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APPLICATION OF THE FMEA METHOD TO SUPPORT RISK ASSESSMENT IN THE ORGANIZATION OF ROAD TRANSPORT OF OVERSIZE LOADS

Summary. The transport of oversize loads is a highly complex logistics process in technical, organizational, and legal terms. It requires precise planning and coordination among numerous stakeholders. Due to potential hazards to road traffic safety and infrastructure, the application of risk assessment tools to support operational decision-making is essential. The aim of this article is to apply the FMEA (Failure Mode and Effects Analysis) method to risk assessment in the organization of oversize road transport. Based on a case study involving the transport of a power transformer, risk factors were identified, values were assigned for severity, occurrence, and detection, and Risk Priority Numbers, RPNs, were calculated. The analysis made it possible to identify the dominant sources of risk and to propose preventive and corrective measures, including control procedures, technical inspections, and weather monitoring. The results confirm that the FMEA method is a useful tool for risk assessment and decision support, enabling the prioritization of hazards and contributing to improved safety and efficiency in oversize transport. The recommendations resulting from the study include the implementation of training, the standardization of procedures, the use of digital

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technologies for real-time risk monitoring and analysis, and the introduction of regular audits and systematic reviews of operational procedures.

Keywords: oversize loads, road transport, risk assessment, FMEA method

1. INTRODUCTION

Compared with other modes of transport, road transport provides significantly greater operational flexibility and shorter delivery times, particularly for smaller consignments. It also facilitates supply chain planning and constitutes a key component of modern logistics systems.

Despite its numerous advantages, road transport has significant limitations and generates specific risks. These include limited load capacity, high susceptibility to road and weather conditions, environmental impacts associated with exhaust emissions and noise, and accelerated degradation of road infrastructure. These issues are particularly relevant in the case of oversize load transport. This type of transport is regarded as one of the most complex and demanding areas of road transport from technical, organizational, and legal perspectives. An oversize load is a load whose transport causes the vehicle or vehicle combination to exceed the permissible dimensional or mass parameters, including length, width, height, gross vehicle weight, or axle load. Such transport requires an individual approach and the use of specialized technical and organizational solutions. The most commonly transported oversize loads include structural components of engineering structures, bridge spans, silos, tanks, generators, transformers, wind turbine components, and large construction machinery.

Each oversize load transport operation is a complex logistics undertaking requiring detailed planning and coordination among multiple entities. This process includes the development of a detailed route plan that accounts for infrastructure constraints, such as the load-bearing capacity of bridges, horizontal curve radii, road width, and vertical clearances under viaducts and other engineering structures. It also involves selecting appropriate transport equipment, preparing the required documentation, and obtaining relevant permits from road authorities. Cooperation with the police, escort services, and operators of energy, railway, and telecommunications infrastructure is often necessary to ensure safe and uninterrupted transport.

Due to the specific characteristics of the load, oversize transport is associated with substantial operational risk. The main risk factors include damage to the load or road infrastructure, delays caused by planning errors, failures of transport equipment, and the risk of road accidents. In addition, unforeseen events, such as adverse weather conditions, road closures, or vehicle breakdowns, require rapid operational decision-making, often under conditions of uncertainty and time pressure. Minimizing these risks requires not only practical experience but also the application of appropriate risk analysis and risk assessment methods at the planning stage. Figure 1 presents a general framework for the implementation process of oversize road transport.

As indicated by the range of aspects shown in Figure 1 that must be considered during planning, the organization of oversize transport is a complex and multidimensional issue. This process requires the simultaneous consideration of numerous interrelated technical, organizational, legal, and logistics factors.

Proper coordination of all elements is crucial to ensuring transport safety, minimizing the risk of disruptions, and ensuring the efficient implementation of the entire transport project.

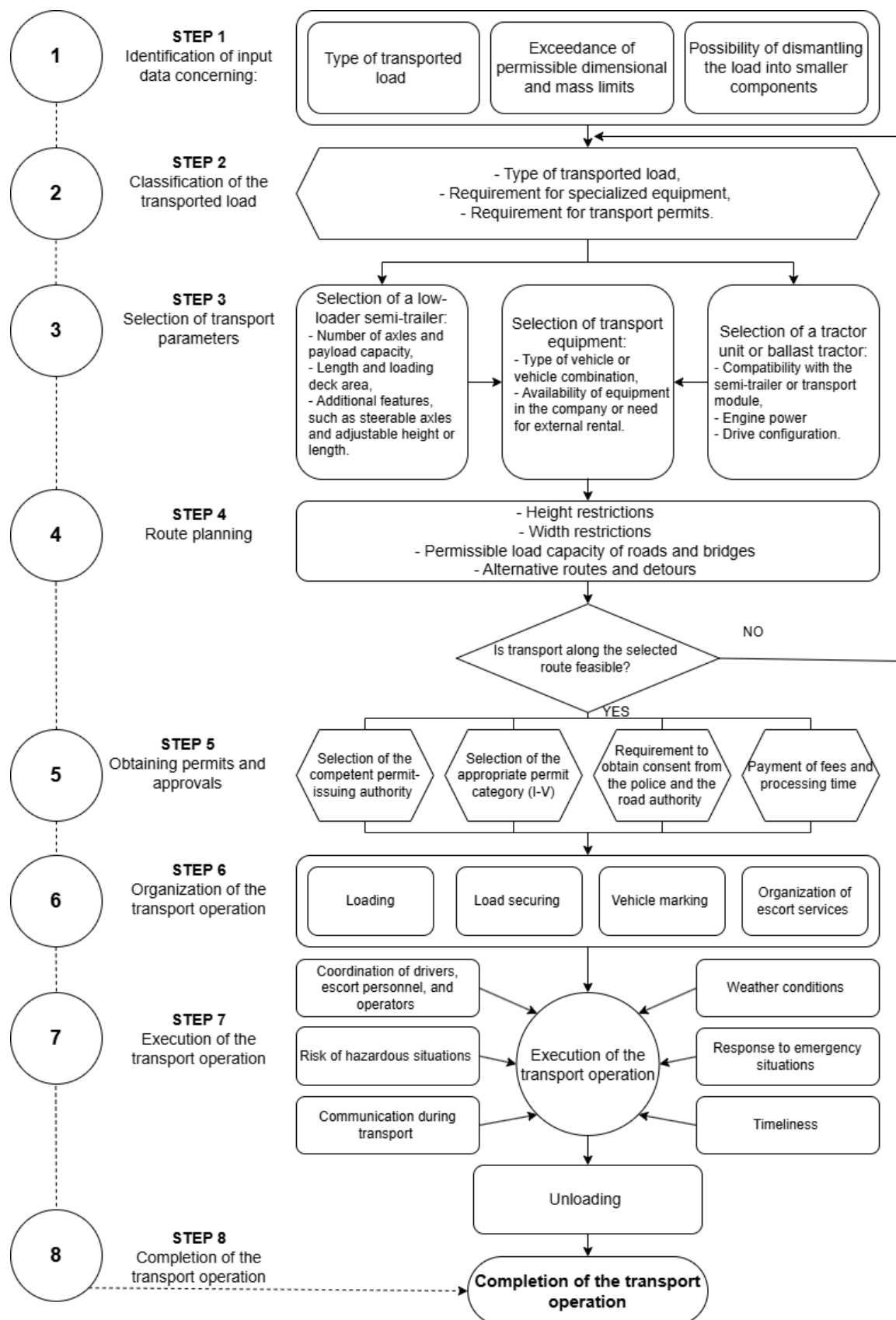


Fig. 1. Framework for organizing oversized road transport

Source: own elaboration

Therefore, the aim of this article is to assess risk using the FMEA (Failure Mode and Effects Analysis) method as a tool to support the decision-making process in planning and organizing safe oversize transport. The work aims to identify and analyze potential sources of risk associated with this type of transport and to develop preventive and corrective measures that can contribute to increased safety and operational efficiency.

The entire article is divided into five parts. The first part is an introduction, outlining the main challenges in organizing oversize transport. The next section is a critical analysis of the literature on risk assessment, oversize transport planning, and ensuring safety in road transport. In this context, the authors point out that a key element of ensuring safety is the identification and assessment of risks at individual stages of transport execution. Furthermore, the role of selecting appropriate measures is emphasized. The third part analyzes the risk and the methods and tools for its measurement. The authors present an algorithm for conducting and assessing the risk of organizing oversize road transport at various stages of implementation. The next sections include an algorithm for risk assessment using the FMEA method and a practical example of its application. The article concludes with conclusions from the conducted analyses.

2. DECISION-MAKING PROBLEMS AND SAFETY IN THE ORGANIZATION OF OVERSIZE TRANSPORT: A LITERATURE REVIEW

2.1. Planning and safety in oversize transport

Road transport of oversize loads may be defined as the movement of a load for which at least one permissible parameter of the vehicle or vehicle combination is exceeded:

- dimensions, namely length, width, height, or any one of these dimensions,
- permissible gross vehicle mass or axle load specified in applicable regulations 36.

In the literature, this type of operation is referred to using terms such as oversize transport, transport with exceeded gauge limits, or exceptional transport with exceeded gauge limits 37.

The concept of an oversize load refers to a load whose transport to the destination, due to its dimensions or mass, requires detailed route planning and the use of specialized means of transport with technical parameters, design, load-bearing capacity, and markings that differ from standard transport equipment. Oversize load units also require the use of loading equipment with a lifting capacity corresponding to the mass of the transported load 7. Oversize loads can be classified according to their external dimensions, mass, and shape. According to the authors of 30, oversize loads can be divided into six basic categories: standard oversize loads, special oversize loads, heavy loads, heavy loads with concentrated mass, bulky loads, and long loads.

Planning oversize transport is a key element in ensuring road transport safety. Due to the specific nature of this type of operation, which involves the movement of loads exceeding permissible dimensional or mass parameters, the planning stage is essential for mitigating technical, organizational, and road safety risks 8. Proper preparation of the process minimizes hazards to both road users and transport infrastructure. The basis for planning is the analysis of risk factors and their impact on safety in various dimensions. Parameters affecting the static and dynamic stability of the vehicle combination are determined at the stage of selecting the means of transport and configuring the vehicle combination. Proper distribution of the center of gravity, appropriate vehicle selection, and effective load securing ensure technical safety by

reducing the risk of damage to the vehicle, the load, and the road surface. Figure 2 presents the relationship between planning and the safety level in oversize road transport.



Fig. 2. Relationship between planning areas and safety management in oversize road transport
Source: own elaboration

From a *technical* perspective, planning primarily involves selecting an appropriate means of transport adapted to the mass, dimensions, and characteristics of the transported load. Determining the center of gravity and the stability of the vehicle combination is also essential, as is selecting appropriate securing devices, such as beams, chains, belts, and wedges. Checking axle loads and ensuring the uniform distribution of mass on the transport platform make it possible to maintain permissible axle loads and ensure vehicle stability during movement 31. Properly planned technical preparation of the vehicle reduces the risk of loss of stability on curves, chassis failure, and load damage, which contributes to a high level of technical safety in transport.

Route planning, in turn, focuses on selecting the optimal route with the lowest risk of collision with infrastructure elements, taking into account vertical clearances under viaducts, turning radii, carriageway width, and road gradient 2. The analysis of road conditions and the development of alternative routes enable an effective response to emergency situations, which contributes to improved road safety and reduced downtime.

In *schedule planning*, it is essential to correctly determine the time of day and the planned transport date, define time windows in urban areas, and coordinate permits with limited validity periods 40. These actions reduce the risk of conflict with general traffic, minimize disruptions to local traffic, and improve the smooth movement of the transport convoy.

Formal and legal aspects also have a significant impact on safety. Obtaining appropriate permits, making arrangements with road authorities, the police, and other relevant services, and preparing complete transport and technical documentation ensure compliance with applicable national and European Union regulations 47. This reduces the risk of administrative sanctions, increases the trust of inspection authorities and logistics partners, and contributes to maintaining high standards of legal and organizational safety.

Organizational planning includes coordinating the work of drivers, escort personnel, and accompanying services, as well as ensuring effective communication and response to emergency situations 39. A clear division of roles, proper organization of stops, and

the development of emergency plans contribute to improved operational safety and reduced risk of human error.

Equally important is the *planning of loading and load securing*, which includes the selection of securing devices, load marking, and stability control 21, 45. A properly prepared loading process helps prevent load displacement during transport, thereby reducing the risk of accidents and material damage.

A comprehensive approach to planning also affects the *economic, social, and environmental dimensions of transport safety*. Route and schedule optimization reduces operating costs and limits noise and exhaust emissions. At the same time, proper transport organization increases the awareness of road users and minimizes the risk of accidents involving third parties 4, 32.

The complexity of the organizational and safety-related processes accompanying this type of operation, which requires a systems approach, is also an important issue. The scale of technical and logistics involvement means that transport safety depends not only on the selection of appropriate vehicles but also on the coordination of activities among multiple entities, proper route planning, and risk assessment and monitoring at every stage of the operation 28. The complexity of this process results from the need to consider technical, legal, and organizational requirements, as well as economic and environmental aspects. Figure 3 schematically presents the structure of a road safety analysis for oversize transport, taking into account the interdependencies among the participants in the transport process, the analyzed stages of transport organization, and the factors influencing the safety level of the operation.

A key element of ensuring safety is the identification and assessment of risks at individual stages, from preparing documentation and obtaining permits, through road infrastructure analysis, to route monitoring and emergency response. Modern decision-support systems based on GPS technologies, sensors, and integrated databases enable ongoing monitoring of transport execution and optimization of actions in the event of deviations from the plan.

The safety of oversize transport is multidimensional. Maintaining it requires coordination among carriers, road authorities, police and other authorized services, and other participants in the process. Only consistent management of information, responsibility, and communication among entities can mitigate technical, organizational, and environmental risks, thereby increasing the efficiency and reliability of the entire transport system.

2.2. Selection of means of transport

Road transport of oversize loads uses specialized vehicles with reinforced structures, adapted to carry high masses and to operate with low-loader or modular trailers. The primary group consists of tractor units coupled to special semi-trailers by means of a fifth wheel and kingpin, as well as ballast tractors designed to tow heavy multi-axle trailers and support vehicle combinations on gradients. Hybrid tractor units, combining the functions of both types, are also increasingly used. Low-loader and modular trailers are another key element of the transport system. Owing to their lowered loading platform, they enable the transport of large and heavy loads. Depending on the characteristics of the load, various trailer types are used, including low-loader semi-trailers, extendable trailers, low-bed trailers, heavy-duty trailers, tank trailers, and modular trailers 10.

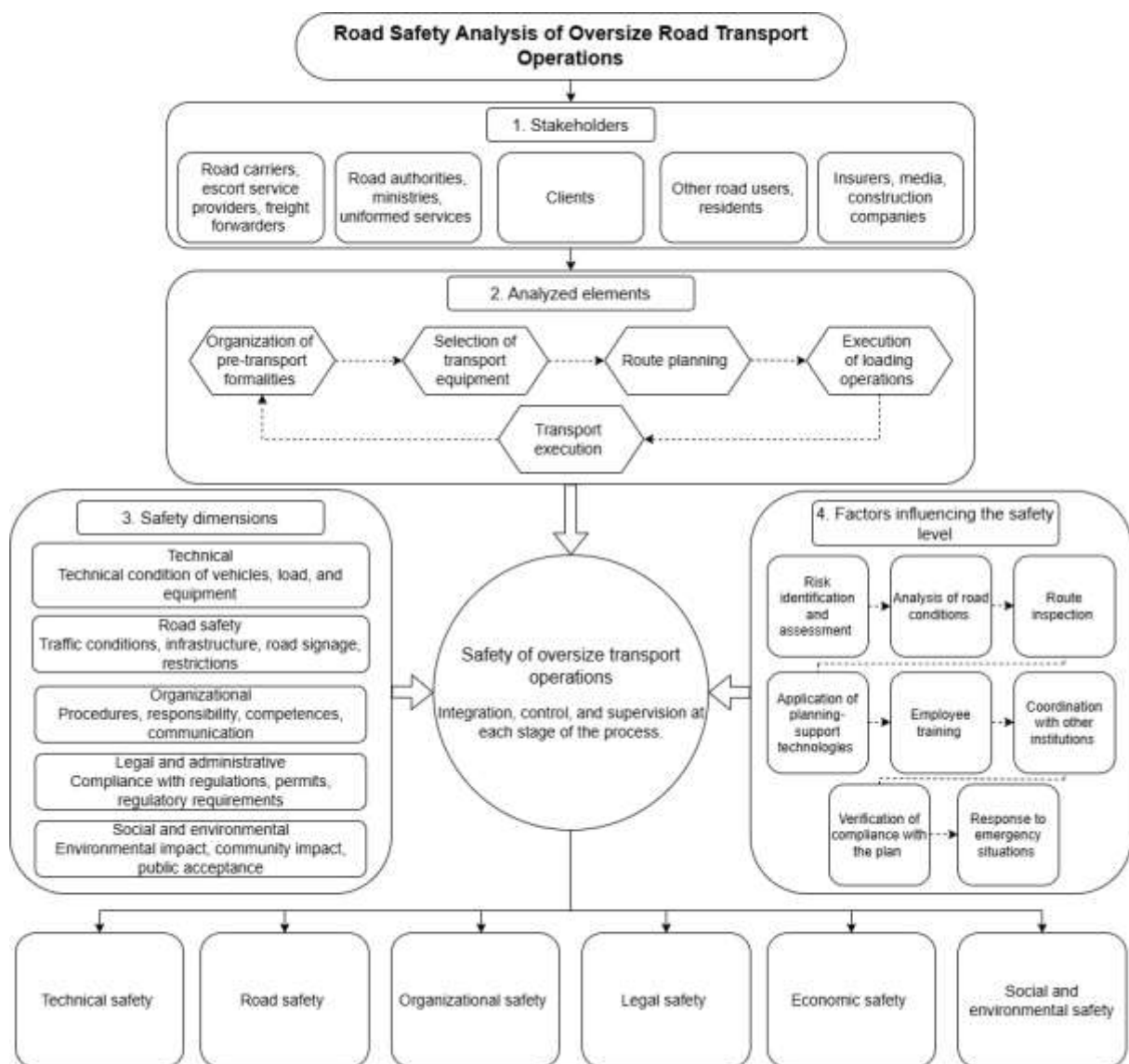


Fig. 3. Safety analysis framework for oversize road transport operations

Source: own elaboration

In road transport of oversize loads, the implementation of the process using appropriate transport equipment is fundamental. Due to its specific physical characteristics, each oversize load requires an individual approach to the selection of dedicated tractor units and trailers or to their appropriate adaptation. Polish legislation strictly defines permissible axle loads on road pavements and maximum vehicle dimensions. Therefore, when transporting heavy loads, the number of axles is a fundamental element of vehicle configuration, as it ensures that the generated loads remain within the specified limits.

The adaptation of a vehicle's loading platform to the requirements of the transported cargo constitutes one of the key aspects in the design of low-bed trailers¹⁹. Parameters such as weight, external dimensions, center of gravity location, and cargo securing method determine both the geometry of the transport platform and the configuration of the axles and structural components of the trailer. The specific nature of oversized cargo also requires the use of appropriately selected structural materials and securing systems to ensure transport safety.

3. RISK IN OVERSIZE ROAD TRANSPORT: A LITERATURE REVIEW

3.1. General remarks

In general terms, risk in road transport is defined as the relationship between the frequency of events and the number of people exposed to a specific level of harm in a given population, resulting from the occurrence of specific hazards 6, 16. According to 29, risk is the product of the probability of a hazard-generating event, such as a road accident involving a heavy goods vehicle carrying a load, and the magnitude of losses resulting from its consequences. Study 38 also defines risk as the frequency of accidents and incidents leading to harm and the severity of that harm, extended by a factor representing the severity of the adverse event. On this basis, risk R may be expressed as follows 14, 46:

$$R = P \times S \quad (1)$$

where:

R – risk level,

P – probability of occurrence of an adverse event during transport,

S – measure of consequences, including damage to cargo, transport equipment, loss of health, life, or environmental damage.

According to 11, 15, the term “risk management” refers to the process of identifying, analyzing, and controlling risk factors that may affect the course and safety of ongoing processes. Risk assessment is an important element of risk management, as it enables the identification of potential hazards and the implementation of measures aimed at reducing the likelihood of adverse events. In the case of oversize road transport, this is particularly important due to the high complexity of transport organization and the need to ensure the safety of road users and transport infrastructure.

Risk management is also defined as a process encompassing the preparation, assessment, and, where necessary, implementation of appropriate strategies aimed at more effective control, monitoring, and mitigation of both routine and exceptional risks in the supply chain 1. In turn, occupational risk analysis 23, in the context of road incidents, considers the probability of a collision or accident and its possible consequences, ranging from minor incidents to serious road accidents that may result in loss of life.

The literature on oversize transport emphasizes that the specific characteristics of these operations generate specific hazards and challenges related to risk identification, analysis, and reduction. The authors of 34 indicate that, in the case of oversize loads, the transport process must account for an increased number of entities and requirements, including escort personnel, specialized equipment, and permits, as well as a higher level of uncertainty regarding execution conditions. Reference 12 emphasizes that the transport of oversize loads requires a separate permitting procedure and is subject to sanctions in the event of non-compliance with regulations, which constitutes an additional operational risk factor.

In 25, the authors note that risk analysis in oversize road transport remains an insufficiently developed research area. They emphasize the lack of sufficient statistical data on accidents and adverse events, as well as the absence of uniform and standardized risk assessment methods for this type of transport. In response to these limitations, they propose a risk assessment model based on the use of a risk matrix that takes into account both transport network parameters, such as infrastructure condition, geometric constraints, and route capacity, and the characteristics of

the transported load, including mass, dimensions, and susceptibility to damage. This model is intended to facilitate the identification of key hazards and determine the risk level associated with a specific oversize transport operation.

The literature analysis indicates that risk assessment can be conducted using appropriate methods, such as FMEA 20 or a risk matrix 27. If the risk level is too high, mitigation measures are implemented, including route changes, the use of safety measures, and modification of load securing. If the risk is acceptable or cannot be further reduced, the transport operation is commenced 4.

3.2. Types of risk

As previously mentioned, a key stage in risk analysis and assessment is the identification of potential adverse events. In oversize transport, these events may be technical, organizational, social, or environmental in nature. Figure 4 presents an example of risks identified during oversize road transport.

The authors of 31 identified 15 typical risks based on an analysis of the transport of wind turbine components. The most important risks included the risk of a road accident, discrepancies between the actual load parameters and the documentation, imprecise route planning, and delays in obtaining permits.

Infrastructure-related factors constitute a key element of risk analysis in oversize transport 37. It is clearly indicated that the geometric limitations of roads, bridges, and intersections, as well as insufficient technical parameters of urban infrastructure, may lead to hazardous situations and necessitate route changes during the transport operation. This risk is particularly evident in urban areas, where maneuvering space is limited and the impact on the surroundings, such as pedestrian traffic and public transport, is significantly greater.

Furthermore, study 3 discusses the organizational and technical conditions for the transport of oversize loads, taking into account documentation requirements, escort services, and equipment specifications. Although the study is not strictly devoted to risk analysis, it provides important context regarding the factors that determine risk in this type of transport.

The study presented in 40 proposes a model for assessing risk associated with the transport of oversize loads in the military sector. The publication analyzes the specific characteristics of this type of transport and identifies key risk factors affecting the safety of transport operations. The factors with the greatest impact on risk include load and transport equipment parameters, the road network, transport conditions, and preparation of the transport operation.

Publication 26 discusses issues related to the transport of oversize loads, using military equipment as an example. The authors identify potential hazards arising from such transport and present a conceptual model for assessing the associated risk.

3.3. Risk assessment methods and tools

Due to the scale of hazards that may occur as a result of collisions or accidents during the transport of oversize loads, risk in this type of transport is increasingly analyzed by researchers 18, 44. Issues related to risk assessment methods are discussed in both national and international literature. In general, these methods are divided into three main groups: qualitative, quantitative, and semi-quantitative. For example, in 43, fault tree analysis and Monte Carlo simulation were applied, which enabled a comprehensive assessment of transport system reliability and the identification of its weakest links. In 50, the relationship between risks occurring in individual subsystems and reliability costs was presented using an advanced

allocation method based on fuzzy logic. In 35 co-authors indicate that risk analysis in road cargo transportation includes the identification of hazards related to the vehicle, transported cargo, human factors, and environmental conditions. The publication also emphasizes that risk assessment methods such as the HAZOP method (Hazard and Operability Study) can support the identification of potential hazards and the evaluation of transport operation safety.

It should be emphasized that the choice of a risk assessment method largely depends on the type of transport and the specific characteristics of the transported load or passengers. For example, in 9, which concerns rolling stock demand planning in a railway company, Monte Carlo simulation was used. The authors assigned specific methods to the organization's level of experience:

- checklists – for entities entering the transport market,
- FMEA, HAZOP, and COSO II – for organizations with at least two years of experience,
- FTA (Fault Tree Analysis) – for large carriers and infrastructure managers with extensive event data.

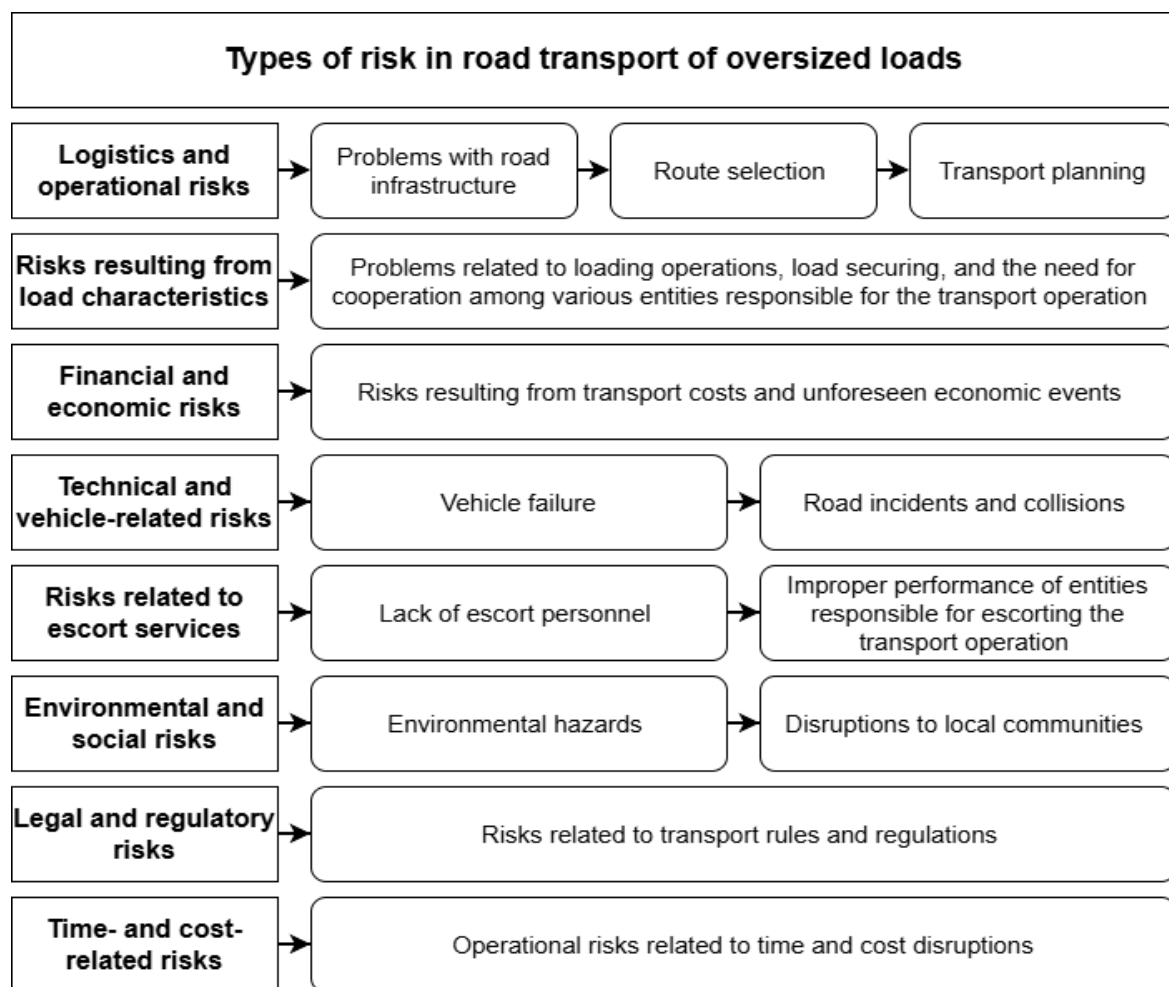


Fig. 4. Types of risk in road transport of oversize loads

Source: own elaboration based on 25

More broadly, the FMEA method has been used to select risk mitigation strategies in road transport. The results presented in 22 indicate that managers should consider both the severity of hazards and available financial resources when developing risk mitigation strategies. The authors also emphasize that combining expert opinion with cost-benefit analysis can lead to reliable risk assessment results. Another study 41 provides a clear classification of FTA methods, focused on practical risk analyses, while 49 presents a review and development of the FTA method, demonstrating its broad application potential in the analysis of the safety and reliability of technical systems.

Reference 48 presents the use of Markov chains for risk assessment in maritime transport. The study enabled the determination of how the system state changes over time and at what point a low-probability incident may escalate into a high-risk event.

In addition to sector-specific analyses, it is also necessary to refer to international risk management standards. One of the key documents in this area is ISO 31000:2018 13, which contains principles and guidelines that can be implemented in organizations. It specifies recommended methods and techniques for selected stages of the risk management process, such as risk identification, risk analysis, risk evaluation, risk treatment, monitoring, review, and reporting. The choice of method should depend on the nature of the analyzed object and the purpose of the study.

The second important document in this area is IEC 31010:2019 14, which expands and complements ISO 31000. It describes approximately 40 risk assessment techniques, including FMEA, FTA, Monte Carlo simulation, and SWOT analysis, and indicates criteria for their selection depending on the specific characteristics of the organization and the analyzed problem. This standard supports decision-making by increasing risk awareness, safety, and operational efficiency. The 2019 update introduced new techniques adapted to contemporary technological and business conditions, making IEC 31010:2019 an important tool supporting the effective identification and mitigation of hazards. Figure 5 presents a set of risk assessment methods used in broadly understood road transport.

4. RISK ASSESSMENT PROCEDURE USING FMEA

4.1. General assumptions

Risk assessment in transport processes requires a structured approach to hazard identification and to determining their impact on the course of operations. It is assumed that, due to the complexity of logistics processes and the interdependence of numerous technical, organizational, and operational factors, risk analysis should be systems-based and should cover all key stages of the transport process. In the case of oversize road transport, this results from the above-standard dimensions of loads, specific technical requirements, infrastructure constraints, and the need to obtain numerous permits 21, 24.

Effective risk management requires a systematic approach that includes hazard identification, risk analysis, and the implementation of measures aimed at reducing the likelihood and consequences of adverse events 42. In practice, the risk assessment process is based on the identification of potential adverse events, determination of their causes, and analysis of possible consequences for the safety, reliability, and continuity of operations. An important element of the study is the identification of areas requiring risk reduction measures and support for the decision-making process.

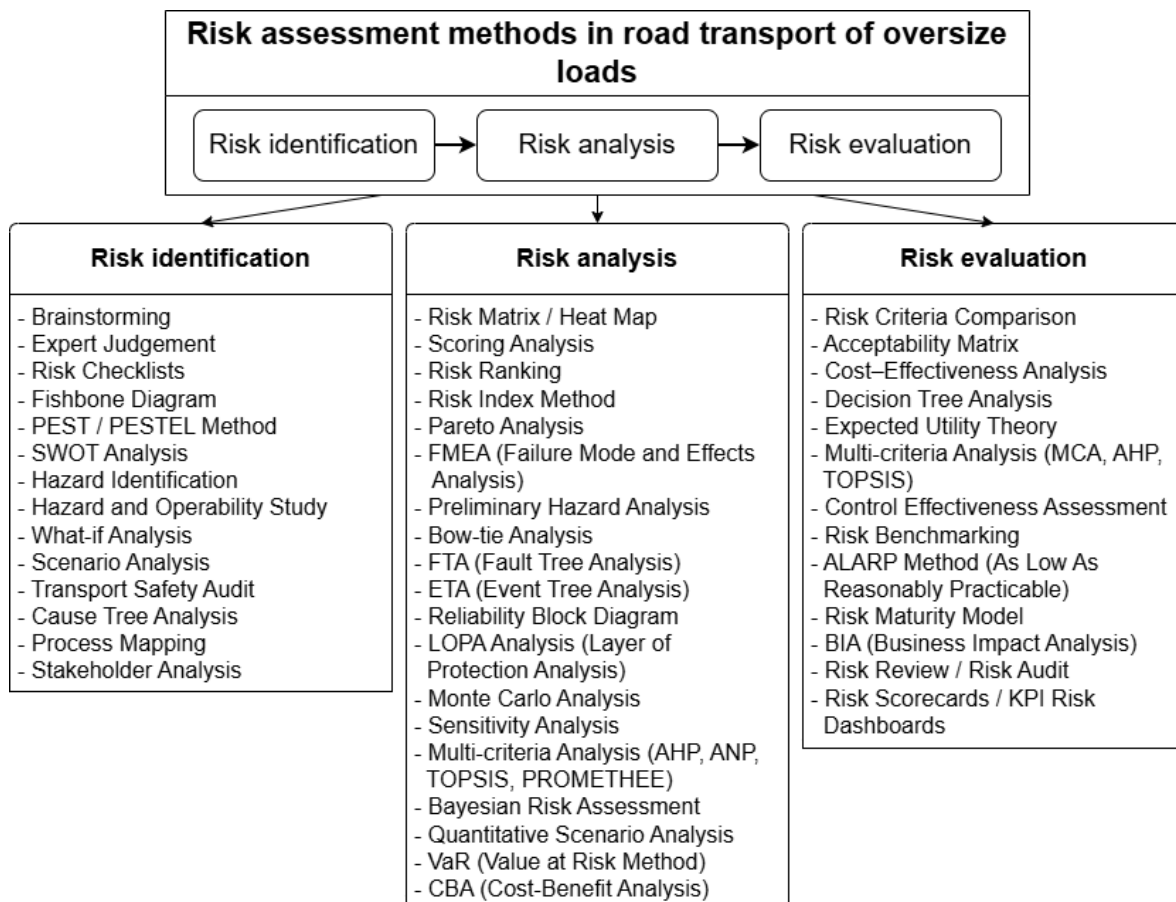


Fig. 5. Risk assessment methods applicable to road transport of oversize loads

Source: own elaboration based on 17

As shown in Figure 6, risk assessment is performed at each stage of transport planning. The process begins with collecting data on the order, including the type and parameters of the load, loading and unloading locations, possible load division, transportability, and special requirements. On this basis, transport parameters are planned, including the selection of transport equipment, loading operations, documentation, route, costs, and time. Risk sources, such as infrastructure constraints, weather conditions, technical risks, human error, and traffic disruptions, are then identified.

FMEA-based risk analysis takes into account both technical factors related to the operation of transport equipment and infrastructure, as well as organizational, operational, and environmental aspects. It is also assumed that the risk assessment process is conducted using expert knowledge and practical experience related to the organization and execution of transport operations. Figure 6 presents an algorithm for risk assessment in the organization of oversize road transport using the FMEA method.

4.2. Risk assessment algorithm for oversize road transport

To demonstrate in practical terms the decision-support process for planning and organizing oversize road transport, the FMEA method, Failure Mode and Effects Analysis, was used. This method enables the systematic identification of potential failure modes and the analysis of their

causes and effects on the process or system under investigation. As part of the analysis, three basic parameters are determined for each identified hazard:

- *S* (Severity) – the severity of the consequences of the event,
- *O* (Occurrence) – the probability of occurrence,
- *D* (Detection) – the difficulty of detecting the hazard, its cause, or its effects before occurrence.

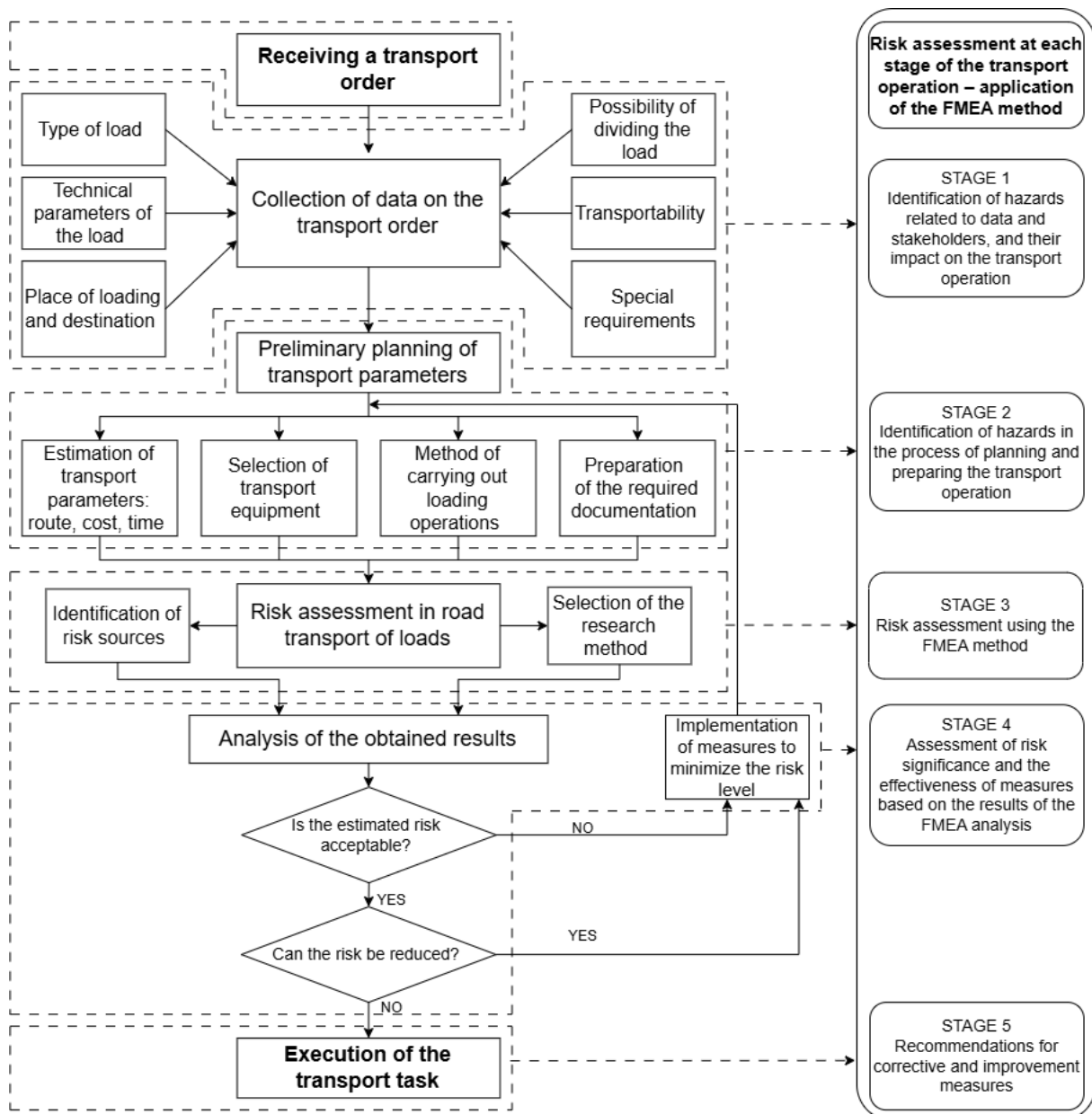


Fig. 6. Risk assessment procedure for the organization of oversize road transport

Source: own elaboration based on 25

Each parameter is rated on a scale from 1 to 10, with higher values indicating a higher risk level. On the basis of these ratings, the Risk Priority Number, RPN, is calculated as the product of the three factors:

$$RPN = S \times O \times D \quad (3)$$

The higher the RPN value, the higher the priority assigned to a given hazard and the greater the need for corrective action. In practice, events with an RPN exceeding a predetermined threshold, for example 150, are considered critical and require detailed analysis and immediate intervention 20. The strengths of the FMEA method include its systematic character, transparency, and ability to quantify the risk level at individual stages of transport. This method enables the identification of potential failure modes, that is, adverse events, as well as the determination of their effects, probability of occurrence, and detectability prior to occurrence. This makes it possible to assign a value to the Risk Priority Number (RPN), and thereby establish a hierarchy of hazards and identify areas requiring preventive action. Figure 7 presents a flowchart of the FMEA method.

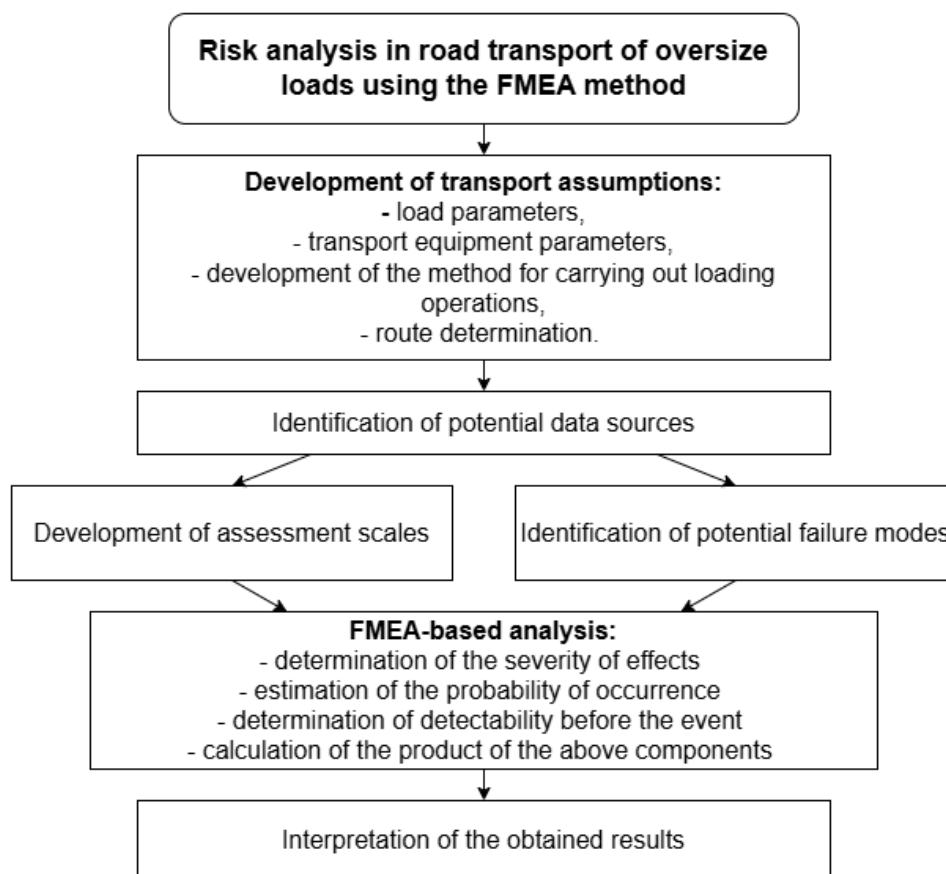


Fig. 7. Flowchart of the FMEA procedure for risk analysis in oversized road transport
Source: own elaboration

5. PRACTICAL EXAMPLE OF RISK ASSESSMENT

5.1. Assumptions – load and transport equipment parameters

To verify in practical terms the feasibility of using the FMEA method to support decision-making in the organization of oversized road transport, a case study was developed, including

a risk analysis for the transport of a power transformer. It was assumed that the load was transported from a production plant in Gliwice to a power substation in Opole. This operation was classified as oversize road transport because the vehicle combination exceeded the permissible parameters specified in the *Polish Road Traffic Act*, Journal of Laws of 2022, item 988 33. Due to the exceedance of permissible dimensional and mass parameters, the transport operation required a Category V permit and escort services. Table 1 summarizes the technical parameters of the sample load.

Tab. 1

Technical data of the sample oversize load

No.	Parameter	Value
1.	Length of the oversize load [m]	8,20
2.	Height of the oversize load [m]	3,60
3.	Width of the oversize load [m]	3,40
4.	Total mass of the oversize load [kg]	65 000

Source: own elaboration

In the case study, a mixed route was used, combining sections of motorway and lower-class roads. The main part of the transport operation was carried out on the A4 motorway, while access to the loading point in Gliwice and the final section leading to the power substation in Opole were carried out via voivodeship and district roads. This solution reflects the typical structure of oversize transport operations in Poland. The transport was carried out using a vehicle combination consisting of:

- a four-axle tractor unit adapted to the transport of oversize loads,
- a 10-axle modular low-bed semi-trailer, ensuring uniform distribution of axle loads on the road surface and maintaining the stability of the vehicle combination,
- two escort vehicles, as required by regulations, including one operating in radio communication with the police patrol on critical sections.

The study was conducted in cooperation with a transport company specializing in oversize transport. The FMEA risk assessment team included a transport manager, a route engineer, a driver and co-driver, a load-securing specialist, an occupational health and safety expert, and a representative of the road authority.

The analysis used load and vehicle documentation, route maps (taking into account the load-bearing capacity of bridges and vertical clearance limits), company operational data, applicable regulations, and cost information. Risk assessment was performed by experts on a 1–10 scale for three criteria: *S* (severity of consequences), *O* (occurrence), and *D* (detection). Where possible, simple quantitative measures were also used, such as the number of bridge structures or the length of sections with limited load-bearing capacity.

5.2. Identification of Risk Areas

Section 3.2 presents a general classification of risks occurring in road transport of oversize loads, including logistics and operational risks, technical risks, environmental risks, legal risks, and economic risks, as shown in Fig. 5. Based on this structure, as well as on practical experience gained in cooperation with a company providing oversize transport services, a detailed identification of specific risk factors, understood as *failure modes*, was conducted.

Hazard identification was conducted in consultation with a team of experts, including the transport manager, the route engineer, escort personnel, a load-securing specialist, and an occupational health and safety expert. The company's practical knowledge was used, including experience from previous transport operations, road infrastructure data, and applicable regulations concerning oversize transport.

Based on the conducted analyses, the most significant risk factors that may arise during the planning, preparation, and execution of the oversize transport of a power transformer on the Gliwice-Opole route were identified. The identified factors reflect actual operational, technical, and organizational hazards, and their characteristics are presented in Table 2.

Tab. 2

Key risk factors in oversize road transport

No.	Identified risk factor
1.	Incorrect or incomplete transport documentation
2.	Incorrect route selection or route planning
3.	Problems related to road infrastructure
4.	Improper load securing
5.	Failure of the vehicle or trailer
6.	Error by escort personnel or lack of convoy coordination
7.	Collision with infrastructure obstacles
8.	Adverse weather conditions
9.	Traffic congestion or roadworks along the route
10.	Disruptions affecting the local community
11.	Non-compliance with transport regulations
12.	Unplanned costs and organizational delays

Source: own elaboration

5.3. Decision-making procedure

After identifying the key hazards occurring in the transport of oversize loads, it is necessary to analyze their impact on the safety and course of the transport operation. The aim of this stage of the study is to determine which of the identified risk factors pose the greatest threat to the proper execution of the transport operation and to identify areas requiring preventive or organizational measures.

The analysis is conducted using the FMEA method, which involves the assessment of three parameters describing the nature of each hazard: severity of consequences S , occurrence O , and detection D . These parameters are assessed through expert consultation within a team composed of representatives of the transport company and the authors of the study. Ratings are assigned on a scale from 1 to 10, in accordance with the adopted qualitative criteria.

The obtained results provide the basis for calculating the RPN , which enables the hierarchy of individual hazards to be determined. Table 3 summarizes the results of the analysis.

As the results indicate (Table 3), the highest Risk Priority Number values are associated with technical and operational hazards. The most significant risks include improper load securing ($RPN = 378$), adverse weather conditions ($RPN = 360$), tractor unit or trailer failure ($RPN = 315$), and incorrect route selection or route planning ($RPN = 288$). These risk factors have a direct impact on transport safety and the continuity of transport operations; therefore, they

require priority treatment in the risk management process. The chart below presents a graphical summary of the results. Figure 8 presents a graphical summary of the results obtained.

Tab. 3

Summary of FMEA analysis results

No.	Risk factor	Consequences	S	O	D	RPN
1	Improper load securing	Load displacement, loss of stability, damage to the load	9	6	7	378
2	Adverse weather conditions	Reduced stability, need to interrupt the transport operation	5	8	9	360
3	Tractor unit or trailer failure	Stoppage, delay, risk of accident	5	7	9	315
4	Incorrect route selection or route planning	Collision with infrastructure elements, extended transport time	6	6	8	288
5	Error by escort personnel or lack of convoy coordination	Incorrect maneuvers, collisions	5	6	8	240
6	Problems related to road infrastructure	Difficult passage, damage to the vehicle or load	5	6	7	210
7	Traffic congestion or roadworks along the route	Delay, need for a detour	4	7	7	196
8	Collision with infrastructure obstacles	Damage to the load or infrastructure	9	3	5	135
9	Unplanned costs and organizational delays	Increased costs, reduced profitability	3	6	4	72
10	Incorrect or incomplete transport documentation	Transport suspension, delay, administrative sanctions	3	5	4	60
11	Disruptions affecting the local community	Complaints, conflicts, traffic restrictions	2	8	2	32
12	Non-compliance with transport regulations	Fines, vehicle detention	4	3	2	24

Source: own elaboration

Analysis of the partial values S, O, and D shows that the dominant factor increasing the risk level is the low detectability of potential hazards before their occurrence. This applies particularly to situations related to vehicle failures, adverse weather conditions, or operational errors during escorting. This indicates the need to implement system-based solutions for monitoring the technical condition of vehicles, ongoing supervision of route conditions, and more effective communication within the transport convoy.

On the other hand, risks with lower RPN values, such as unplanned costs and organizational delays (RPN = 72), incomplete transport documentation (RPN = 60), or disruptions affecting the local community (RPN = 32), have a limited impact on transport safety but may affect its economic efficiency and the company's image.

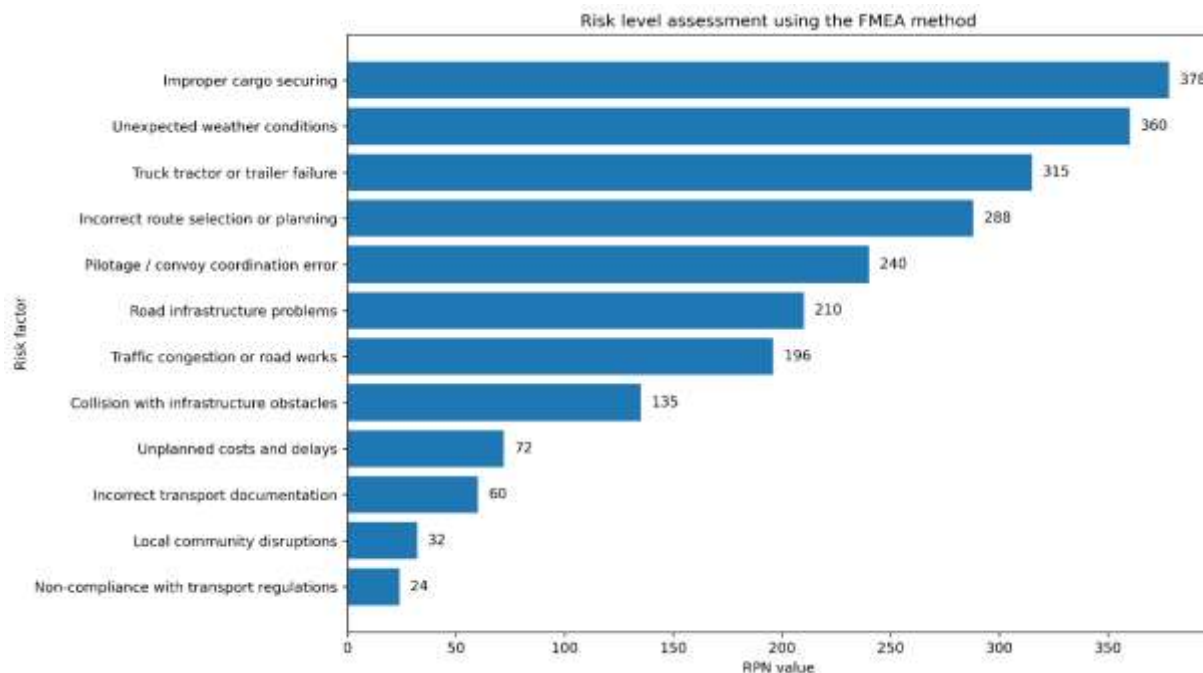


Fig. 8. Graphical presentation of the obtained results

Source: own elaboration

5.4. Corrective and preventive measures

Corrective and preventive measures are an important element of the risk management process in the transport of oversize loads. Their aim is to reduce the likelihood of hazards and minimize their potential consequences if they occur. These measures may include organizational, technical, and procedural solutions aimed at eliminating sources of risk during the planning and preparation stages of transport. Corrective measures, in turn, are intended to restore the stability of the transport process after an adverse event and to prevent its recurrence. Table 4 presents proposed preventive and corrective measures for risk factors with the highest RPN values, as well as an assessment of their expected effectiveness.

Tab. 4

Preventive and corrective measures for selected risk factors

No.	Risk factor	Preventive measures	Corrective measures
1	Improper load securing	Introduction of certified load-securing systems, mandatory training in load securing, use of pre-departure checklists, and additional inspection by the transport manager	Stopping the transport operation and re-securing the load, analyzing the causes of the error, and retraining loading personnel
2	Adverse weather conditions	Continuous monitoring of weather forecasts and GIS systems, flexible scheduling of transport dates, and development of emergency procedures for	Temporary suspension of the transport operation, securing the load and vehicle, route adjustment, or continuation of the transport after the hazard has passed

		adverse conditions, such as strong winds or precipitation	
3	Tractor unit or trailer failure	Regular technical inspections, implementation of a preventive maintenance plan, replacement of consumables before the planned transport operation, and inspection of tires, braking systems, and hydraulic systems	Securing the incident site, calling a mobile repair service, using a replacement vehicle, documenting the incident, and analyzing its causes

Source: own elaboration

6. CONCLUSIONS

The technical, organizational, and legal complexity of oversize road transport requires the use of structured planning and decision-support methods. Managing the transport process for oversize loads requires the integration of activities in the areas of transport engineering, logistics, and road safety. Particular attention should be paid to the importance of route planning, the selection of transport equipment, and operational coordination, as these factors directly affect the safety and efficiency of the entire transport operation.

The identification of risk factors made it possible to determine the key hazards affecting the safety of transport operations. The results clearly indicate that the highest RPN values were obtained for technical and operational hazards, including improper load securing, adverse weather conditions, and tractor unit or trailer failures. The results confirm that these factors constitute the most significant sources of uncertainty in the transport process and should be treated as priorities in safety management.

The study also proposes a set of preventive and corrective measures whose implementation may significantly reduce operational risk. The use of solutions such as certified load-securing systems, inspection procedures, ongoing technical monitoring of vehicles, and the integration of weather data into route planning may increase the resilience of the transport system to adverse events. Reassessment of risk after the implementation of corrective measures may indicate a noticeable reduction in the RPN value, thereby confirming the effectiveness of the proposed approach.

The results indicate the feasibility of adapting the FMEA method to real operating conditions, both in transport companies and in road administration units. In the longer term, the development of integrated decision-support systems based on risk analysis and digital technologies, such as GIS, IoT, and simulation tools, may contribute to improving the safety and efficiency of oversize transport in Poland and internationally.

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