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Methodological aspects of risk mapping in multimode transport systems

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Highlights

- Risks characteristic for different modes of transport are combined.
- The problem of risk assessment in multimodal transport systems is discussed.
- New contribution to the discussion on risk factors in multimodal transport is provided.
- Mathematical model to assess the risk in a multimodal transport system is provided.

Abstract

Efficient transport solutions are based on multimodal systems, with the dominant role of rail and road transport in land versions of the systems and the connecting and directing part of intermodal terminals, transhipment terminals or warehouse centres. The implementation of transport processes is always associated with the risk of lack of timeliness (quality) or threats to people, equipment and cargo (safety) resulting from human, technical, organizational and global factors like pandemics or war. The article contains a risk mapping method in multimodal transport systems configured to estimate the risk of lowering the quality of logistics services (on-time deliveries, etc.). The method combines factors usually considered separately in studies on individual modes of transport. A formal notation of risk factors as a mathematical model was proposed, and a case study was provided to picture the implementation.

Keywords
multimodal transport, intermodal transport, risk, timeliness, modelling.

1. Introduction

Transport systems in the second decade of the 21st century, operating in the conditions of the global market, ceased to be closed systems based on homogeneous transport technologies - railway, road, air or water transport. Single-mode transport systems, especially on a global scale, are no longer sufficient due to the specific features of these technologies, which on the one hand, constitute their undoubted advantages, but on the other hand, limit the application to particular areas. Effective and efficient transport requires the involvement and coordination of various modes of transportation, which in a complementary way, using the specific features of individual modes, ensure flexible and reliable implementation of transport services. Multimodal transport systems combine the mass character and low unit cost of transport in rail or sea modes with the flexibility, accessibility and feeding and collecting role of road transport. The most commonly used types of multimodal transport systems include intermodal and combined systems, in the land version, using various configurations of rail, road and internal transport.

The multimodal transportation requires a broader organizational and technological perspective to implement complex, intermodal coordination and functional combination of road, rail and internal transport rules. The organization of multimodal transport has been the subject of research since the 1960s, focusing primarily on estimating operations costs and synchronizing individual modes of transportation within one service, network or supply chain. But still, issues related to risk assessment in multimodal transport systems, especially in terms of timeliness of service or work safety, offer research potential.

In most studies, timeliness or reliability-improving solutions are developed for individual modes of transport. The possible connection between these modes is determined on the ground of time coordination and shared volumes of cargo. Therefore, the individual transport systems' boundary conditions are mostly fixed. The situation is similar in the studies on the safety and

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reliability of particular modes of transport. When interconnections between modes are fixed, information determining quality (timeliness and reliability) and safety in transport systems of particular types is flattened and blurred and will not influence the next chain. Continuity is not maintained, and information about factors shaping reliability, timeliness or security is lost at the expense of moving to a higher level of inter-industry organization.

The risk of unfavourable phenomena in transport systems leading to a reduction in service reliability or safety is a measure of the effectiveness of organizing and designing transport solutions. Although the mathematical tools and methods for risk estimation are fundamentally similar for different types of transport, phenomena modelling and dynamics, parameters, types, and basic features of risks are different for individual types of transport. The variety of methods makes it difficult to obtain a comprehensive picture, unambiguously describing the entire transport system in terms of the risk of factors negatively affecting the reliability and safety of their operation.

Global risk assessment is a characteristic element of research on supply chains and logistics networks, which results from the very nature of these structures. Supply chains are created to meet the consumption needs reported by final recipients. They are responsible for the entire service's final result, including the service's reliability, safety and security during its implementation. However, in the case of research on supply chains, the transport component is usually considered in a simplified (technical) way as a cost-generating and time-determining service factor. The emphasis in supply chain research is put on process planning at the coordination level of organizations in the supply chain. This approach has some limitations from the point of view of narrower considerations, not touching the elements of the network organization or the configuration of the supply chain itself.

In this light, it seems reasonable to develop methods that allow for holistic modelling (mapping) of risks related to the quality of services or safety of participants in transport processes, equipment and loads in multimodal transport systems. This approach should combine various specific features of individual transport modes into universal risk assessment methods.

In recent years, road and rail transport in Poland and the world has been undergoing dynamic development. A number of significant infrastructural investments are being implemented, both linear (roads, railway lines) and nodal (intermodal terminals, railway stations). An inseparable element related to the assets carried out, and later to the operation and maintenance of this infrastructure, is ensuring users' safety and reliability of future services. In almost every branch of transport, more and more emphasis is placed on safety management systems and risk analysis, which ultimately increases safety. Air transport was a pioneer in this area. Air transport safety management systems have been in operation for several decades. Another branch of transport that has been implementing safety management systems since the beginning of the 21st century is rail transport. The applicable Railway Safety Directive (2016/798) indicates as the primary safety objective to maintain a high level of safety at the expected level in the conditions of liberalization of the rail transport market and implementation of interoperability. As part of achieving the goal and maintaining a high level of safety, the European Union Agency for Railways published packages of common safety objectives (CST). It obliged the member states to monitor the safety level of their railway systems constantly. Each entity analyses the threats related to its activity and impact on the railway system and implements the necessary security measures on an ongoing basis. The concept of safety is closely related to the concept of risk, an essential requirement in safety management systems in the certification process of interoperability components in rail transport.

Therefore, we propose a method for risk mapping in multimodal transport systems. The method concerns estimating the risk of lowering the quality of logistics services (on-time deliveries, etc.) in a multimodal transport system. The method combines factors usually considered separately in the research on particular modes of transport.

The remainder of this article is as follows. Section 2. provides the literature review on the safety and management methods in multimodal transport systems. The 3. section discusses the method of risk mapping in multimodal transport systems and its formal notation. Section 4. provides a numeric example of the method implementation. The article is closed with a discussion of results and conclusions.

2. Literature review

In most cases, the risk is defined in a specific technical, technological or organizational context, but in general, it can be defined as 'the possibility that something will go wrong; also: an undertaking whose outcome is uncertain" [21]. In rail transport, the concept of risk in relation to safety is defined in the CSM RA Regulation (Polish regulations) [11] as "frequency of accidents and incidents leading to damage (caused by a threat) and the degree of severity of this damage". The concept of risk defined in terms of potential adverse effects is often related to the human factor, i.e. [14] "human interaction with other elements of the situation, i.e. equipment, tasks, people, physical environment, focusing on the perception and processing of information". The human factor can be considered dominant in most cases, but it should be emphasized that the risk may be related to random events, such as breakdowns, disasters or a pandemic, as presented in the method proposed in section 3. The risk then, if considered holistically for multimodal transport systems, will touch on one hand the safety of people, equipment and cargo, and different aspects of service quality on the other hand.

The literature on risk assessment for transportation systems is extensive and covers a wide range of topics, from safety to timeliness, reliability, cost, and manageability. The concept of risk can be defined separately and differently depending on the scope of the application. To organize the state of knowledge, the following research areas were listed:

- safety (risk) management methods and general risk modelling,
- rail transport system safety,
- risk in multimodal systems,
- threats in intermodal transport,
- risk and quality in supply chains and logistics structures.

The development of risk management methods was described by Bernstein [8] or Aven [5]. Risk management is considered separately in different areas of technical activity, depending on the tasks performed, with some of these approaches being applicable in multimodal systems areas. Research conducted in the field of operational management [50], projects [45], public strategy [10], or crisis management [39] seems to be important in this respect.

Risk management standards were developed as part of the risk management theory, which are a set of best practices for implementing the risk management process. The most prevalent risk management standards include FERMA, COSO II and the PN-ISO 31000 standard [45] or ISO 31010 [22]. Each of these standards defines risk and the risk management process on a different level of detail.

The FERMA standard defines risk "as a combination of the probability of an event occurring and its consequences" (ISO/IEC Recommendation No. 73), indicating the staged course of the risk management process and exemplary risk factors. The COSO II standard is a multi-directional and interactive process. This standard indicates the correlation between the four types of goals that the organisation wants to achieve and the components of risk management [55]. The ISO 31000:2018 standard describes a staged risk management process [45]. The principles of risk management indicated in the Standard are universal and constitute guidelines for the entire organisation's design, implementation and maintenance of the risk management process.

In 2009, a universal method of risk management in transport TRANS-RISK was also proposed, which integrates two phases: the risk assessment phase (risk analysis and evaluation) and the risk response phase (risk management, monitoring and risk communication) [27].

But in most cases the risk is related to safety, as in railway transport.

Risk management in rail transport is a well-developed research topic (e.g. [13]), but it is also significantly regulated by law. Researchers focus on defining the risk [49], risk appetite [3], change management [17], risk assessment methods [9, 51], safe integration [29, 34], risk assessment units and the implementation and operation of the CSM RA [19].

In the case of rail transport, risks are mainly considered in connection with security assurance systems. Since 2009, a standard safety method for railway risk evaluation and assessment (Regulation CSM RA) [11] has been adopted, providing risk management guidelines. The CSM RA defines the risk management process as "a comprehensive and multi-stage risk assessment including system definition, risk analysis (identification of hazards and selection of the risk acceptance principle), risk evaluation and demonstration of compliance with safety requirements". Risk management according to CSM RA means "planned application of management policies, procedures and practices as part of risk analysis, valuation and supervision tasks". Therefore, risk management in transport should be carried out throughout the entire life cycle of the organisation, facilities, and for all users of transport systems, including in multimode systems.

In rail transport, risk and quality management organisational structures exist at many levels: international, central, regional and local. Different risks and quality issues are managed at each level, so these risks will vary depending on the scale of operation of the multimode transport system. Each level of the organisation also has a degree of accuracy in assessing and responding to risk and how it influences the quality of service. Therefore, there are strategic, long-term risks related to making long-term decisions by institutions managing transport safety in the analysed area of the country, region, or city (strategic risk can be interpreted as a social, group and individual risk) and operational - short-term related to day-to-day activities of the transport administration, carrier, operator, etc. [44]. In rail transport, this risk can be equated with process risk. Two types of risk are provided for analysing and assessing operational risk: group and individual.

Other risk aspects considered in this article concern multimodal transport systems, supply chains and logistics structures and are considered mainly from the point of view of the quality of transport services.

Risks and related quality issues in multimodal transport systems may relate to global events such as pandemics, political changes (e.g. Brexit), climate phenomena or wars. Bandyopadhyay A., Bhatnagar [6], and Auad et al. [4] represent the research branch focused on the impact of pandemics on the resilience of multimodal transport systems. The COVID-19 pandemic led to lockdowns worldwide and disruption in the global supply chains. It hit all modes of transport, including multimodal transport and logistics systems. The authors list factors influencing the transport operation in labour, vehicle capacity, material flows volumes and structures and policy situations and conclude that the catalogue of threats and risks is not fixed and global phenomena like the COVID-19 pandemic affect a multilevel and multithreaded way. In this area Wang et al. [59] indicate the need to identify critical nodes in transport networks affecting their reliability in disaster conditions, and Guo, Du, and He [18] point to the location factor of emergency rescue facilities as critical for the resilience of the multimodal transport network.

Supply chain research browsing provides results about risk management. Vilko J., Ritala P., and Hallikas [58] call the supply chain complexity, disintegration and handing over the risk management to outside service providers as significant risk management challenges. Collaboration in supply chain risk management is essential, as an awareness of the risks and their control mechanisms do not necessarily reside in the same company. Tang et al. [54] construct a risk model of the assembly supply chain network based on production capability loss. The authors assess network robustness at different node thresholds and linking intensity. Lie et al. [37] call the robustness of complex networks a core issue in complex network research. Vilko and Hallikas [57] name the extensive list of supply, operational, security, macro, policy and environmental risks and their effects on the supply chain, especially delays. This set of risks can be a base for risk identification in multimodal transport networks. Aqlan and Lam [2] present an integrated supply chain risk assessment framework. They use a fuzzy inference system to calculate the total risk score considering the risk management parameters and predictability. Authors call risk factors for main components in the supply chain: supplier risks, customer risks, process and control risks, technology risks, product risks, occupational risks, culture risks, transportation risks, and commodity risks. The paper provides a very extensive literature review on risks in supply chains (also [46], [47] and 48). Nooraie and Parast [41] investigate the relationship among supply chain visibility, supply chain risk, and supply chain cost of new and seasonal products. Qazi et al. [46] propose supply chain risk network management process to tide interdependencies between risks, multiple performance measures and risk mitigation strategies within a network setting. Fan, Sun and Cheng [15] propose an information processing system comprising risk information sharing, risk analysis and assessment, and risk sharing mechanism to manage supply chain risk and underline the role of information in risk management. In a similar way Jacyna and Semenov [25] analyse information uncertainty influencing service quality risks. Marufuzzaman, Eksioglu and Wang [40] combine intermodal transport risk with supply chain. Jacyna-Gołda et al. [26] discuss elements influencing perfect order rate as a measure of high-quality logistics service and name the factors influencing it, which can be considered in terms of risk. Wasiak et al. [60] provide model to assess the reliability of supply chain configurations.

Multimodal transport systems are also subject to risk-related research. Lahuta, Kardoš, and Hudáková [35] propose a general integrated risk management system in transport. Tubis and Werbińska-Wojciechowska [56] discuss general risk assessment issues in transport. Koohathongsumrit and Meethom [33] propose an integrated framework of fuzzy risk assessment model, data envelopment analysis, and multiple criteria decision-making approaches for routing and risk prediction in multimodal transport networks. Fan and Yang [16] provide the study of emerging security and classic safety-related risks in a holistic manner using safety and security co-analysis for accident prevention. Szaciłło et al. [52] propose a traditional risk matrix method for assessing the risk of implementing rail freight services. Pineda-Jaramillo J. and Viti [43] use machine learning models to predict the delay times caused by the disruptions and disturbances in intermodal freight rail operations on the national and pan-European network. Luo and Xu [38] consider the complementarity of the car (bus) and rail transport to reduce the risk of delays in transportation and failure to complete tasks. Jingni et al. [28] proposed a quantitative method of risk propagation based on improved percolation theory. The authors analyse the risk propagation law of the multimodal transport network under different attack types and load preferences. Adjetey-Bahun et al. [1] discuss the concept of resilience to measure the system's ability to absorb perturbations and also its ability to rapidly recover from perturbations. Authors propose a model for quantifying resilience in mass railway transportation systems by quantifying passenger delay and passenger load as the system's performance indicators. Leleń and Wasiak [36] define other types of risks in multimodal transport systems related to the transport of perishable cargo. Basallo-Triana, Vidal-Holguín and Bravo-Bastidas [7] and Jacyna, Pyza, and Jachimowski [24] review solutions in designing intermodal hub networks, listing the factors presented in Chapter 3 as affecting the effectiveness of solutions and thus reducing the risks associated with the provision of transport services. Ke and Verma [31] proposed a framework based on optimization and regression analysis for recovery from random disruptions of intermodal rail terminals. Hosseini and Verma [20], Conca, Ridella, and Sapori [12] or Izdebski, Jacyna-Gołda, and Gołda [23] discuss handling hazardous materials and how to plan their movement as a factor shaping the risk of hazardous events in multimodal systems.

The literature review outlines the research areas collectively addressed in this article. The risk estimation method presented in Chapter 3 contains the elements given by Karasiewicz [30] but covers a wide range of factors listed in various literature items, including rail, road, internal (terminal) transport and supply chains. The presented approach has not been identified in the analysed literature.

3. Method of risk mapping in multimodal transport systems

Risk assessment in multimodal transport systems may concern various aspects, such as damage to the shipment, loss of the shipment, extended delivery time, or primary events related to the disruption of the functioning of individual links of these systems, etc., related to failures of their equipment, errors from human resources or events on the transport network.

The method proposed in the article concerns estimating the risk of lowering the quality of logistics services (on-time deliveries, etc.) in multimodal transport and was developed using the elements proposed by Karasiewicz [30]. The risk of failure to meet the deadline for the completion of a logistics task in a multimodal transport system depends both on the extension of the delivery time by external transport between the origin and the sending multimodal terminal and then between subsequent terminals and between the receiving terminal and the recipient of the cargo, as well as on delays occurring in individual multimodal terminals.

Extending the delivery time by external transport may result from reasons attributable to the sender, recipient or carrier and may also be not the fault of any of these parties. Importantly, not every extension of the transport process time will be treated as a delay in transport. In the case of multimodal transport, the catalogue of events resulting in the extension of the time of the transport process (delay) is significantly expanding. In this case, besides the activities of individual carriers implementing a given process, activities in multimodal terminals and other point facilities of the logistics infrastructure, such as warehouse centres, should also be taken into account.

In the case of external transport, an essential factor in the occurrence of delays for which the transport company will be responsible are any disruptions to the transport network (accidents, traffic congestion), as well as disruptions in the functioning of this company related to, e.g. vehicle breakdowns, extended time of other transport tasks, improper preparation of drivers, human errors. In addition, delays in the transport of shipments by external transport may result from, among others, the fault of the carrier (only when the carrier is responsible for taking the following actions or extending the time of their implementation):

- checking the shipment, as a result of which no discrepancies with the data from the bill of lading were found, or failure to comply with the provisions regarding items allowed for transport under special conditions,
- performing activities required by special provisions, including activities related to the shipment,
- changes to the contract of carriage or obstacles to the carriage or release of the shipment,

- overloading or the need to correct the loading.

On the other hand, the risk of delays in multimodal transport terminals depends on the timely reporting of means of external transport for service and on irregularities during the shipment or collection of cargo, as well as on the size and equipment of this terminal, its staff and the level of terminal automation. Disturbances on the transport network depend primarily on the average daily load of its sections and on the season, type of day and time, type of transport network section, and on-road incidents. At the same time, the occurrence of road accidents is affected, in addition to those mentioned above, by several other factors related to the geometry of the road and its course in the plan, as well as the "development" of the right-of-way, its surroundings and weather conditions (clouds, precipitation, fog, etc.). The modelling of these phenomena and the search for a relationship between these factors and the type of road accidents and the frequency of their occurrence is a separate extensive research area (cf., e.g. [32, 42, 46, 47, 61]).

Considering the above, it was assumed that the risk of a delay in the implementation of a logistics task when moving a shipment by external transport depends on the following:

- unpredicted traffic congestion, *NKR*,
- road incident, *LZD*,
- delayed triggering of the transport task due to too late provision of the means of transport, *ORP*,
- need to secure (tie) the cargo additionally while driving, *PMŁ*,
- need to reload or improve the cargo distribution due to (for example) providing an unsuitable vehicle, *PPŁ*,
- vehicle (mean of transport) breakdown, *ASP*,
- lack of suitable means to secure cargo while picking it up, *UAV*,
- lack of competence of the driver and/or loading staff in effective cargo tying, *BKK*,
- undertaking an unreasonable checking of the shipment, *NSP*,
- incorrect reaction of the carrier to the order to change the contract of carriage, *NRZ*,
- incorrect reaction of the carrier in difficulty to releasing the parcel, *NRP*,
- incorrect decisions of the driver regarding the assumed transport route, *BWT*,
- stopping the vehicle for inspection due to the driver's failure to comply with traffic regulations, *ZZK*.

On the other hand, the risk of a delay in the implementation of a logistics task when handling a shipment in a multimodal terminal depends on the following:

- failure of cargo handling equipment in the terminal, *AUO*,
- errors in making the cargo available for shipment (mistakes in preparing the shipment), *PPP*,
- availability of loading devices at the required time, *DUŁ*,
- failure of loading devices, *AUŁ*,
- failure of IT systems in the terminal, *AIT*,
- current terminal load, *WOT*,
- level of automation of goods movement processes, *PAP*,
- strikes by terminal workers, *SPT*,
- availability at the required moment of loading equipment operators and other loading employees, *DPŁ*,
- lack of competence of the loader in the scope of carrying out loading works, including the arrangement of the load on the means of transport, *NPŁ*,
- failure to provide the carrier with information enabling choosing the right vehicle and means to secure the load, *BIP*,
- handing over a shipment in poor condition or without proper packaging, *PUP*,
- failure to provide the carrier promptly with documents related to the shipment required during transport, *NDP*.

Not all of the perturbations mentioned above may cause delays in certain situations. Moreover, delays arising in a given stage of cargo movement may be reduced or increased in subsequent stages of transport, depending on the flexibility of a given subsystem and its current load. This makes modelling this phenomenon a complex issue. Generally, in this case, the considered system is of a series type, the elements of which are series-parallel systems with possible redundancies.

Then, the risk of delay in the R_{MUT} multimodal transport system consisting of N multimodal terminals and $N+1$ transport connections operated by specified carriers, understood as the probability of delay, can be determined according to the formula (1):

$$R_{MUT} = 1 - \prod_{i=1}^{N}(1 - R_{TM}(i)) \cdot \prod_{j=1}^{N+1}(1 - R_{TZ}(j)) \qquad (1)$$

where:

$R_{TM}(i)$ – risk of delay in the i-th multimodal terminal,
$R_{TZ}(j)$ – risk of delay in the j-th stage of cargo movement by external transport,

At the same time, the risk of delay in the i-th multimodal terminal in this approach can be determined according to the formula (2):

$$R_{TM}(i) = \frac{\Delta t_{TM}(i)}{T - \sum_{i'=1}^{i-1}\Delta t_{TM}(i') - \sum_{j'=1}^{i}\Delta t_{TZ}(j')} \qquad (2)$$

where:

$\Delta t_{TM}(i)$ – delay in the i-th multimodal terminal,
$\Delta t_{TZ}(j)$ – delay on the j-th stage of cargo movement by external transport,
T – assumed period of completion of the logistics task.

On the other hand, the risk of delay when handling cargo with external transport is determined according to (3):

$$R_{TZ}(j) = \frac{\Delta t_{TZ}(j)}{T - \sum_{j'=1}^{j-1}\Delta t_{TZ}(j') - \sum_{i'=1}^{j-1}\Delta t_{TM}(i')} \qquad (3)$$

where:

$\Delta t_{TZ}(j)$ – delay on the j-th stage of cargo movement by external transport,
$\Delta t_{TM}(i)$ – delay in the i-th multimodal terminal,
T – assumed period of logistic task completion.

As previously agreed, the risk of a delay in the implementation of a logistics task when handling a shipment in a multimodal terminal depends on many factors that may occur individually or in any configuration. The probability and effects of these factors can be determined based on empirical data on delays in a given terminal and their causes and duration. For further consideration, we assume that the average delay times of the logistics process are known due to the specified factors marked as: $\Delta t_{TM\_AUO}(i)$, $\Delta t_{TM\_PPP}(i)$, $\Delta t_{TM\_DUŁ}(i)$, $\Delta t_{TM\_AUŁ}(i)$, $\Delta t_{TM\_AIT}(i)$, $\Delta t_{TM\_WOT}(i)$, $\Delta t_{TM\_PAP}(i)$, $\Delta t_{TM\_SPT}(i)$, $\Delta t_{TM\_DPŁ}(i)$, $\Delta t_{TM\_NPŁ}(i)$, $\Delta t_{TM\_BIP}(i)$, $\Delta t_{TM\_PUP}(i)$, $\Delta t_{TM\_NDP}(i)$. In this approach, the total expected delay at the *i*-th multimodal terminal is as follows:

$$\begin{aligned}\Delta t_{TM}(i) = \Delta t_{TM_{AUO}}(i) + \Delta t_{TM_{PPP}}(i) + \Delta t_{TM_{DUŁ}}(i) \\ + \Delta t_{TM_{AUŁ}}(i) + \Delta t_{TM_{AIT}}(i) \\ + \Delta t_{TM_{WOT}}(i) + \Delta t_{TM\_PAP}(i) \\ + \Delta t_{TM\_SPT}(i) + \Delta t_{TM\_DPŁ}(i) \\ + \Delta t_{TM\_NPŁ}(i) + \Delta t_{TM\_BIP}(i) \\ + \Delta t_{TM\_PUP}(i) + \Delta t_{TM\_NDP}(i)\end{aligned} \tag{4}$$

The causes and effects of delays in external transport in relation to individual carriers and fragments of the transport network can be determined in the same way as in the case of multimodal terminals. However, in this case, the relative extension of the journey time due to this extension $\Delta\tau$ shall be determined instead of the average delay. Then the total expected delay in the *j*-th stage of the cargo movement by external transport will be as follows:

$$\begin{aligned}\Delta t_{TZ}(j) = T_{TZ}(j) \cdot (\Delta\tau_{TZ\_NKR}(j) + \Delta\tau_{TZ\_LZD}(j) \\ + \Delta\tau_{TZ\_ORP}(j) + \Delta\tau_{TZ\_PMŁ}(j) \\ + \Delta\tau_{TZ\_PPŁ}(j) + \Delta\tau_{TZ\_ASP}(j) \\ + \Delta\tau_{TZ\_BSP}(j) + \Delta\tau_{TZ\_BKK}(j) \\ + \Delta\tau_{TZ\_NSP}(j) + \Delta\tau_{TZ\_NRZ}(j) \\ + \Delta\tau_{TZ\_NRP}(j) + \Delta\tau_{TZ\_BWT}(j) \\ + \Delta\tau_{TZ\_ZZK}(j))\end{aligned} \tag{5}$$

In the proposed approach, the effects of individual factors in terms of delays in cargo movement can also be estimated for various technical and organizational solutions included in a given terminal or on a given connection served by external transport. Especially in the case of designing new solutions or introducing significant changes to the currently functioning multimodal transport system, such an approach is necessary due to the lack of reliable historical data in the analysed scope.

Taking into account the above approach, it can be assumed that, for example, the delay effect resulting from the current terminal load (*WOT*) depends on the following:

- terminal type, TM_{RT},
- terminal size (capacity), TM_{WT},
- volumes of cargo handled by the terminal (reloading works, etc.), $TM_{PŁ}$,
- average daily reserve of loading equipment, TM_{DU},
- average daily reserve of terminal staff, TM_{LP},
- type of traffic control devices in the terminal, TM_{SR},
- technical condition of the terminal's railway infrastructure, TM_{IK},
- technical condition of the terminal's road infrastructure, TM_{ID},
- level of professional preparation of individual terminal staff, TM_{PW},
- age of individual terminal staff, TM_{WP},
- seniority in the position of individual terminal service employees, TM_{SP},
- level of automation of loading works, $TM_{AŁ}$,
- level of automation of identification, control and registration systems for transport units and vehicles, TM_{AI},
- advancement of the loading planning and work organization system on storage yards and in buildings, TM_{ZP}.

Taking into account the listed parameters, the formal record allowing to estimate the total expected delay in the *i*-th multimodal terminal for its current load has the general form (6):

$$\begin{aligned}\Delta t_{TM_{WOT}}(i) = f(TM_{RT}(i), TM_{WT}(i), TM_{PŁ}(i), TM_{DU}(i), \\ TM_{LP}(i), TM_{SR}(i), TM_{IK}(i), TM_{ID}(i), TM_{PW}(i), \\ TM_{WP}(i), TM_{SP}(i), TM_{AŁ}(i), TM_{AI}(i), TM_{ZP}(i))\end{aligned} \tag{6}$$

The form of the formula (6) was adopted as follows:

$$\begin{aligned}\Delta t_{TM\_WOT}(i) = \alpha_{TM\_WOT} \cdot (TM_{RT}(i) + TM_{WT}(i) + \\ TM_{PŁ}(i) \cdot min\{TM_{DU}(i), TM_{LP}(i)\} + TM_{SR}(i) \cdot TM_{IK}(i) \cdot \\ TM_{ID}(i) + TM_{PW}(i) \cdot TM_{WP}(i) \cdot TM_{SP}(i) + TM_{AŁ}(i) \cdot \\ TM_{AI}(i) \cdot TM_{ZP}(i))\end{aligned} \tag{7}$$

It should be noted here that including a wide range of parameters poses problems related to the availability and possibility of data acquisition, various technical measures of factors and correlation between them, stochastic nature of factors, or difficulty of estimating the effects of changing measures describing the mentioned factors. For this reason, mapping the risks associated with the factors mentioned above was implemented at the general level to obtain a broad picture of the multimodal system under consideration and to draw conclusions about the risks associated with implementing the assumed tasks by this system.

4. Case study

The problem of estimating the delay resulting from the current load on the terminal was considered a case study. Tables 1-14 show the parameters and the influence on the delay resulting from the current terminal load assigned to their various levels. The classification and division of terminals were taken from publications [53, 59]. The influence of individual parameters on the analysed delay for their various levels, marked with the k index, was defined in the range of (0-5) points on the base of literature and the expert method.

Table 1. Range of the parameter 'terminal type' $TM_{RT(k)}$

Parameter range	Terminal type	How does the parameter influence the delay
Level 1	universal cargo terminal	$TM_{RT(1)} = 0{,}5$
Level 2	universal bulk terminal	$TM_{RT(2)} = 1{,}0$
Level 3	mixed-cargo universal terminal	$TM_{RT(3)} = 2{,}0$
Level 4	specialized general cargo terminal	$TM_{RT(4)} = 3{,}0$
Level 5	specialized ferry terminal	$TM_{RT(5)} = 4{,}0$
Level 6	specialized terminal for handling unit loads	$TM_{RT(6)} = 4{,}5$
Level 7	specialized bulk terminal	$TM_{RT(7)} = 5{,}0$

Table 2. Range of the parameter 'terminal size (capacity)' $TM_{WT(k)}$

Parameter range	Terminal size (capacity)	How does the parameter influence the delay
Level 1	small terminal (below 25 000 itu)	$TM_{WT(1)} = 0{,}5$
Level 2	medium terminal (25 000 ÷ 50 000 itu)	$TM_{WT(2)} = 1{,}0$
Level 3	large terminal (50 000 ÷ 100 000 itu)	$TM_{WT(3)} = 2{,}0$
Level 4	very large terminal (over 100 000 itu)	$TM_{WT(4)} = 3{,}5$

Table 3. Range of the parameter 'volumes of cargo handled by the terminal' $TM_{PŁ(k)}$

Parameter range	Volumes of cargo handled by the terminal	How does the parameter influence the delay
Level 1	exceeds 150% of the average daily load	$TM_{PŁ(1)} = 4{,}5$
Level 2	does not exceed 150% of the average daily load	$TM_{PŁ(2)} = 3{,}5$
Level 3	does not exceed 120% of the average daily load	$TM_{PŁ(2)} = 2{,}5$
Level 4	does not exceed the average daily load	$TM_{PŁ(4)} = 1{,}0$
Level 5	does not exceed 80% of the average daily load	$TM_{PŁ(5)} = 0{,}5$

Table 4. Range of the parameter 'average daily reserve of loading equipment' $TM_{DU(k)}$

Parameter range	Average daily reserve of loading equipment	How does the parameter influence the delay
Level 1	up to 10% of devices of a given type	$TM_{DU(1)} = 4{,}5$
Level 2	over 10% to 20% of devices of a given type	$TM_{DU(2)} = 3{,}5$
Level 3	over 20% to 30% of devices of a given type	$TM_{DU(3)} = 2{,}5$
Level 4	over 30% to 40% of devices of a given type	$TM_{DU(4)} = 1{,}5$
Level 5	over 40% of devices of a given type	$TM_{DU(5)} = 0{,}5$

Table 5. Range of the parameter 'average daily reserve of terminal staff' $TM_{LP(k)}$

Parameter range	Average daily reserve of terminal staff	How does the parameter influence the delay
Level 1	up to 10% of employees in a given work category	$TM_{LP(1)} = 4{,}5$
Level 2	over 10% to 25% of employees in a given work category	$TM_{LP(2)} = 2{,}5$
Level 3	over 25% to 35% of employees in a given work category	$TM_{LP(3)} = 1{,}5$
Level 4	over 35% of employees in a given job category	$TM_{LP(1)} = 0{,}5$

Table 6. Range of the parameter 'type of traffic control devices in the terminal' $TM_{SR(k)}$

Parameter range	Type of traffic control devices in the terminal	How does the parameter influence the delay
Level 1	mechanical railway traffic control devices	$TM_{SR(1)} = 2{,}0$
Level 2	electromechanical railway traffic control devices	$TM_{SR(2)} = 1{,}5$
Level 3	relay rail traffic control devices	$TM_{SR(3)} = 1{,}0$
Level 4	computerized railway traffic control devices	$TM_{SR(4)} = 0{,}5$

Table 7. Range of the parameter 'technical condition of the terminal's railway infrastructure' $TM_{IK(k)}$

Parameter range	Technical condition of the terminal's railway infrastructure	How does the parameter influence the delay
Level 1	unsatisfactory condition	$TM_{IK(1)} = 2{,}0$
Level 2	sufficient condition	$TM_{IK(2)} = 1{,}0$
Level 3	good condition	$TM_{IK(3)} = 0{,}5$

Table 8. Range of the parameter 'technical condition of the terminal's road infrastructure' $TM_{ID(k)}$

Parameter range	Technical condition of the terminal's road infrastructure	How does the parameter influence the delay
Level 1	unsatisfactory condition	$TM_{ID(1)} = 2{,}0$
Level 2	sufficient condition	$TM_{ID(2)} = 1{,}0$
Level 3	good condition	$TM_{ID(3)} = 0{,}5$

Table 9. Range of the parameter 'level of professional preparation of individual terminal staff' $TM_{PW(k)}$

Parameter range	Level of professional preparation of individual terminal staff	How does the parameter influence the delay
Level 1	basic vocational, not industry-specific education	$TM_{PW(1)} = 4{,}5$
Level 2	non-business secondary education	$TM_{PW(2)} = 4{,}0$
Level 3	higher education not related to transport	$TM_{PW(3)} = 3{,}5$
Level 4	basic industry education	$TM_{PW(4)} = 2{,}5$
Level 5	vocational secondary education	$TM_{PW(5)} = 1{,}0$
Level 6	higher education related to transport	$TM_{PW(6)} = 0{,}5$

Table 10. Range of the parameter 'age of individual terminal staff' $TM_{WP(k)}$

Parameter range	Age of individual terminal staff	How does the parameter influence the delay
Level 1	up to 30 years	$TM_{WP(1)} = 3{,}5$
Level 2	31-40 years	$TM_{WP(2)} = 1{,}0$
Level 3	41-50 years	$TM_{WP(3)} = 1{,}5$
Level 4	over 50 years	$TM_{WP(4)} = 2{,}5$

Table 11. Range of the parameter 'seniority in the position of individual terminal service employees' $TM_{SP(k)}$

Parameter range	Seniority in the position of individual terminal service employees	How does the parameter influence the delay
Level 1	up to 5 years	$TM_{SP(1)} = 3{,}0$
Level 2	6-15 years	$TM_{SP(2)} = 1{,}5$
Level 3	16-30 years	$TM_{SP(3)} = 1{,}0$
Level 4	over 30 years	$TM_{SP(4)} = 0{,}5$

Table 12. Range of the parameter 'level of automation of loading works' $TM_{AL(k)}$

Parameter range	Level of automation of loading works	How does the parameter influence the delay
Level 1	no automation	$TM_{AL(1)} = 2{,}0$
Level 2	semi-automatic	$TM_{AL(2)} = 1{,}0$
Level 3	automatic	$TM_{AL(3)} = 0{,}5$

Table 13. Range of the parameter 'level of automation of identification, control and registration systems for transport units and vehicles' $TM_{Al(k)}$

Parameter range	Level of automation of identification, control and registration systems for transport units and vehicles	How does the parameter influence the delay
Level 1	no automation	$TM_{Al(1)} = 2{,}0$
Level 2	semi-automatic	$TM_{Al(2)} = 1{,}0$
Level 3	automatic	$TM_{Al(3)} = 0{,}5$

Table 14. Range of the parameter 'advancement of the loading planning and work organization system on storage yards and in buildings' TMZP(k)

Parameter range	Advancement of the loading planning and work organization system on storage yards and in buildings	How does the parameter influence the delay
Level 1	no planning	$TM_{ZP(1)} = 3{,}0$
Level 2	planning using traditional methods	$TM_{ZP(2)} = 1{,}5$
Level 3	planning using specialized applications	$TM_{ZP(3)} = 0{,}5$

As part of checking the theoretical assumptions, calculations were made for the two most extreme variants. The first variant adopted the parameters that can cause the most significant delays in the terminal. In turn, variant 2 includes parameters that may cause the slightest delays in the intermodal terminal. The value of the parameter α_{TM_WOT} was adopted in the calculations as following: 0.5; 1.0; 2.0; 3.0; 4.0; 4.5, and 5.0.

Variant 1

$$\alpha_{TM\_WOT} = 0{,}5$$
$$\Delta t_{TM_{WOT}}(1) = 0{,}5 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 39$$
$$\alpha_{TM\_WOT} = 1{,}0$$
$$\Delta t_{TM_{WOT}}(2) = 1{,}0 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 78$$
$$\alpha_{TM\_WOT} = 2{,}0$$
$$\Delta t_{TM_{WOT}}(3) = 2{,}0 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 156$$
$$\alpha_{TM\_WOT} = 3{,}0$$
$$\Delta t_{TM_{WOT}}(4) = 3{,}0 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 234$$
$$\alpha_{TM\_WOT} = 4{,}0$$
$$\Delta t_{TM_{WOT}}(5) = 4{,}0 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 312$$
$$\alpha_{TM\_WOT} = 4{,}5$$
$$\Delta t_{TM_{WOT}}(6) = 4{,}5 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 351$$
$$\alpha_{TM\_WOT} = 5{,}0$$
$$\Delta t_{TM_{WOT}}(7) = 5{,}0 \cdot (5{,}0 + 3{,}5 + 4{,}5 \cdot min\{0{,}5, 0{,}5\} + 2{,}0 \cdot 2{,}0 \cdot 2{,}0 + 4{,}5 \cdot 3{,}5 \cdot 3{,}0 + 2{,}0 \cdot 2{,}0 \cdot 3{,}0) = 390$$

Variant 2

$$\alpha_{TM\_WOT} = 0{,}5$$
$$\Delta t_{TM_{WOT}}(1) = 0{,}5 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 0{,}875$$
$$\alpha_{TM\_WOT} = 1{,}0$$
$$\Delta t_{TM_{WOT}}(2) = 1{,}0 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 1{,}75$$
$$\alpha_{TM\_WOT} = 2{,}0$$
$$\Delta t_{TM_{WOT}}(3) = 2{,}0 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 3{,}5$$
$$\alpha_{TM\_WOT} = 3{,}0$$
$$\Delta t_{TM_{WOT}}(4) = 3{,}0 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 5{,}25$$
$$\alpha_{TM\_WOT} = 4{,}0$$
$$\Delta t_{TM_{WOT}}(5) = 4{,}0 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 7{,}0$$
$$\alpha_{TM\_WOT} = 4{,}5$$
$$\Delta t_{TM_{WOT}}(6) = 4{,}5 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 7{,}875$$
$$\alpha_{TM\_WOT} = 5{,}0$$
$$\Delta t_{TM_{WOT}}(7) = 5{,}0 \cdot (0{,}5 + 0{,}5 + 0{,}5 \cdot min\{0{,}5, 0{,}5\} + 0{,}5 \cdot 0{,}5 \cdot 0{,}5 + 0{,}5 \cdot 0{,}5 \cdot 1{,}0 + 0{,}5 \cdot 0{,}5 \cdot 0{,}5) = 8{,}75$$

The analytical calculations presented above represent two extreme cases. Checking a more significant number of possible combinations of solutions requires extensive data collection and scenario analyse for plausible sets of conditions.

The factors influencing delays of operations in the terminal, proposed through the expert method and presented in tables 1-14, as well as formulas (6) and (7), are used to determine the maximum and minimum values of delays. On this basis, four ranges of acceptability were assumed. Risk management and reliability standards and others define the number of ranges.
To assess the obtained calculation results, the acceptability ranges of the solution can be assumed. Table 15 presents the accepted ranges of acceptability along with the delay acceptance category.
Two calculation examples covering extreme cases are presented, i.e. the variant causing the most significant delays in the operation of the terminal and the variant that results in the most minor delays. For the first variant characterised by the most significant delays (level 1), the maximum values of all 14 parameters were assumed. In the case of the second variant, the minimum values of the parameters determining the slightest delays in the implementation of the terminal's tasks were adopted. Examination of the extreme values of the task parameters made it possible to estimate the variability range of potential delays in the facility's operation.

Table 15 Acceptability ranges and delay acceptance categories

Acceptability range	Delay acceptance categories
small <300-390)	Not tolerated
medium <200-300)	Undesirable
large <100-200)	Tolerable
very high (0.5-100)	Negligible

Next, the remaining variants of parameter variability should be analysed. The number of 14 used parameters affecting the quality of the terminal's operation, the range of their variability and their stochastic nature make the task computationally complex. An essential element of the work is obtaining information or researching to determine the actual delays adopted by the authors using the expert method. This would allow validation and extension of the proposed method.
The practical application of the method allows for the optimisation of terminal operation from the point of view of minimising delays that may result from reasons related to technical equipment, human resources, maintenance of technical infrastructure and other factors presented in the article.

5. Conclusions

The proposed risk mapping method in multimode transport systems presented in the article is based on theoretical assumptions. This method can help optimize the operation of multimodal transport systems (e.g. minimize time losses), which in their structure use, apart from transport subsystems, also nodal infrastructure like intermodal or transhipment terminals. The application of proposed approach will lead to selecting appropriate operating parameters of multimodal systems framed on rail and road transport subsystems and with internal transport integrating these branches with the entire technical infrastructure used for cargo work.
The presented method creates a universal framework for estimating the risk associated with lowering the quality of transport services, expressed mainly by the timeliness of deliveries. Timeliness is and remains a key factor in assessing material flow reliability in supply chains. It is of great importance for the propagation of disturbances in supply chains (bullwhip effect), which is considered a fundamental factor. However, this framework can be extended to include factors related to the safety of the cargo (quality) and the safety of people and equipment. Safety is a factor that is particularly intensively studied in rail transport due to the formalized organizational and technological system of rail transport, therefore it is necessary to take it into account also at the stage of discussing issues related to the quality of transport services.
An important role in the area of risk mapping is played by the human factor, which is the main cause of disruptions in supply chains, and thus in the operation of multimode transport systems due to the decisive role of humans. For this reason, the method takes into account factors such as employee competencies, including e.g. age, seniority and education of employees employed to operate the terminals. Consideration of such factors is not common in methodological research on multimodal transport systems on a large scale due to the difficulties associated with the quantification of the human factor.
The next step in order to expand and validate the proposed method will be research on determining the delay times for the adopted parameters. The obtained information will make the theoretical assumptions more realistic.

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