every country. One of the significant areas of transport is the transport of dangerous goods 19. According to the literature definition, dangerous goods 33, 21 include objects and materials which, due to their physical, chemical or biological properties, if improperly handled during transport, may cause loss of health or bodily injury, contamination of the natural environment, damage or destruction of other material goods and even death12.

The total volume of road transport of dangerous goods 48 without division into categories in all EU member states in 2022 was almost 67.4 million tkm (tonne-kilometers). Germany continues to be the leader in international road transport of this type of cargo. In the last decade, Poland has also significantly increased its share in international road transport of dangerous goods, from 6.81 million tkm in 2012 to 7.70 million tkm in 2022 (fig. 1.) 17. Poland currently ranks fourth in terms of the volume of international transport of dangerous goods 6, including explosives and gases, infectious substances and other substances that have not been assigned to a general category. In the case of domestic transport, 4.84 million tkm of dangerous goods were transported in 2022, which places Poland in fifth place in the EU. It is worth adding that, according to available data, 88-90% of dangerous goods in Poland are transported by road, and only 8-10% by rail.

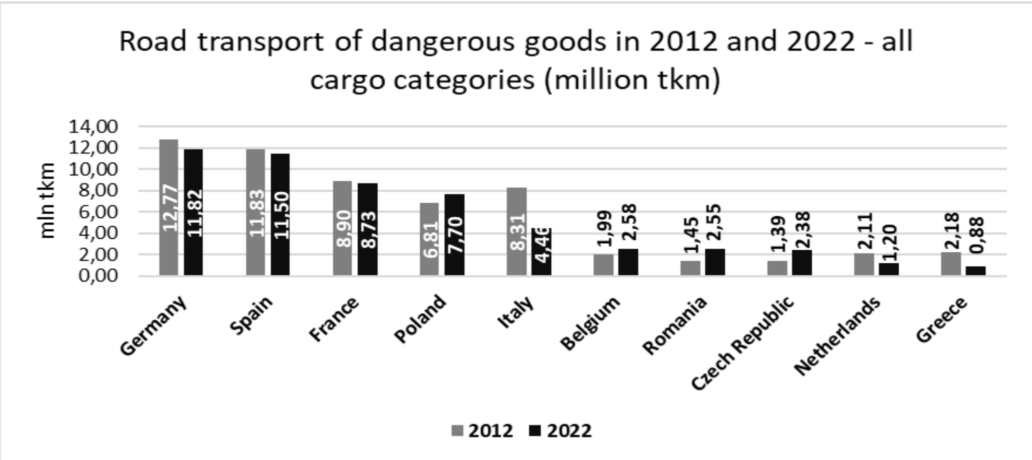


Fig. 1. List of dangerous goods transport in individual years without division into categories
Source: own elaboration based on 17

Recently, the rapid economic development of countries has been accompanied by constantly increasing traffic intensity and the demand for the transport of dangerous goods. The most common way of transporting this type of cargo in Europe is road transport. Although the number of accidents involving dangerous goods has never been very high, the consequences of an incident involving vehicles carrying this type of cargo can be tragic. Considering the safety and efficiency of road transport systems, it is important to assess the risks arising from this type of transport 40.

Due to the significant dependence of road transport on random events and the actions of third parties, the identification of threats and risk management is particularly significant – both on the part of carriers, senders, recipients and administrative units 18. An extremely important factor influencing the level of risk in the transport of dangerous goods by road means of transport is the exemplary organization of the transport process 55. This is directly related to the coordinated work of qualified staff and good and unwavering communication between individual entities responsible for organizing transport. This, in turn, translates directly into the safety of the project 38.

The aim of the article is to perform a multi-aspect analysis of the assessment of threats affecting the risk of accidents in the road transport of dangerous goods. The article is divided into three main parts. The first one pointed out the threats arising from the planning and organization of individual stages of the transport process and made a critical review of the literature, including the legal and organizational conditions for the transport of dangerous goods. The second part of the article is a description of the FTA method as a fault tree method and its main functionalities. It was emphasized that the FTA method is a logical diagram consisting of a peak event and a structure specifying the ways of its occurrence. The last part of the article presents a case study. An assessment of adverse events was carried out on real data, indicating environmental contamination combined with a threat to human health or life as the peak event. The analyses carried out were supported by verification using TopEvent FTA computer software, which enables the construction, analysis, and correction of error trees.

2. ORGANIZATION OF THE PROCESS OF TRANSPORTATION OF DANGEROUS LOADS

2.1. Legislation governing the transportation of dangerous cargoes

In any debate on the transport of dangerous goods in which the effectiveness of existing legal controls is questioned, it is crucial to fully understand the scale of the risks involved and their main causes, so that well-informed decisions can be made 39. Due to the need to ensure the safety of people and the environment, we transport dangerous goods 1 both in the general context and in the case of road transport has been subject to numerous regulations and restrictions 35, 46. Legal provisions introduce special rigor in allowing such cargo to be transported both domestically and internationally, which is preceded by packaging, marking, selection of means of transport and performance of loading activities. 44, 45.

The basic legal act regulating the transport of dangerous goods by road is the European Agreement concerning the international carriage of dangerous goods by road ADR (fr. Accord européen relatif au transport international des marchandises dangereuses par route) 16.

Annex A of this Agreement covers general and specific footnotes relating to dangerous goods 56, including definitions, classification rules, conditions of use of packaging and tanks, including construction and periodic inspection requirements, as well as shipping procedures and transport conditions. In accordance with Annex A of the ADR Agreement, the division of dangerous goods is considered according to the type of dominant hazard and divides the goods into 9 classes, which in turn correspond to 13 classes in individual branch regulations (tab. 1).

Tab. 1

Division of dangerous goods into classes

Class	Name
1.	Explosive materials and articles
2.	Gases
3.	Flammable liquids
4.	Flammable solids, materials liable to spontaneous combustion, materials which, in contact with water, emit flammable gases
5.	Oxidizing materials and organic peroxides
6.	Poisonous and infectious materials
7.	Radioactive materials
8.	Corrosive materials
9.	Various hazardous materials and items

Source: own elaboration based on 16

The division system is important in determining transport conditions, including marking, selection of packaging, requirements for means of transport. 13. A given material or substance is classified into a specific category based on the hazard it poses, but if it is characterized by several types of hazards, the hazard with the dominant influence is decisive. Within a class, the type of hazard is expressed using a classification code. The basic hazard symbols can be listed: F – flammability, T – toxic effect, C – corrosive effect. Annex B sets out guidelines relating to means of transport and cargo operations, including requirements regarding the work of the vehicle crew, mandatory equipment, documentation, and procedures, as well as the construction of vehicles and their approval for road traffic 16.

There are also other legal acts that partially influence the regulation of the movement of dangerous cargo units, including laws on the control of the transport of dangerous cargo 36, technical supervision of vehicles carrying this type of load 47 and broadly understood road traffic law 43.

2.2. Requirements for means of transport for the transport of dangerous goods

Each vehicle used to transport dangerous goods by road should be appropriately adapted for this purpose. In addition to the standard equipment specified in the Road Traffic Act, vehicles should have additional equipment to protect the driver, other people, and the environment in emergency situations 2. Means of transport used in the transport of dangerous goods should additionally meet the designed requirements in the field of electrical installation, quality of cables, fuel tanks, exhaust system, auxiliary heating, driver's cabin, and speed limiter. An important element is also the labeling, which should be appropriate to the method of transport and the type of cargo. These can be, for example:

- in the case of transporting piece goods (e.g., containers, palletized loads), orange plates placed at the front and rear of the vehicle. In the case of containerized cargo, the container should be marked with warning stickers (orange stickers with the UN number and stickers indicating the class of dangerous goods transported) placed on its four walls.

- in the case of transporting dangerous goods in bulk or in tanks, the vehicle marking should consist of orange plates containing the product identification number and the hazard identification number. Identification numbers should be indelible and remain legible after 15 minutes in fire. Another type of marking may be orange plates without identifying marks and warning stickers placed on the front and rear of the vehicle 13.

An information board is placed on road means of transport specialized for the transport of dangerous goods. In the upper part of the board, the identification number of the danger, the degree of danger and additional dangerous features are entered. In turn, the marking at the bottom of the table indicates the mentioned UN number — designating the material.

3. LITERATURE REVIEW

3.1. Risk and methods of its assessment

Due to the size of the threats that may be caused by a road accident during the transport of dangerous goods, the risk aspect is increasingly being analysed by many authors 5, 42. Issues related to risk assessment methods are described in both domestic and international publications 27, and in general terms, it is most often assigned to one of three groups: quantitative methods, qualitative methods or quantitative-qualitative methods. For example, work 14 reviewed the most important sources of knowledge related to this area and detailed mathematical models for carrying out various types of reliability analyzes for transport systems. The use of a fault tree and Monte Carlo simulation in item 41 enabled a qualitative and quantitative assessment of reliability by identifying weak links in the transport system. In contrast, the paper 53 presents the relationship between reliability costs and potential subsystem risk by applying a comprehensive allocation method based on fuzzy logic. The approach related to the use of the HAZOP method (z ang. Hazard and operability studies) to assess process risk is presented in position 34. Thanks to the method used, it was possible to identify potential threats and losses that may occur during the implementation of tasks.

It should be emphasized that the choice of risk assessment method may be determined by the specificity of the mode of transport in which cargo or passengers are transported. As part of planning the demand for rolling stock by a railway carrier, article 22 uses the Monte Carlo simulation method. The authors assigned the risk assessment methods recommended to railway companies to be used in the following approach:

- checklists – organizations starting the process on the transport market,
- analysis of the types and effects of possible errors (Failure Mode and Effect Analysis, FMEA), analysis of threats and operational capabilities (Hazard and Operability Study, HAZOP), COSO II – an organization with extensive experience in the process (e.g., Polish carriers with at least 2 years of experience)
- FTA (Fault Tree Analysis) – an organization with extensive experience in the process, with a large amount of data on events — the largest freight and passenger carriers, main infrastructure managers.

The issues related to ensuring safety in the air traffic management system are presented in the publication 15. The authors identified potential threats and assigned them to one of three tolerance areas. A methodology based on the use of Markov chains for assessing the security risk of the maritime transport system is included in the article 50. The authors studied changes in the system state and identified the moment when a low-probability incident turns into a high-risk event.

In addition to aspects related to the modal approach to transport, it is also necessary to indicate international standards that describe and indicate risk assessment methods. One of the standards used around risk management is the ISO 31000:2018 standard 25. The document presents guidelines and principles that can be implemented in enterprises, and assigns methods and techniques recommended for use to individual stages of risk management. The standard presents dedicated methods for stages such as risk identification, risk analysis, risk assessment, risk evaluation and recording and reporting. Proper risk management is a process established to protect also transport companies against the effects of undesirable phenomena. The purpose of this process is to take actions to minimize the risk to achieve better business results, which have a direct impact on ensuring the quality of the transport services provided. In connection with the above, it should be emphasized that the selection of the risk assessment method depends primarily on the object being examined and the purpose of the analyses performed.

3.2. Areas of risk assessment in the transport of dangerous goods

It is worth specifying what this risk is at the beginning. According to article 3 transport risk in a general sense can be defined as the probability of an undesirable event that may result in loss of life or health of persons responsible for the transport or loss of the subject of shipment. Each type of risk is a source of undesirable costs, which include: financial resources incurred to reduce the risk, financial resources intended to finance the risk, expenses resulting from the cessation of a specific activity due to the associated risk or costs resulting from the lack of reimbursement of specific losses 23, 20.

Analyzing the general issue of risk analysis in the road transport of dangerous goods, the literature on the issues of threats arising from the transport of this type of cargo is very extensive. Most often, multi-criteria or multi-criteria methods for determining vehicle routes are used as the main point for risk assessment. For example, the authors of item 54 developed a risk analysis system for the transport of hazardous materials based on a geographic information system (GIS). According to them, the risk of an accident involving dangerous goods can be divided into two elements: the probability of an accident occurring and the consequences of an accident if it occurs. In turn, in publication 11 the authors conclude that in previous studies the risk occurring on a given route was analysed on the basis of research based on operational methods, without methods taking into account historical data on accidents, which is not entirely correct. Publication 30 discusses in detail the statistical models that can be used to analyze accident data. The lessons learned resulted in the improvement of existing methods and the development of an approach that uses historical accident data to calculate the risk occurring in the multimodal transport of dangerous goods in Flanders.

In the case of item 49 a method was developed for risk analysis and route optimization in road transport of dangerous goods, based on a path selection model that comprehensively measures the risk and cost of road transport in time-varying conditions. On this basis, considering the principle of avoiding high-risk transport routes, the authors proposed a method for selecting the optimal transport path in accordance with the assumed preferences. Another important issue is the issue of determining vehicle routes in the transport of dangerous goods in the context of minimizing the probability of a road incident with serious damage to the vehicle performing the transport. The authors of the publication 26 recommended an original model aimed at minimizing the probability of an accident in the transport of dangerous goods. The research on the selected region of Poland was based on the use of the heuristic ant algorithm and Dijkstra's algorithm. The authors finally concluded that the ant algorithm provides valuable information in solving complex problems related to the transport of dangerous goods and is much more acceptable compared to Dijkstra's algorithm.

Article 29 presents Greek experience in the use of quantitative risk assessment (QRA) methods in the transport of dangerous goods through tunnels located along Greek transport routes. The publication 8 also discusses the issue of cargo transport through road tunnels. The authors focused on analyzing the impact of air quality on the transport of dangerous goods. Scenarios for transport in completely fresh air conditions and in the event of tunnel ventilation failure were analysed. The article 7 focused in detail on the transport of hydrogen in one-way highway tunnels. Studies based on event tree and parametric analysis showed an increased level of risk in the presence of transported hydrogen.

The safe transportation of dangerous goods depends on many factors. Item 4 addresses the issue of examining the conditions of transport of this type of cargo and identifying factors that have a significant impact on the transport of these goods by road. According to the survey conducted in Lithuania, three groups of such factors were identified. The research results presented in the article indicate that the greatest influence on the probability of an accident during the road transport of dangerous goods has the main factors of group I. The main factors include incorrect loading, vehicle condition, driver fatigue, weather, and road conditions. Factors from the second group determine, among others: tightness of the transport vehicle and the technical condition of the vehicle. Group III are organizational factors and include: the risk associated with the transport of goods, the selection of an appropriate route and the risk of communication with emergency services.

The authors of the publication 32 focused on understanding the relationship between the risk of driving a commercial truck transporting dangerous goods and risk exposure factors. The aim of the work was to find a way to assess risk in a specific transport environment, such as a specific route. The research is based on statistical data from six companies located in China. Using the Weibull distribution, it was shown that factors such as weather, traffic intensity, travel time and average speed have the most significant impact on accident-free travel on the designated route.

The FTA method is a universal tool whose functionalities can be used both in the field of transport and in other areas of industry. An example of performing risk analysis using the fault tree method is position 31. The authors of the above-mentioned publication focused on the analysis of infectious medical waste management at the Clinical Centre in Serbia. The research was based on three aspects of the FTA method — functional, qualitative, and quantitative. The authors of the publication used the fault tree method to perform the research due to the possibility of analyzing individual threats and assessing the relationships and interdependencies between these threats.

Considering the above, the authors of the article decided to use the fault tree method to estimate the risk of road transport of dangerous goods in Poland.

4. CONSTRUCTION OF A DECISION-MAKING MODEL FOR ASSESSING THE RISK OF TRANSPORTATION OF DANGEROUS GOODS USING THE FAULT TREE METHOD

4.1. General comments

The FTA (Fault Tree Analysis) method is an advanced deductive technique used to analyze the factors that cause adverse events 10. Analysis using a fault tree is a cause-and-effect graphical method modelling how failures of individual parts of the process occur, leading to the failure of the entire system 51. The method consists in illustrating individual factors that may lead to an undesirable event and its potential effects on the so-called error tree. The error tree indicates the interdependencies between the potential event and the main event (the so-called peak event) and the causes of this event. Specific causes marked on the error tree are closely related and may be defined as human errors, failures, environmental conditions, or other events that may influence the failure. The risk analysis process using the fault tree method is used for qualitative analysis, when focusing on the risk and understanding the situation to which the risk relates. It also enables qualitative analysis, enabling the determination of the probabilities of sequences of events. The algorithm for hazard analysis using the failure tree method is shown in fig. 2. The method has several basic steps:

- identification of the peak event,
- identification of events threatening/leading to the occurrence of a peak event — indirect events,
- creating a hierarchical structure of the error tree considering all intermediate events and connecting these events with logic gates,
- defining the basic events that are the sources of the peak event,
- determining the probability of events occurring,
- determining the elementary events leading to the occurrence of the peak event,
- determining the probability of a peak event occurring 57.

The probability of a peak event is estimated based on individual adverse events. Each such event should be considered individually 52. However, if the probabilities of all individual events are not determined, the final probability of the peak event will be unreliable. In turn, shortcomings, or faults at the lowest level of the fault tree are the basic and key factors that have a decisive impact on the occurrence of the peak event. It is on them that the company should focus the most attention and take actions to limit the occurrence of the event 37.

Taking the above into account, the authors of the article decided to assess the risk of transporting dangerous goods using the unsuitability tree method due to seven important aspects affecting the attractiveness of this method. It should be added that none of the risk analysis methods is universal, and the choice depends on the characteristics of the project, available resources and the specific nature of the industry. However, FTA is an effective tool, especially when there is a need for a structural and logical analysis of the causes of risk. The mentioned features supporting the FTA method are presented in the table. 2.

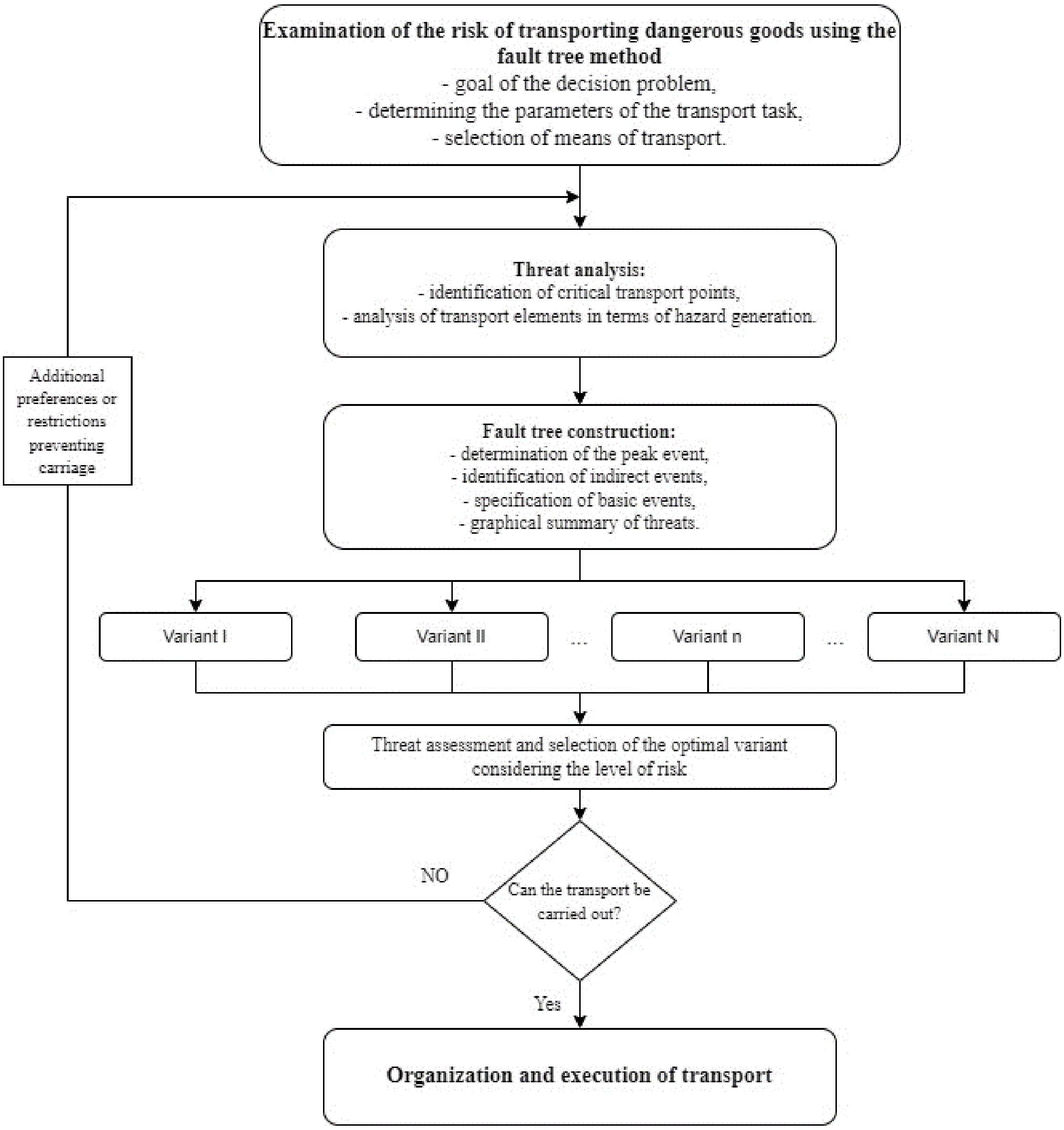


Fig. 2. Algorithm for hazard analysis in road transport of dangerous goods using the fault tree method

Source: own elaboration

Tab. 2

Special features of the unfitness tree method

1. NO.	Characteristic feature	Comment
1.	Possibility of structural interpretation of events	Through the graphical and structural representation of events, FTA allows you to understand how factors and the connections between them may contribute to the occurrence of risk.
2.	Identification of critical factors	The method allows you to identify elements that have a key impact on the stability and functionality of the tested system.

3.	Ease of interpretation of the included data	Thanks to the graphical representation of events, both the creators and recipients of the analyses performed can quickly understand the risk structure and significant dependencies.
4.	Assessment of the probability of events	In further research, the method can be expanded to include the probabilities assigned to each element. This will enable risk assessment and assessment of which event has the greatest impact on transport.
5.	Integration with other risk analysis methods	The FTA method can be used as an element of a more comprehensive risk analysis method.
6.	Application in various industries	The FTA method is a flexible tool and, apart from transport, it can be used in other industries, such as the chemical, aviation, energy, and IT industries.
7.	Failure prevention	FTA analysis helps to identify critical points characterized by an increased probability of threat occurrence. This allows project teams to implement appropriate countermeasures and prevent potential problems more quickly.

Source: own elaboration

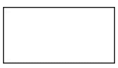
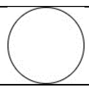
4.2. Principles of constructing a fault tree

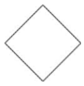
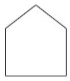
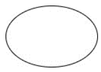
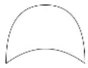
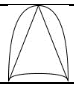
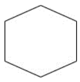
A classic fault tree consists of three types of nodes: events, logic gates and transfer symbols. The FTA method distinguishes three types of events, depending on their location in the tree. These are: base events, intermediate events, and peak events. At the lowest level of the tree there are basic events that, according to the assumptions, are not subject to further analysis because they constitute a direct source of threat. The combination of basic events triggers the occurrence of intermediate events that describe changes in the structure and functioning of subsystems. In turn, combinations of intermediate or intermediate events combined with basic events cause the occurrence of subsequent intermediate events and ultimately lead to the occurrence of a peak event.

Logical relations in the failure tree, as mentioned earlier, are described using logic gates. These operators, depending on their type, have one or more inputs and only one output. The input to the gate usually includes primary events, intermediate events or combinations of internal transfers marked with triangles. The output of the gate usually contains higher level intermediate events or peak events. The designations of individual elements used to create unsuitability trees are presented in tab. 3.

Tab. 3

Symbolism of the fault tree

1. NO.	**Symbol**	**Characteristics**
1.		Intermediate event. A fault caused by a logical combination of other events occurring further down the tree. It is often a type of logic gate.
2.		Basic event. Its further analysis is not possible. This is a source of danger.

3.		Undeveloped event. An event whose contribution is not considered in the analysis because it is considered unnecessary, or the available information is insufficient.
4.		External event. It does not represent any error and is part of the nominal behaviour of the system. An event occurs or does not occur.
5.		Conditioning event. Does not necessarily indicate a fault. Serves as a special condition or restriction for certain types of gates.
6.		OR gate. Used to show a scenario in which an output event will occur if at least one of the input events occurs.
7.		AND gate. Links single faults to a peak event. Occurs only when all events are true. Furthermore, the events must occur simultaneously.
8.		XOR gate. Occurs when one and only one of the output events is true.
9.		INHIBIT gate. It is a special case of an AND gate. Occurs when its only input event is true in the presence of a conditioning event.

Source: own elaboration based on 28

In the fault tree, logic gates act as event connectors. Each gateway can connect one input event to one or more output events. Event labeling should be done in a way that allows easy identification of connections between parts of the fault trees. The most used logic gates are AND and OR gates. AND gate means that the output event E_p is generated when all input events E_1, E_2, …, E_n occurs 9:

$$E_p = E_1 \cap E_2 \cap \dots \cap E_n = \bigcap_{i=1}^{n} E^i \tag{1}$$

Analyzing two independent events E_1 and E_2 the probability of occurrence of the output event $P(E_p)$ for the AND gate can be presented using the following equation:

$$P(E_p) = P(E_1) \cdot P(E_2) \tag{2}$$

For an AND gate with n independent input events, the probability of an output event is:

$$P(E_p) = \Pi_{i=1}^{n} P(E_i) \tag{3}$$

The OR gate, in turn, is used when adding input events. The output event E_p is generated when at least one of the input events E_1, E_2, …, E_n 9:

$$E_p = E_1 \cup E_2 \cup \dots \cup E_n = \bigcup_{i=1}^{n} E_i \tag{4}$$

For an OR gate, the probability of the output event $P(E_p)$ for two independent events can be expressed in the following form:

$$P(E_p) = P(E_1) + P(E_2) - P(E_1) \cdot P(E_2) \approx P(E_1) + P(E_2) \tag{5}$$

For an OR gate with n independent output events, the probability of generating an output event is:

$$P(E_p) = \coprod_{i=1}^{n} P(E_i) \tag{6}$$

5. CASE STUDY

5.1. Preliminary assumptions for risk assessment of the transportation of dangerous cargoes

According to data from 2022, apart from Poland, Germany, Spain, and France are the largest carriers of dangerous goods and materials in Europe. In Poland, approximately 150 million tons of dangerous goods are transported by road every year, 66% of which are flammable liquid materials. The second-largest group, accounting for 25% of the total transport of dangerous goods, are gases. Approximately 430,000 tons are transported daily. Based on the available literature and statistical data, the most common causes of hazards during the entire transport process of dangerous goods were identified. These can be:

1. non-compliance of the transport performed with ADR requirements,
2. inadequate technical condition of packaging and loading units,
3. technical condition of the means of transport inconsistent with the requirements,
4. incorrect fastening of the load on the loading surface of the means of transport,
5. poor technical condition of transport routes along which transport is carried out,
6. inadequate equipment at transshipment points,
7. poor technical condition of infrastructure and transshipment equipment,
8. the lack of adequate theoretical and practical preparation for the transport of dangerous goods in individual links of the transport chain,
9. improper organization and technology of transport of dangerous goods,
10. failure to properly protect reloading equipment against the penetration of released hazardous substances into the natural environment,
11. excessive influence of other road users on the transport of dangerous goods, resulting in road collisions as a result of human error.

5.2. Construction of the fault tree

In the case under consideration, the unsuitability tree was applied to the problem of risk analysis in road transport of dangerous goods. In accordance with point 4.2. The peak event of the constructed unsuitability tree is environmental contamination combined with a threat to human health or life. The peak event consists of 4 main intermediate events. These are:

1) occurrence of a road accident (RA),
2) leakage of substances or gas escape during the organization and execution of transport,
3) improper organization and technology of cargo transport (IOaT),
4) non-compliance of the transport performed with the requirements of the ADR Convention (ADR).

For the sake of uniformity and transparency of the analysis, the unsuitability tree was divided into five integral parts (figs. 3-7). In each component of the analysis, the markings in the form of isosceles triangles represent the above-mentioned transfers to increase the transparency of the model. Markings in the form of rectangles reflect indirect events, while circles are basic events that are the direct cause of the threat.

Risk analysis in the transport of dangerous goods performed using the FTA method consists of 37 indirect events that have a significant impact on the organization of transport. In addition, 60 basic events were specified, which are also sources of danger in this type of transport. 38 logic gates were used as connecting points, of which only 4 are "AND" logic gates. Figs. 3-5. and 7 contain the logical analysis of the main intermediate events of the fault tree. In turn, fig. 6 complements the indirect event – the occurrence of a road accident.

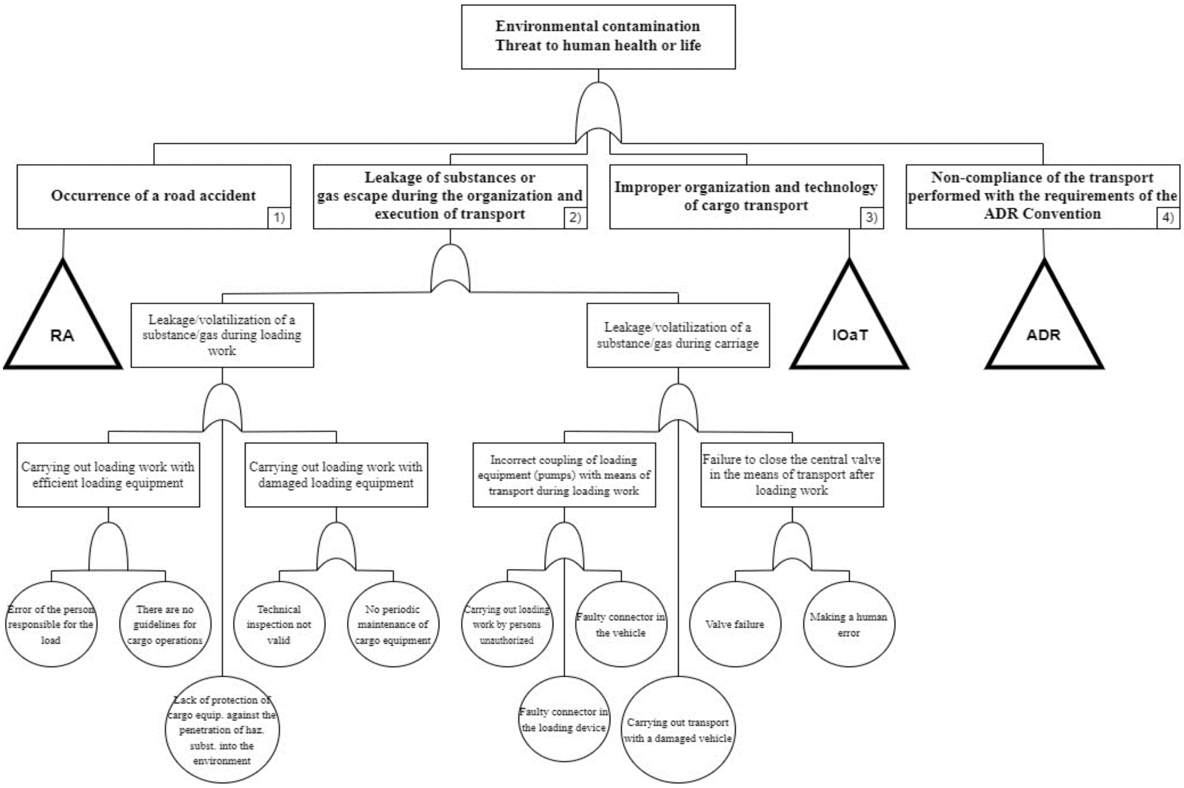


Fig. 3. First part of the fault tree – peak event analysis
Source: own elaboration

5.2. Fault tree construction using TopEvent FTA computer software

To verify and check the correctness of the tests performed using the failure tree method, a structure analysis was performed using TopEvent FTA computer software. Thanks to the above-mentioned software, you can create complex error trees and perform analyzes on ready-made diagrams. The article checked the correctness of connections between individual events and logical operators. The verification of the proposed non-compliance tree did not reveal any irregularities; therefore, it can be concluded that the structure is constructed correctly and the line of reasoning itself is correct. Top-Top 4 elements represent individual components of the inconsistency tree (according to figs. 3 - 7). In turn, at the bottom there is an error list bar. When the probabilities of each intermediate and base event are clearly defined, the software also allows you to generate the probability of a peak event. This functionality has been omitted due to the illustrative nature of the article. Fig. 8 shows a screenshot of the software view with a reflected incompatibility tree.

The presented analysis is a theoretical structure based on a general approach to the threats occurring in the road transport of dangerous goods. Future research may focus on building an unsuitability tree adapted to the individual realities of transporting dangerous goods, or expanding the current scheme to include dedicated threats resulting from the specific nature of transporting the specific types of dangerous goods. It is also possible to expand the analyses with probabilities for each element of the diagram. This will enable risk assessment and assessment of which event has the greatest impact on the occurrence of the investigated peak event.

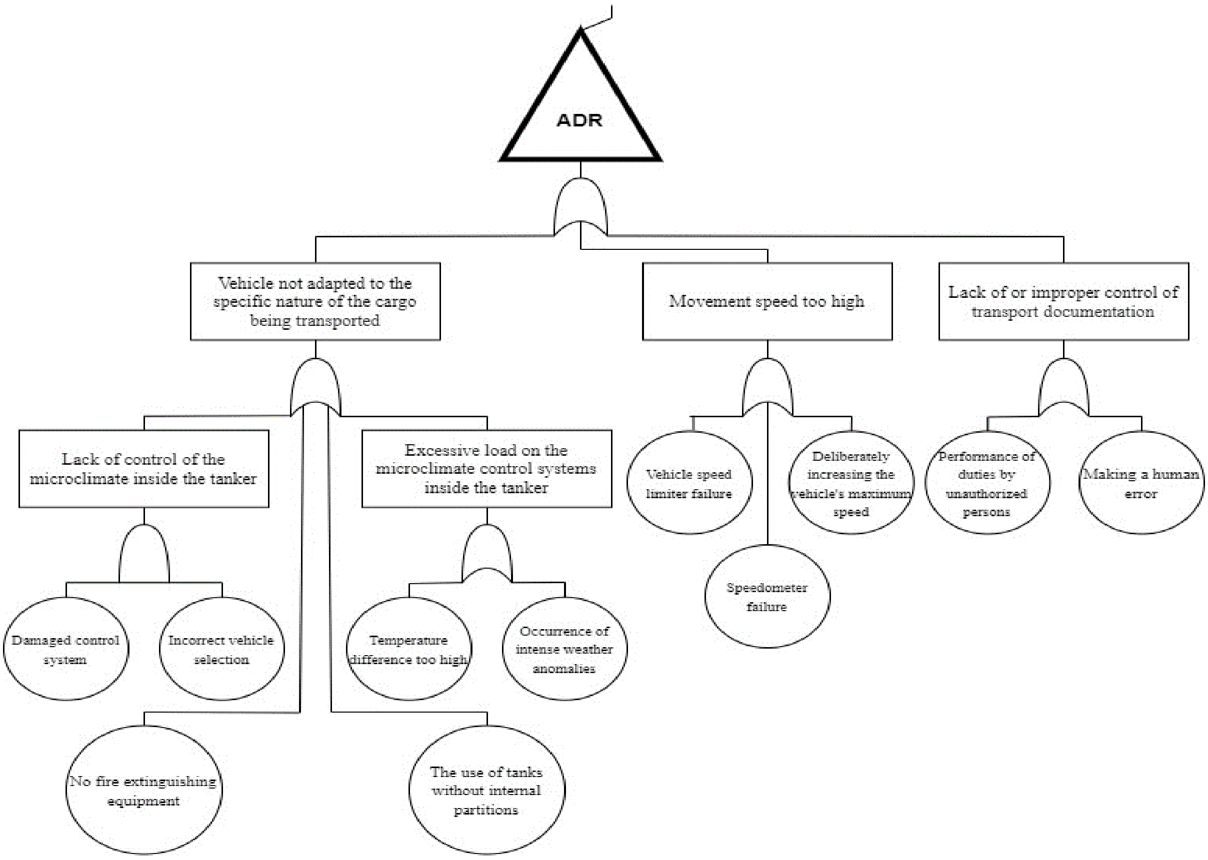


Fig. 4. Analysis of an intermediate event – non-compliance of the transport performed with the requirements of the ADR Convention
Source: own elaboration

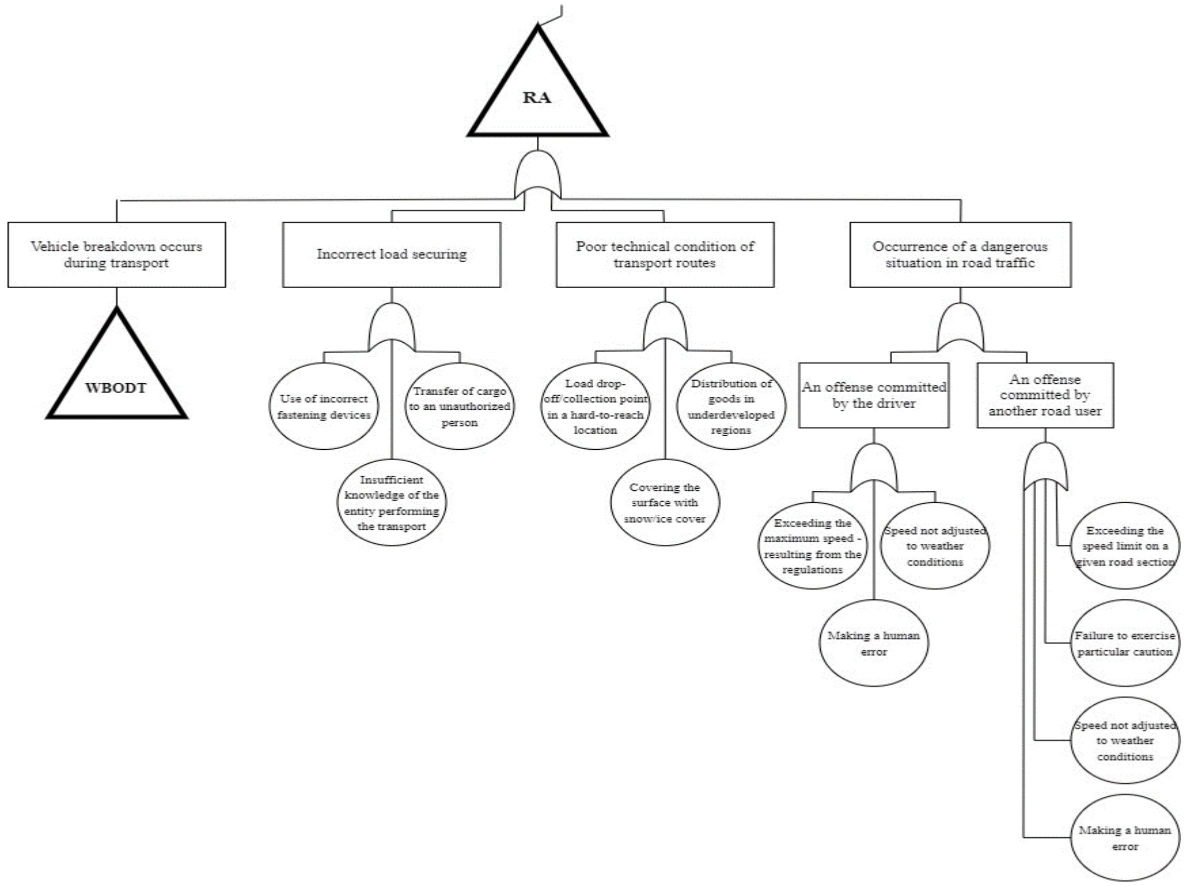


Fig. 5. Analysis of an intermediate event – occurrence of a road accident
Source: own elaboration

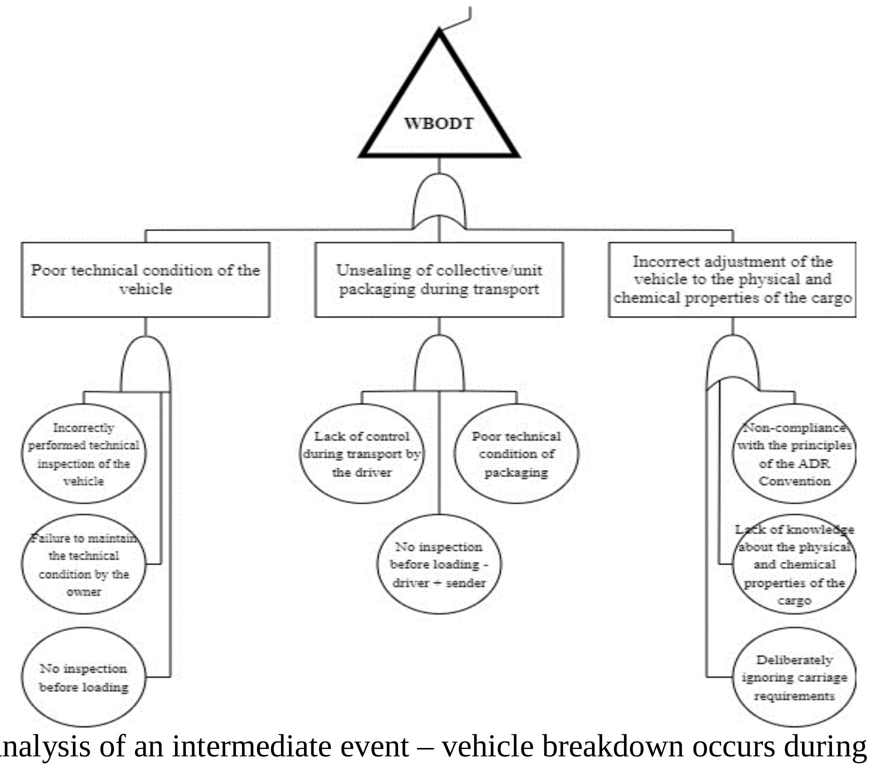


Fig. 6. Analysis of an intermediate event – vehicle breakdown occurs during transport
Source: own elaboration

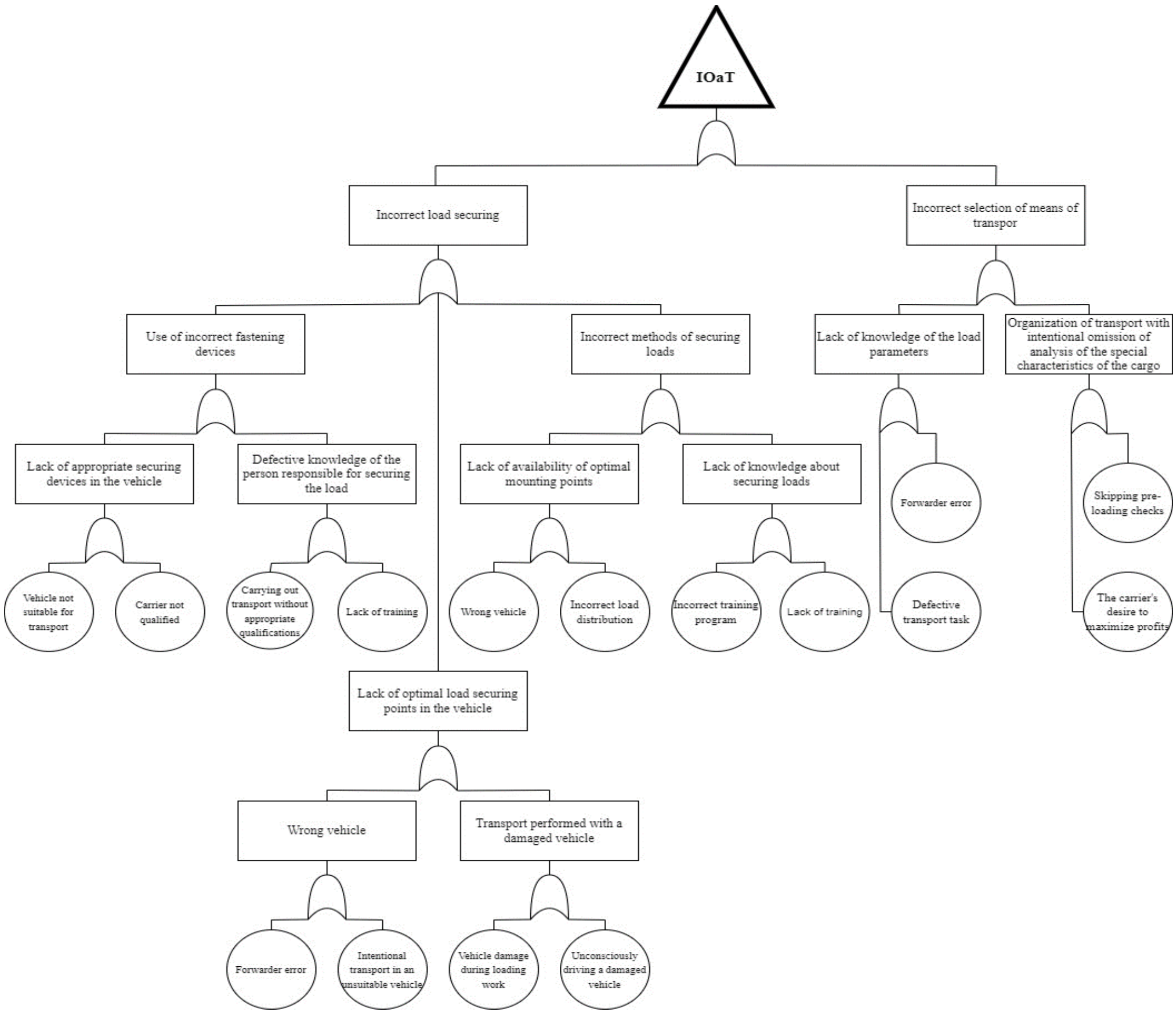


Fig. 7. Analysis of an intermediate event - improper organization and technology of cargo transport
Source: own elaboration

6. SUMMARY

The article focuses on risk analysis during the broadly understood transport of dangerous goods. The first part included a review of the literature, which touched upon the specificity of the transport of dangerous goods, the generally understood risk and legal regulations. The requirements for road means of transport were also characterized. Moreover, based on statistical data, the volume of dangerous goods transport in ten European Union countries dominating in this field of road transport was estimated and compared.

In the next part of the article, based on the available literature and statistical data, threats arising from the processes of organizing and carrying out road transport of dangerous goods are identified. The paper identifies 11 basic threats that are the most common causes of dangerous situations during transport. The threats include but are not limited to non-compliance of transport with applicable regulations, poor technical condition of means of transport and loading equipment, poor condition of collective packaging, incorrect fastening of the load on the loading surface of the vehicle or, mainly speaking, incorrect organization of the transport process.

The third part of the work presents the analysis of hazards and the resulting risks in the transport of dangerous goods using the unsuitability tree method, also known as the error tree in the literature. The peak event in the analyses carried out was environmental contamination and exposure of people to loss of life or health. Four main indirect events were analysed: the occurrence of a road accident, leakage, or escape of a substance/gas during the organization and performance of road transport, improper organization and technology of cargo transport, and non-compliance of transport with the provisions of the ADR Convention. Due to its extensiveness and the inability to read it conveniently, the analysis was divided into five separate parts, constituting a coherent whole. In addition to the main indirect events, the analysis using the unfitness tree includes another 33 indirect events. Ultimately, the list consists of 60 basic events, which are also sources of the existing threat. To verify the correctness of the tests performed, a failure tree analysis was performed using TopEvent FTA computer software. The verification of the inconsistency tree did not reveal any irregularities; therefore, it can be concluded that the reasoning and the graphic design of the method were performed correctly.

Analyzing the results, the most common indirect events that have a significant impact on the occurrence of hazards during the transport of dangerous goods are a deficient level of knowledge, lack of training aimed at appropriate preparation of employees and damage to cargo equipment/means of transport. However, the broadly understood human error has the most significant impact on the level of risk.

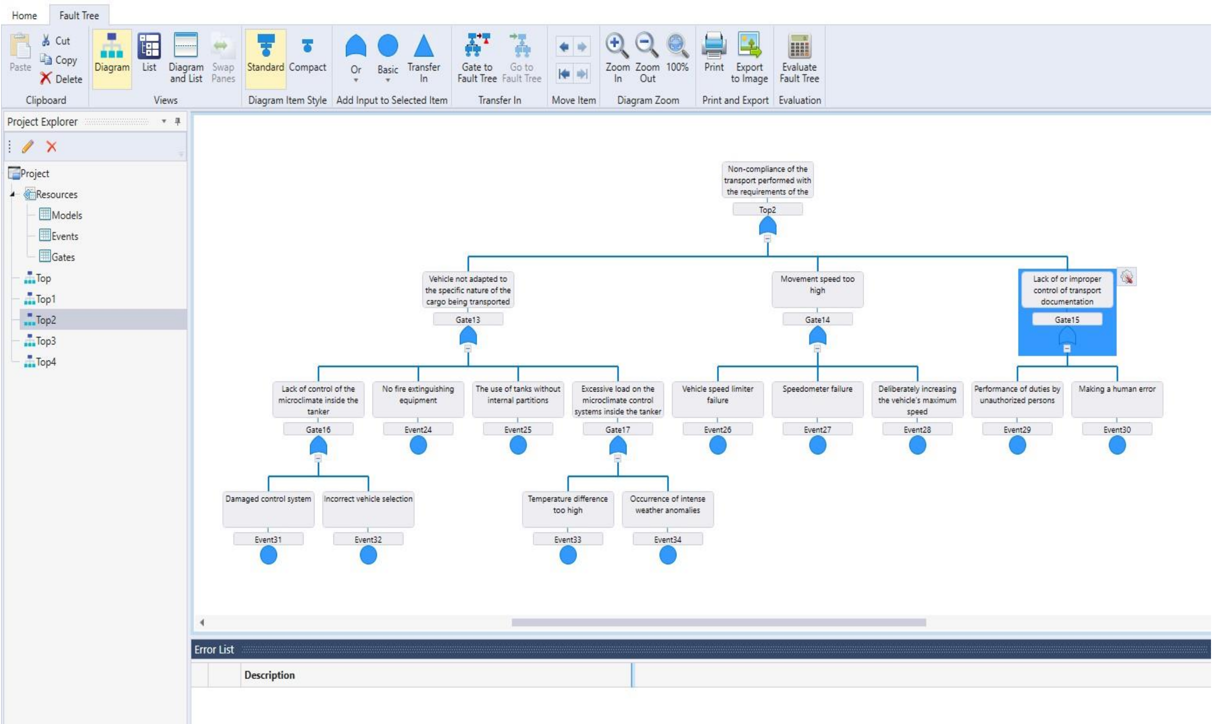


Fig. 8. Preview of the TopEvent FTA software
Source: own elaboration

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References

1. Accettura Antonella, Roberto Bubbico, Fabio Garzia, Barbara Mazzarotta. 2014. „Improving security in road transportation of hazardous materials". *International journal of safety and security engineering* 4(4): 289-305. DOI: 10.2495/SAFE-V4-N4-289-305.
2. Batarlienė Nijole. 2008. „Dangerous goods transportation: new technologies and reducing of the accidents". *Journal of Konbin* 8(1): 211-222. DOI: 10.2478/v10040-008-0114-7.
3. Batarliene Nijole. 2008. „Risk analysis and assessment for transportation of dangerous freight. *Transport* 23(2): 98-103. DOI: https://doi.org/10.3846/1648-4142.2008.23.98-103.
4. Batarliene Nijole. 2020. „Essential safety factors for the transport of dangerous goods by road: A case study of Lithuania". *Sustainability* 12(12): 1-16 4. DOI: https://doi.org/10.3390/su12124954.
5. Benekos Ioannis, Dimitris Diamantidis. 2017. „On risk assessment and risk acceptance of dangerous goods transportation through road tunnels in Greece". *Safety science* 91: 1-10. DOI: https://doi.org/10.1016/j.ssci.2016.07.013.
6. Budny Adrian, Tomasz Rokicki. 2021. „Road transport of dangerous goods in Poland". *Ekonomika i Organizacja Logistyki* 6(3): 13-21. ISSN: 2450-8055. DOI: https://doi.org/10.22630/EIOL.2021.6.3.18.
7. Caliendo Ciro, Gianluca Genovese. 2021. „Quantitative risk assessment on the transport of dangerous goods vehicles through unidirectional road tunnels: an evaluation of the risk of transporting hydrogen". *Risk analysis* 41(9): 1522-1539.DOI: https://doi.org/10.1111/risa.13653.
8. Caliendo Ciro, Maria Lusia De Guglielmo. 2017. „Quantitative Risk Analysis on the Transport of Dangerous Goods Through a Bi-Directional Road Tunnel". *Risk Analysis* 37(1), 116-129: DOI: https://doi.org/10.1111/risa.12594.
9. Chybowski Leszek. 2017. *Analiza drzewa niezdatności: Podstawy teoretyczne i zastosowania.* Szczecin: Wydawnictwo Naukowe Akademii Morskiej w Szczecinie. [In English: *Unfitness Tree Analysis: Theoretical Foundations and Applications.* Szczecin: Scientific Publishing House of the Maritime University of Szczecin].
10. Ciszewski Tomasz, Waldemar Nowakowski, Zbigniew Łukasik. 2020. „A fault tree analysis-based method of railway traffic control systems safety assessment". *Prace Naukowe Politechniki Warszawskiej. Transport* (128): 49-57. DOI: 10.5604/01.3001.0014.0902.
11. Clark M. Rene, Mary E. Besterfield-Sacre. 2009. „A new approach to hazardous materials transportation risk analysis: decision modelling to identify critical variables". *Risk Analysis: An International Journal* 29(3): 344-354. DOI: https://doi.org/10.1111/j.15396924.2008.01163.x.

12. Conca Andrea, Chiara Ridella, Enrico Sapori. 2016. „A risk assessment for road transportation of dangerous goods: a routing solution". *Transportation Research Procedia* 14: 2890-2899. DOI: https://doi.org/10.1016/j.trpro.2016.05.407.
13. Cooper Laura, Dennis Nolan, Richard Bales, Stephen Befort, Lise Gelernter, Michael Green. 2020. *ADR in the Workplace*. Fort Worth. West Academic.
14. Dhillon Balbir. 2011. *Transportation Systems Reliability and Safety*. New York: CRC Press Taylor & Francis Group. ISBN: 978-1-4398-4641-4.
15. Dudek Ewa, Karolina Krzykowska-Piotrowska, Mirosław Siergiejczyk. 2020. „Risk management in (air) transport with exemplary risk analysis based on the tolerability matrix". *Transport Problems* 15(2): 143-156. DOI: https://doi.org/15.10.21307/tp-2020-027.
16. *European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR)*. Drawn Up in Geneva on 30 September 1957 (Dz.U. [Journal of Laws] of 1975, No. 35, Item 189).
17. Eurostat-Statistics. „Road freight transport of dangerous goods by type of dangerous goods and territorial coverage – annual data". Available at: https://ec.europa.eu/eurostat/databrowser/view/road_go_ta_dg/default/table?lang=en.
18. Fabiano Bruno, Fabio Currò, Andrea Pietro Reverberi, Renato Pastorino. 2005. „Dangerous good transportation by road: from risk analysis to emergency planning". *Journal of Loss Prevention in the process industries* 18(4-6): 403-413. DOI: https://doi.org/10.1016/j.jlp.2005.06.031.
19. Fabiano Bruno, Fabio Currò, Emilio Palazzi, Renato Pastorino. 2002. „A framework for risk assessment and decision-making strategies in dangerous good transportation". *Journal of hazardous materials* 93(1): 1-15. DOI: https://doi.org/10.1016/S0304-3894(02)00034-1.
20. Forigua Julio, Liliana Lyons. 2016. „Safety analysis of transportation chain for dangerous goods: A case study in Colombia". *Transportation Research Procedia* 12: 842-850. DOI: https://doi.org/10.1016/j.trpro.2016.02.037.
21. Galierikova Andrea, Jarmila Sosedova. 2018. „Intermodal transportation of dangerous goods". *NAŠE MORE* 65(3): 8-11. DOI: https://doi.org/10.17818/NM/2018/3.8.
22. Gołębiowski Piotr, Ignacy Góra, Yaroslaw Bolzhelarskyi. 2023. „Risk assessment in railway rolling stock planning". *Archives of Transport* 65(1): 137-154.
23. Guo Jian, Cheng Luo. 2022. „Risk assessment of hazardous materials transportation: A review of research progress in the last thirty years". *Journal of traffic and transportation engineering (English edition)*. DOI: https://doi.org/10.1016/j.jtte.2022.01.004.
24. https://doi.org/10.5604/01.3001.0016.2817.
25. ISO 31000:2018. *Risk Management – Guidelines*. London: BSI Standards Limited 2018.
26. Izdebski Mariusz, Ilona Jacyna-Gołda, Paweł Gołda. 2022. „Minimisation of the probability of serious road accidents in the transport of dangerous goods". *Reliability Engineering & System Safety* 217: 108093. DOI: https://doi.org/10.1016/j.ress.2021.108093.
27. Janno Jelizaveta, Ott Koppel. 2018. „Operational risks in dangerous goods transportation chain on roads". *LogForum* 14(1): 33-41. ISSN: 1895-2038. DOI: 10.17270/J.LOG.2018.261.
28. Kabir Sohag. 2017. „An overview of fault tree analysis and its application in model based dependability analysis". *Expert Systems with Applications* (77): 114-135. DOI: https://doi.org/10.1016/j.eswa.2017.01.058.

29. Kalogeraki Marianna, Fani Antoniou. 2021. „Improving Risk Assessment for Transporting Dangerous Goods through European Road Tunnels: A Delphi Study". *Systems* 9(4): 80. DOI: https://doi.org/10.3390/systems9040080.
30. Lord Dominique, Fred Mannering. 2010. „The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives". *Transportation research part A: policy and practice* 44(5): 291-305. DOI: https://doi.org/10.1016/j.tra.2010.02.001.
31. Makajic-Nikolic Dragana, Natasa Petrovic, Ana Belic, Mihailo Rokvic, Jelena Andreja Radakovic, Vojin Tubic. 2016. „The fault tree analysis of infectious medical waste management". *Journal of Cleaner Production* 113: 365-373. DOI: https://doi.org/10.1016/j.jclepro.2015.11.022.
32. Niu Shifeng, Satish V. Ukkusuri. 2020. „Risk Assessment of Commercial dangerous-goods truck drivers using geo-location data: A case study in China". *Accident Analysis & Prevention* 137: 105427. DOI: https://doi.org/10.1016/j.aap.2019.105427.
33. Nowacki Gabriel, Krysiuk Cezary, Rafał Kopczewski. 2016. „Dangerous goods transport problems in the European Union and Poland". *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation* 10(1): 143-150. DOI: 10.12716/1001.10.01.16.
34. Pruszkowski Leszek. 2015. „HAZOP jako metoda wspomagająca zarządzanie bezpieczeństwem procesowym w przedsiębiorstwie". *Acta Universitatis Nicolai Copernici. Zarządzanie* 42(3): 7-20. DOI: https://doi.org/10.12775/AUNC_ZARZ.2015.029. [In English: „HAZOP as a method to support process safety management in an enterprise". *Acta Universitatis Nicolai Copernici. Management*].
35. Regulation of the Minister of Defence of 28 September 2012 on the Issuance of Military Permits for Vehicles Carrying Dangerous Goods (Dz.U. No. 227, Item 1367, and No. 244, Item 1454).
36. Regulation of the Ministers of Communications and Internal Affairs of 2 December 1983 on the Inspection of the Transport of Dangerous Goods (Dz.U. No. 67, Item 301, and of 1986, No. 42, Item 206).
37. Ruijters Enno, Marïelle Stoelinga. 2015. „Fault tree analysis: A survey of the state-of-the-art in modelling, analysis and tools". *Computer science review* 15: 29-62. DOI: https://doi.org/10.1016/j.cosrev.2015.03.001.
38. Semenov Iouri, Marianna Jacyna. 2022. „The synthesis model as a planning tool for effective supply chains resistant to adverse events". *Eksploatacja i Niezawodność - Maintenance & Reliability* 24(1): 140-152. DOI: 10.17531/ein.2022.1.16.
39. Slavinskaitė Neringa, Nijole Batarlienė. 2022. „Investigation of safety conditions in the transport of dangerous goods by railway". *Transport* 37(1): 64-72. DOI: https://doi.org/10.3846/transport.2022.16985.
40. Staniuk Wiesław, Michał Staniuk, Norbert Chamier-Gliszczynski, Marianna Jacyna, Michał Kłodawski. 2022. „Decision-Making under the Risk, Uncertainty and COVID-19 Pandemic Conditions Applying the PL9A Method of Logistics Planning-Case Study". *Energies* 15(2): 639. DOI: https://doi.org/10.3390/en15020639.
41. Szkoda Maciej, Grzegorz Kaczor. 2016. „Ocena niezawodności systemu transportowego z wykorzystaniem metody dynamicznego drzewa niezdatności". *Autobusy* 17(6): 1593-1598. ISSN: 1509-5878. [In English: „Reliability assessment of transport system using dynamic unfitness tree method". *Bus*].

42. Tanackov Ilija, Zdenko Janković, Siniša Sremac, Milica Miličić, Marko Vasiljević, Jelena Mihaljev-Martinov, Ivan Škiljaica. 2018. „Risk distribution of dangerous goods in logistics subsystems". *Journal of Loss Prevention in the Process Industries* 54: 373-383. DOI: https://doi.org/10.1016/j.jlp.2018.03.013.
43. The Act of 1 February 1983 – Traffic Law (Dz.U. of 1992, No. 11, Item 41, No. 26 and Item 114; Dz.U. [Journal of Laws] of 1995, No. 104, Item 515).
44. The Act of 10 April 1986 – Atomic Energy Law (Dz.U. No. 12, Item 70, and of 1987, No. 33, Item 180).
45. The Act of 15 November 15, 1984 – Transport Law (Dz.U. of 1995, No. 119, Item 575).
46. The Act of 19 August 2011 on the Transport of Dangerous Goods (Dz.U. 2011, No. 227, Item 1,367).
47. The Act of 19 November 1987 on Technical Inspection (Dz.U. No. 36, Item 202, and of 1995, No. 104, Item 515).
48. Torretta Vincenzo, Elena Cristina Rada, Marco Schiavon, Paolo Viotti. 2017. „Decision support systems for assessing risks involved in transporting hazardous materials: A review". *Safety science* 92: 1-9. DOI: https://doi.org/10.1016/j.ssci.2016.09.008.
49. Van Raemdonck Koen, Cathy Macharis, Olivier Mairesse. 2013. „Risk analysis system for the transport of hazardous materials". *Journal of safety research* 45: 55-63. DOI: https://doi.org/10.1016/j.jsr.2013.01.002Get rights and content.
50. Wang Siqi, Jingbo Yin J, Rafi Ullah Khan. 2020. „The Multi-State Maritime Transportation System Risk Assessment and Safety Analysis". *Sustainability* 12(14): 5728. DOI: https://doi.org/10.3390/su12145728.
51. Yazdi Mohammad, Farzaneh Nikfar, Mahnaz Nasrabadi. 2017. „Failure probability analysis by employing fuzzy fault tree analysis". *International Journal of System Assurance Engineering and Management* 8: 1177-1193. DOI: 10.1007/s13198-017-0583-y.
52. Yazdi Mohammad, Javad Mohammadpour, He Li, Hong Zhong Huang, Esmaeil Zarei, Reza Ghasemi Pirbalouti, Sidum Adumene. 2023. „Fault tree analysis improvements: a bibliometric analysis and literature review". *Quality and Reliability Engineering International* 39(5): 1639-1659. DOI: https://doi.org/10.1002/qre.3271.
53. Yu Hui, Genbao Zhang, Yan Ran, Mengqi Li, Yang Wang. 2018. „A comprehensive and practical reliability allocation method considering failure effects and reliability costs". *Maintenance and Reliability* 20(2): 244-251. DOI: https://doi.org/10.17531/ein.2018.2.09.
54. Yu Miao, Ting Deng, Jie Fu. 2012. „Application of RFID and GPS technology in transportation vehicles monitoring system for dangerous goods". In: *2012 2nd International Conference on Remote Sensing, Environment and Transportation Engineering, IEEE Xplore:* 1-4. DOI: 10.1109/RSETE.2012.6260409.
55. Zabielska Aleksandra, Marianna Jacyna, Michał Lasota, Karol Nehring. 2023. „Evaluation of the efficiency of the delivery process in the technical object of transport infrastructure with the application of a simulation model". *Eksploatacja i Niezawodnosc - Maintenance & Reliability* 25(1): 1-12. DOI: https://doi.org/10.17531/ein.2023.1.1.
56. Zhang Lukai, Xuesong Feng. 2021. „Planning tank-truck hazardous materials shipments in intercity road transportation networks". *Applied Mathematical Modelling* 89: 1860-1880. DOI: https://doi.org/10.1016/j.apm.2020.09.009.

57. Zhou Kan, Ge Huang, Shan Wang, Kai Fang. 2020. „Research on transportation safety of hazardous chemicals based on fault tree analysis (FTA). In: *2020 9th International Conference on Industrial Technology and Management (ICITM)*: 206-209. DOI: 10.1109/ICITM48982.2020.9080360.

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