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RISK ASSESSMENT IN RAILWAY ROLLING STOCK PLANNING

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Abstract:

Rolling stock planning is one of the steps in the traffic planning process considered from the railway undertaking's point of view. It is directly related to the efficiency of rolling stock utilisation, which should be ensured at the highest possible level in the case of rail transport. The planning work stage is subject to certain risks (threats and opportunities), which, if they materialise, will impact it. It, therefore, makes sense to carry out analyses that can anticipate specific events in good time and introduce appropriate countermeasures in advance. This article aims to conduct a risk assessment process concerning rolling stock planning. It was assumed that the considerations were carried out based on the M_o_R (Management of Risk) methodology. Based on this methodology, risk identification and risk analysis (estimation of risk impact) were carried out. Risk assessment was carried out using the Monte Carlo simulation method. The work identified sixteen risks that represent threats. The principle of risk description was used to identify risks. It requires indicating for each risk the reason for its occurrence and the effect it may have. As a part of risk estimation, variables were selected to assess each risk's impact on the objectives of the stage. Publicly available statistical data were used to define the variables. The variables were expressed in monetary units. The work identified five variables describing impact, which were assigned to the individual risks. As a triangular probability distribution was used for the variability of impact description, the variable's minimum, most likely, and maximum value was identified. A risk assessment was carried out for only two impact description variables (for those variables used to describe the impact of the most significant number of risks). For each variable, statistical parameters were indicated and analysed. The resulting value of the variable describing the impact was then read out for each percentile, and the expected value of the risk was calculated. A detailed risk assessment was made for the lower, middle and upper quartiles. A histogram of the incidence of each variable value was presented, and an assessment was made.

Keywords: *railway rolling stock planning, risk assessment, risk identification, risk impact estimation, Monte Carlo method*

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1. Introduction

Every activity is exposed to risk, that is, the possibility of events which, if they occur, will have an impact (positive or negative) on its objectives (AXELOS Ltd., 2010). The same is true for the rolling stock planning carried out by the railway undertakings (both passenger and freight). If carried out correctly, it directly impacts the efficiency of rolling stock utilisation. The materialisation of negative risks may have serious consequences, affecting the undertaking's profits. Therefore, conducting analyses to identify risks and assess their impact and influence on the planning process is reasonable. It will allow, among other things, an assessment of the possibility of implementing measures at an early enough stage to prevent the possibility of the risk materialising, as well as the specification of appropriate responses to the risk should it materialise, which will need to be implemented at an early enough stage.

Rolling stock planning is one of the seven stages (the fifth one) of the traffic planning process considered from the railway undertaking's point of view (Goossens, van Hoesel, & Kroon, 2006). It takes place based on the train timetable produced by the infrastructure manager (the work outputs in the fourth stage of the traffic planning process). The findings of the fifth stage provide the input for the seventh stage - planning shunting and maintenance work. Consequently, every effort should be made to maintain the highest degree of safety (Burdzik, Nowak, Rozmus, Słowiński, & Pankiewicz, 2017), i.e. by conducting a risk analysis. A literature analysis of both Polish-language and English-language works found that no publications address the issue of risk analysis in rolling stock planning. There are, however, references to risk management in the following areas, among others:

- control command and signalling devices (Celiński, Burdzik, Młyńczak, & Kłaczyński, 2022), (Kycko, Kukulski, & Pawlik, 2021), (Kycko & Zabłocki, 2017), (Lewiński, Toruń, & Perzyński, 2011),
- rail transport infrastructure (Bałuch, 2007), (Kukulski, Gołębiowski, Makowski, Jacyna-Gołda, & Żak, 2021), (Liu & Dick, 2016), (Smoczyński & Kadziński, 2016),
- implementation of railway freight transport (Gołębiowski, Jacyna, & Stańczak, 2021), (Kwaśnikowski, Gill, & Gramza, 2011), (Semenov i Jacyna, 2022), (Szaciłło, Jacyna, Szczepański, & Izdebski, 2021), (Szaciłło, Krześniak, Jasiński, & Valis, 2022),
- rolling stock fleet development (Sitarz, Chruzik, Banaszek, & Raczyński, 2016),
- rail traffic safety (Baranovskyi, Muradian, & Bulakh, 2021), (Zhao, Martin, Cui, & Liang, 2017),
- traction power supply problems (Chovančíková & Dvořák, 2019), (Urbaniak & Kardas-Cinal, 2022),
- traffic at level crossings (Berrado, El-Koursi, Cherkaoui, & Khaddour, 2010),
- health issues concerning rail transport (Burdzik, 2021),
- the use of ICT tools in rail traffic (Paś, Rosiński, Chrzan, & Białek, 2020).

The main EU document related to the issue of risk in rail transport is the European Commission Regulation 402/2013 (European Commission Regulation 402/2013, 2013), which established Common Safety Methods for the valuation and assessment of risks in rail transport. Its main objective was to introduce uniform risk management processes in railway organisations, such as a railway undertaking (railway operator) or an infrastructure manager. The guidelines relating to this regulation (Office of Rail Transport, 2022b) indicate several techniques which can be used to identify, value and assess risks (PN-EN IEC 31010:2020-01, 2020). It guides recommendations for using particular methods concerning Regulation 402/2013. However, there are no recommendations for other spheres of rail transport activity. As planning the operation of rolling stock is related to safety in rail transport, the recommendations in the document above should be used.

The Office of Rail Transport guide (Office of Rail Transport, 2022b), as well as other studies (e.g. (Stelmach, Góra, & Zięba, 2022), indicate that recommended risk assessment methods include:

- FMEA Method (Failure Mode and Effect Analysis) (Jacyna & Szaciłło, 2017),
- HAZOP Method (Hazard and Operability Study) (Chruzik, 2014); this method uses so-called risk matrices (Karasiewicz, 2019) (Szaciłło, Jacyna, Szczepański, & Izdebski, 2021),
- FTA Method (Fault Tree Analysis) (Bester & Toruń, 2014),

- ETA Method (Event Tree Analysis) (Kim, Wang, Park, & Cho, 2009),
- PHA Method (Berrado, El-Koursi, Cherkaoui, & Khaddour, 2010); this method uses so-called risk matrices (Karasiewicz, 2019), (Szaciłło, Krześniak, Jasiński, & Valis, 2022),
- Brainstorming (Boholm, 2010),
- SWIFT Method (What – If?) (Mateu, Fernández, & Franco, 2021),
- Checklist (Zou & Li, 2010),
- Ishikawa diagram (Zajac & Swieboda, 2015).

Probabilistic risk models have received relatively little attention in the literature on risk analysis in rail transport. By taking advantage of the possibility of determining the values of variables in a random (probabilistic) manner in favour of giving up deterministically determined quantities, the possibilities for research in this area expand. It also involves a more real possibility of describing probabilistic risks. Using appropriate probability distributions makes it possible to predict the occurrence of events that may not have been considered in standard analysis. It will result in better responses to the possibility of a particular risk occurring. Therefore, for this article, risk assessment in rolling stock planning was performed using the Monte Carlo simulation method (Harrison, 2010), (Zio, 2013). This method is strongly recommended for risk assessment by the Office of Rail Transport guide (Office of Rail Transport, 2022b).

This paper aims to conduct a risk assessment process concerning rolling stock planning. It was assumed that the considerations carried out in this paper were based on the M_o_R (Management of Risk) methodology (AXELOS Ltd., 2010), which Axelos developed based on the experience of UK entrepreneurs. Based on this methodology, risk identification and risk analysis (estimation of risk impact) were carried out. Risk assessment was carried out using the Monte Carlo simulation method. In order to achieve this research objective, the following scope of work was carried out. Section one provides an introduction to the issues addressed in the paper. Section two presents the essence of rolling stock planning. Section three presents the method that was used for risk assessment, together with its formal notation. Section four identifies the risks estimated in section five and then evaluated using the Monte Carlo method in section six. Section seven provides a summary of the research conducted in this article.

2. The essence of the rolling stock planning

In order to realise the assumed train timetable, it is necessary to plan the work of rolling stock rationally - traction vehicles (with propulsion - locomotives, multiple units, rail buses and diesel buses) and trainsets (assembled railway vehicles without active traction vehicles). It involves the preparation of two documents: an operational plan for traction vehicles and trainsets circuits. The operational plan for traction vehicles can be expressed in two forms: figure circuits and flat circuits, while trainset circuits are usually drawn up in the form of flat circuits (Jacyna, Gołębiowski, Krześniak, & Szkopiński, 2019).

The operational plan for traction vehicles defines the sequence of trains that a traction vehicle can serve. The set of trains that a given traction vehicle can serve is created based on a previously developed timetable (both preliminary and as a result of traffic planning on the network). The train allocation to a given traction vehicle should take into account (Jacyna, Gołębiowski, Krześniak, & Szkopiński, 2019):

- parameters assumed in the timetable, based on which the train running time was established (e.g. type and weight of the train),
- parameters of the trainset from which it consists,
- parameters of the railway routes on which the train will run (among others, profiles of the line, the strength of the surface and bridges),
- the driver's qualifications (knowledge of, among others, the line sections, vehicles or language).

The work of a given traction vehicle shall start and end at its home locomotive depot (or electric locomotive depot) (the locomotive depot / electric locomotive depot to which it is assigned). The place where traction vehicle terminates after operating a specific train is referred to return station, or in the case of a descent into a locomotive depot, as the return locomotive depot. A vehicle should return to its home locomotive depot no later than the expiry of the maintenance interval (expressed in days or hours) for the first level of maintenance (former control inspection).

When planning the operation of traction vehicles, adequate time should be added:

- before the vehicle starts operating the first train, related to the preparation of the vehicle for train operation (time counted from the moment the

driver starts the vehicle to the moment of declaring the readiness to depart with the first train at the departure station),
- for service of the traction vehicle in the return station,
- after operating the last train designated in the operational plan until the driver switches off the vehicle,
- to carry out the appropriate maintenance levels of the traction vehicles, particularly maintenance level 1 (former control inspection), in good time.

The trainset operational plan, or trainset circulation, determines the train sequence a vehicle serves. In the first instance, the allocation of the trains to be served by a given trainset should be made. This allocation should be made based on a previously prepared timetable. A trainset, from the point of view of the railway traffic planning problem, should meet the following conditions (Jacyna, Gołębiowski, Krześniak, & Szkopiński, 2019):
- should be consisted of railway vehicles that are suitable for this train and incorporated into the main line of the brake,
- the length and weight of the trainset should be that for which the timetable has been prepared by infrastructure manager, possibly less,
- the train composition should be configured according to the train composition plan (the train composition should respect the order of cars and compatibility with the type - especially in case of trains with places reservation; in case of necessity of changing a car, it should be ensured that the number of reservation places is not smaller than planned),
- the length of trainsets should not be longer than 300 m and should be adapted to the length of platforms at which the train is scheduled to stop,
- a train length of more than 300 m and not more than 400 m is permissible if the correct length of platforms is maintained, the brake on the train is fast acting, and all vehicles have the correct type of buffers.

The circulation of a trainset starts and ends at its home stabling station (the stabling station to which it is assigned). The place of termination of a given trainset after service of a particular train is referred to as the return station or, in the case of descent into a stabling station, return stabling station. A trainset shall return to its home stabling station no later than the expiry of the intermediate time (expressed in days or hours).

Adequate time must be added when planning the operation of trainsets:
- before the trainset starts operating the first train, related to the preparation of it for train operation,
- for service of the trainset in the return station,
- after operating the last train designated in the operational plan,
- to carry out the appropriate maintenance levels of the vehicles constituting the trainset at the appropriate time.

A traction vehicle can have a similar circuit to a trainset. However, it should be noted that nowadays, due to the small number of active traction vehicles, optimisation (rationalisation) of the allocation of vehicles to trainsets is used.

In the literature, the analysed problem is called the Rolling Stock Circulation Problem - RSCP. Researchers have addressed the following issues related to this problem:
- review of models and methods for solving the problem (review article) (Caprara, Kroon, Monaci, Peeters, & Toth, 2007),
- the application of different approaches to solving the RSCP problem, including branch-and-price (Peeters & Kroon, 2008), linear programming (Mo, et al., 2020), and artificial intelligence (Ying, Chow, & Chin, 2020),
- efficient rolling stock circulation consisting of pairing and pooling of rolling stock (Alfieri, Groot, Kroon, & Schrijver, 2006), also for passenger trains only (Fioole, Kroon, Maróti, & Schrijver, 2006) and energy efficiency (Mo, et al., 2020),
- reconsideration of the RSCP problem after a timetable change (Budai, Maróti, Dekker, Huisman, & Kroon, 2010), also in real-time after an adverse event (Wang, et al., 2021), and with dynamically changing passenger flows (Kroon, Maróti, & Nielsen, 2015),
- consideration of the RSCP problem for a specific area of the railway network, such as for high-speed urban rail systems (Canca, Sabido, & Barrena, 2014),
- considering the RSCP problem from a long-term (scheduling) point of view, taking into account different boundary conditions,

e.g. maintenance constraints (Giacco, D'Ariano, & Pacciarelli, 2014), as well as from a resilience point of view (Cacchiani, et al., 2012), (Cadarso & Marín, 2011),

- considering different types of rolling stock in the RSCP problem (Yuhua, Marcella, Pacciarelli, & Shaoquan, 2022),
- computer-aided RSCP problem (Ambroziak & Piętka, 2008), (Cordeau, Soumis, & Desrosiers, 2001),
- considering the RSCP problem together with other issues, such as, among others: the problem of locating the maintenance place for rolling stock (Canca & Barrena, 2018), (Zomer, Bešinović, de Weerdt, & Goverde, 2021), the problem of timetable construction (Michaelis & Schöbel, 2009), (Wang, et al., 2018), the delay management problem (Flier, Nunkesser, Schachtebeck, & Schöbel, 2008), the conductor team management problem (Wolniewicz, 2019).

3. Risk assessment method for rolling stock planning

Risk assessment in rolling stock planning will be carried out according to the developed method. The universal method assesses all stages of the railway traffic planning process (Goossens, van Hoesel, & Kroon, 2006). With some modifications, it can be used to evaluate other processes, not only in rail transport.

The developed method consists of three steps:

STEP 1 – the risks should be identified - both opportunities and threats, then proceed to STEP 2; the identification of risks was carried out according to the guide-lines of the M_o_R methodology (AXELOS Ltd., 2010) and is described in section 4 of this article,

STEP 2 – for each risk, an estimation of the impact of the risk on the objectives of the analysed process should be made, then proceed to STEP 3; the estimation of the impact was carried out based on publicly available statistical data and accepted variables describing the impact,

STEP 3 – simulation risk assessment should be carried out for each risk; this step com-pletes the method; the risk assessment will be carried out using the Monte Carlo method.

4. Risks in rolling stock planning

The identification of risks in rolling stock planning was carried out according to the guidelines of the M_o_R methodology (AXELOS Ltd., 2010) – the following were identified: the individual risks, the causes that could lead to the risks materialising, and the effects that the materialisation of the risks could cause:

- **RISK 1:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):
  - CAUSE: a type of rolling stock may be added to the set of trains operated by a given type of rolling stock, which may be inappropriate in terms of the parameters assumed in the timetable,
  - EFFECT: a situation may arise where railway undertakings have to transfer an unsuitable train from one planning set to another and reschedule the work of a given type of rolling stock, thereby having to do the same work twice,
- **RISK 2:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):
  - CAUSE: a type of rolling stock may be added to the set of trains operated by a given type of rolling stock, which may be inappropriate in terms of the parameters assumed in the timetable,
  - EFFECT: there may be a situation where the railway undertaking will have to revise the train timetable, which will require the same work to be done twice,
- **RISK 3:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):
  - CAUSE: a type of rolling stock may be added to the set of trains, which may not be suitable in terms of train composition parameters,
  - EFFECT: a situation may arise where railway undertakings have to transfer an unsuitable train from one planning set to another and reschedule the work of a given type of rolling stock, thereby having to do the same work twice,
- **RISK 4:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):

  - CAUSE: a type of rolling stock may be added to the set of trains, which may not be suitable in terms of train composition parameters,
  - EFFECT: there may be a situation where the railway undertaking will have to revise the train timetable, which will require the same work to be done twice,
- **RISK 5:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):
  - CAUSE: a type of rolling stock may be added to the set of trains, which may not be suitable in terms of the railway infrastructure parameters,
  - EFFECT: a situation may arise where railway undertakings have to transfer an unsuitable train from one planning set to another and reschedule the work of a given type of rolling stock, thereby having to do the same work twice,
- **RISK 6:** the scheduled operation of a given type of rolling stock may not be suitable (the circuits may be arranged incorrectly) (threat):
  - CAUSE: a type of rolling stock may be added to the set of trains, which may not be suitable in terms of the railway infrastructure parameters,
  - EFFECT: there may be a situation where the railway undertaking will have to revise the train timetable, which will require the same work to be done twice,
- **RISK 7:** the scheduled operation of a given type of rolling stock may not be suitable, as the number of units of rolling stock owned by the railway undertaking necessary to operate the assumed trains may be too low (threat):
  - CAUSE: too many trains may be added to the set of trains operated by a given type of rolling stock,
  - EFFECT: a situation may arise where the railway undertaking has to transfer an unsuitable train from one planning set to another (change of rolling stock type) and reschedule the work of a given rolling stock type, which will entail the same work twice,
- **RISK 8:** the timetable (journey times) determined based on the traction parameters of the rolling stock may not be appropriate (threat):
  - CAUSE: some trains may be operated by different rolling stock than assumed,
  - EFFECT: there may be a situation where the railway undertaking has to revise the train timetable, requiring the same work to be done twice,
- **RISK 9:** the timetable (journey times) determined based on the traction parameters of the rolling stock may not be appropriate (threat):
  - CAUSE: some trains may be operated by different rolling stock than assumed,
  - EFFECT: there may be delays on the railway network for which the railway undertaking will have to pay compensation to the infrastructure manager and, as a consequence, the timetable produced may be erroneous,
- **RISK 10:** it may not be possible to carry out a maintenance level 1 inspection (earlier control inspection) of a traction vehicle assigned to a circuit after its completion (threat):
  - CAUSE: the vehicle circuit may be incorrectly arranged,
  - EFFECT: a situation may occur where a traction vehicle cannot serve the specific train(s) foreseen in the operational plan, and vehicles may have to be substituted, which may generate additional costs; these costs can be expressed in terms of the amount of compensation due to delays caused by reasons grouped under "rolling stock",
- **RISK 11:** the vehicle to pick up the first train in the operational plan may not be prepared in due time (threat):
  - CAUSE: the vehicle operating plan may not allow sufficient time to receive the vehicle before operating the first train in the circulation plan,
  - EFFECT: the first train in the operating plan may be started late, and the railway undertaking may have to pay compensation for delays due to causes grouped as "rolling stock",

- **RISK 12:** there may not be enough time for the vehicle to "transition" from a terminating vehicle with one train to a starting train according to the operating plan (threat):
  - CAUSE: the vehicle operating plan may not allow sufficient time for the vehicle to transition from a train to a train at the turning station according to the circulation plan,
  - EFFECT: the next train in the operating plan may be started late, and the railway undertaking may have to pay compensation for delays due to causes grouped as "rolling stock",
- **RISK 13:** there may not be enough time for the vehicle to "transition" from a terminating vehicle with one train, which is delayed to a starting train according to the operating plan (threat):
  - CAUSE: the vehicle operating plan may not allow sufficient time for the vehicle to transition from a train to a train at the turning station according to the circulation plan,
  - EFFECT: the next train in the operating plan may be started late, and the railway undertaking may have to pay compensation for delays due to causes grouped as "rolling stock",
- **RISK 14:** the maximum driving time by one train driver may be exceeded, or train drivers may have to be substituted (threat):
  - CAUSE: the vehicle operating plan may not allow sufficient time for the vehicle to depart after having handled the last train in the working timetable,
  - EFFECT: a situation may arise where the railway undertaking may have to commit an additional traction crew to complete the circulation plan, thereby incurring increased operating costs related to human resources,
- **RISK 15:** maintenance activities within maintenance level 1 may not be carried out correctly (threat):
  - CAUSE: the vehicle operating plan may not allow sufficient time for the maintenance level 1 (earlier: control inspection) to be carried out carefully,
  - EFFECT: a situation may arise where the railway undertaking may have to engage an additional maintenance team to carry out maintenance level 1, thereby incurring increased operating costs related to human resources,
- **RISK 16:** the supply of seats may not be matched with the demand for travel (threat):
  - CAUSE: train composition may not be compiled according to the compilation plan,
  - EFFECT: there may be a partial loss of revenue for the railway undertaking as passenger needs may not be met at an adequate level.

It should be noted that some of the risks listed above are very unlikely (may occur with very low probability). Their occurrence may be due to factors that are unlikely to occur and difficult to predict - e.g. human error (action of the planner) or delay of a train operated by a particular vehicle. It is reasonable to carry out risk analyses using probabilistic models.

5. Estimating the impact of risk in rolling stock planning

Estimating the risks' impact on the specific project's objectives involves identifying risks. In order to be able to do this, it is necessary to identify variables that can be used to describe the impact of risks on the objective of a particular process. For the research carried out in this article, it was assumed that the following variables would be used to estimate the impact of risks:

- *SFPZL-1* – the amount of the railway undertaking's financial losses related to human resources wastage - 1 (for risks 1, 3, 5, 7),
- *SFPZL-2* – the amount of the railway undertaking's financial losses related to human resources wastage - 2 (for risks 2, 4, 6, 8, 14, 15),
- *REKPR* – compensation for delay to be paid by the railway undertaking to the infrastructure manager (for risk 9),
- *REKTAB* – the amount of compensation related to delays caused by causes grouped as "rolling stock" (for risks 10 – 13),
- *UCP* – loss of part of revenue (for risk 16).

The following publicly available statistics were used to define and calculate the individual variables (Office of Rail Transport, 2021b):

- unit revenue of the passenger railway undertaking per passenger in 2020 (*jp*) was 29,83 PLN/passenger,
- number of passengers carried in 2020 (*lpp*) was 209,399 million passengers/year,
- the passenger rail punctuality rate in 2020 (*wp*) was 94,62%,
- the number of trains launched per day by passenger railway undertakings in 2020 (*lp*) was 4319 trains/day,
- average delay time in 2020 (*sropozn*) was 8,3 minutes/train (8 minutes and 18 seconds) (Office of Rail Transport, 2021a),
- compensation per minute of delay in 2021 (*wrek*) was 5,55 PLN/minute (PKP Polskie Linie Kolejowe S.A., 2020),
- the fault of the railway undertaking as the perpetrator of delays in 2020 (*winapr*) was confirmed for 33,9% of delays (Office of Rail Transport, 2021a),
- causes grouped as "rolling stock" in 2020 were the generator in the case of 25,54% of delays (*winatab*) (Office of Rail Transport, 2021a),
- the average salary in Poland in 2021 (*pw*) was 5662,53 PLN/month (Zakład Ubezpieczeń Społecznych, 2022).

Furthermore, as recommended in the M_o_R methodology manual (AXELOS Ltd., 2010), it was assumed that triangular probability distribution would describe the variables describing the impact. Therefore, for each variable, its characteristic values - minimum value, desired value and maximum value - should be indicated.

It was assumed that the value of the variable describing the impact of the "amount of the railway undertaking's financial losses related to human resources wastage - 1" (*SFPZL-1*) would be equal to the average salary in Poland (*pw*). The result must be multiplied by 12 to express the annual losses per unit. It can be expressed using the formula (1) (the symbols are explained at the beginning of the section).

$$SFPZL-1 = pw \cdot 12 \quad [\text{million PLN/year}] \tag{1}$$

The variable *SFPZL-1* takes the value of 0,068 million PLN/year. The calculated value should be multiplied by the share of time needed to perform a given activity in the monthly working time to obtain characteristic values. The minimum value of the variable *SFPZL-1* – $SFPZL\text{-}1_{\min}$ is the average salary multiplied by 10% (it is assumed that a minimum of 10% of the monthly working time is needed per shift). Therefore $SFPZL\text{-}1_{\min}$ = 0,0068 million PLN/year. The maximum value of variable *SFPZL-1* – $SFPZL\text{-}1_{\max}$ is the average salary multiplied by 50% (it was assumed that a minimum of 50% of monthly working time is needed per shift). Therefore, $SFPZL\text{-}1_{\max}$ = 0,034 million PLN/year. The desired value of the variable *SFPZL-1* – $SFPZL\text{-}1_{\text{mid}}$ is the average salary in Poland (*SFPZL-1*) multiplied by 30% (it was assumed that a minimum of 30% of monthly working time is needed per shift). Therefore, $SFPZL\text{-}1_{\text{mid}}$ = 0,02 million PLN/year.

It was assumed that the value of the variable describing the impact of the "amount of the railway undertaking's financial losses related to human resources wastage - 2" (*SFPZL-2*) would be equal to the average salary in Poland (*pw*). The result must be multiplied by 12 to express the annual losses per unit. It can be expressed using the formula (2) (the symbols are explained at the beginning of the section).

$$SFPZL-2 = pw \cdot 12 \quad [\text{million PLN/year}] \tag{2}$$

The variable *SFPZL-2* takes the value of 0,068 million PLN/year. The calculated value should be multiplied by the share of time needed to perform a given activity in the monthly working time to obtain characteristic values. The minimum value of the variable *SFPZL-2* – $SFPZL\text{-}2_{\min}$ is the average salary multiplied by 5% (it is assumed that a minimum of 5% of the monthly working time is needed per shift). Therefore $SFPZL\text{-}2_{\min}$ = 0,0034 million PLN/year. The maximum value of variable *SFPZL-2* – $SFPZL\text{-}2_{\max}$ is the average salary multiplied by 15% (it was assumed that a minimum of 15% of monthly working time is needed per shift). Therefore, $SFPZL\text{-}2_{\max}$ = 0,01 million PLN/year. The desired value of the variable *SFPZL-2* – $SFPZL\text{-}2_{\text{mid}}$ is the average salary in Poland (*SFPZL-2*) multiplied by 10% (it was assumed that a minimum of 10% of monthly working time is needed per shift). Therefore, $SFPZL\text{-}2_{\text{mid}}$ = 0,0068 million PLN/year.

It was assumed that the value of the variable describing the impact: "compensation for delay to be paid by the railway undertaking to the infrastructure manager" (*REKPR*), should be calculated using theformula (3) (the symbols are explained at the beginning of the section).

$$REKPR = \left(\left(\left((1 - wp) \cdot lp\right) \cdot sropozn \cdot wrek\right) \cdot winapr\right) \cdot 365 \quad [\text{million PLN/year}] \tag{3}$$

The variable *REKPR* takes the value of 1,324 million PLN/year. The calculated value must be multiplied by the corresponding value of the non-punctuality index (see Table 15 in (Office of Rail Transport, 2021b)) and expressed as a percentage to obtain the characteristic values. The minimum value of the variable *REKPR* – $REKPR_{\text{min}}$ is the compensation multiplied by the smallest value of the non-punctuality index – 0%. Therefore $REKPR_{\text{min}}$ = 0 million PLN/year. The maximum value of variable *REKPR* – $REKPR_{\text{max}}$ is the compensation multiplied by the highest value of the non-punctuality index – 13,6%. Therefore $REKPR_{\text{max}}$ = 0,18 million PLN/year. The desired value of the variable *REKPR* – $REKPR_{\text{mid}}$ is the compensation multiplied by the average value between the largest and smallest values of the non-punctuality index – 6,8%. Therefore $REKPR_{\text{mid}}$ = 0,09 million PLN/year.

It was assumed that the value of the variable describing the impact: "the amount of compensation related to delays caused by causes grouped as "rolling stock"" (*REKTAB*), should be calculated using the formula (4) (the symbols are explained at the beginning of the section).

$$REKTAB = \left(\left(\left((1 - wp) \cdot lp\right) \cdot sropozn \cdot wrek\right) \cdot winatab\right) \cdot 365 \quad [\text{million PLN/year}] \tag{4}$$

The variable *REKTAB* takes the value of 0,998 million PLN/year. The calculated value must be multiplied by the corresponding value of the non-punctuality index (see Table 15 in (Office of Rail Transport, 2021b) and expressed as a percentage to obtain the characteristic values. The minimum value of the variable *REKTAB* – $REKTAB_{\text{min}}$ is the compensation multiplied by the smallest value of the non-punctuality index – 0%. Therefore $REKTAB_{\text{min}}$ = 0 million PLN/year. The maximum value of variable *REKTAB* – $REKTAB_{\text{max}}$ is the compensation multiplied by the highest value of the non-punctuality index – 13,6%. Therefore $REKTAB_{\text{max}}$ = 0,136 million PLN/year. The desired value of the variable *REKTAB* – $REKTAB_{\text{mid}}$ is the compensation multiplied by the average value between the largest and smallest values of the non-punctuality index – 6,8%. Therefore $REKTAB_{\text{mid}}$ = 0,068 million PLN/year.

It was assumed that the value of the variable describing the impact: "loss of part of revenue" (*UCP*), the number of passengers carried (*lpp*) should be multiplied by the unit revenue of the railway undertaking (*jp*). It can be expressed using the formula (5).

$$UCP = lpp \cdot jp \quad [\text{million PLN/year}] \tag{5}$$

The variable *UCP* takes the value of 6246,37 million PLN/year. In order to obtain characteristic values, the calculated value should be multiplied by the increase in the number of passengers transported between 2000 and 2019, expressed in percentage terms (Office of Rail Transport, 2022). The minimum value of the variable *UCP* – UCP_{min} is the total revenue multiplied by the smallest decrease in the number of passengers carried – 0,48%. Therefore UCP_{min} = 29,9 million PLN/year. The maximum value of variable *UCP* – UCP_{max} is the total revenue multiplied by the largest decrease in the number of passengers carried – 8,46%. Therefore UCP_{max} = 528,4 million PLN/year. The desired value of the variable *UCP* – UCP_{mid} is the total revenue multiplied by the average value between the largest and smallest decrease in the number of passengers carried – 3,99%. Therefore UCP_{mid} = 249,2 million PLN/year.

6. Rolling stock planning risk assessment

For this article, it was assumed that the risk assessment would be presented for the two selected variables that describe the most risks. Thus, the assessment was performed for the variables *SFPZL-2* and *REKTAB*.

The data in section 5 of the article assessed the risks using the Monte Carlo method described with the *SFPZL-2* variable. The simulations resulted in the following statistical parameter results:

- average value – *m*(*SFPZL-2*) = 0,006682843 million PLN/year,
- number of trials – *n*(*SFPZL-2*) = 1000,

- standard error – *SE*(*SFPZL-2*) = 0,0000413899 million PLN/year,
- minimum value – *min*(*SFPZL-2*) = 0,003523057 million PLN/year,
- maximum value – *max*(*SFPZL-2*) = 0,009849588 million PLN/year,
- median – *Me*(*SFPZL-2*) = 0,006709741 million PLN/year,
- range – *R*(*SFPZL-2*) = 0,006326531 million PLN/year,
- standard deviation – *SD*(*SFPZL-2*) = 0,00130952 million PLN/year,
- variance – SD^2(*SFPZL-2*) = 0,00000171484 (million PLN/year)^2,
- skewness – *SKE*(*SFPZL-2*) = -0,04,
- kurtosis – *K*(*SFPZL-2*) = 2,44.

The simulation (1,000 trials) produced a median value for the variable with the interpretation of the amount of the railway undertaking's financial losses related to human resources wastage - 2 of approximately 0,0067 million PLN/year, which varied by 0,00004 million PLN/year depending on the trial (standard error). The median value reached approximately 0,0067 million PLN/year. The minimum value of the variable was recorded at around 0,0035 million PLN/year, and the maximum at 0,0098 million PLN/year. The range was, therefore, approximately 0,0063 million PLN/year. The standard deviation is relatively low, representing approximately 19% of the mean value. The variance assumes a low value, i.e. the results of individual observations are pretty far from the average value. The resulting distribution is left-asymmetric and leptokurtic - the intensity of extreme values is higher than for a triangular distribution.

The risk assessment for the *SFPZL-2* variable in rolling stock planning is shown in Table 1 and illustrated in Figure 1.

The minimum expected risk value assumes 0 million PLN/year (probability assessment 0%, impact assessment 0,0035 million PLN/year), and the maximum 0,0099 million PLN/year (probability assessment 100%, impact assessment 0,0099 million PLN/year). Assuming probability assessment at the level of the middle quartile, the impact value can be estimated at 0,0067 million PLN/year, which allows for an expected value - a risk assessment of 0,0034 million PLN/year. Thus, with a probability of 50%, the expected value is less than 0,0034 million PLN/year. Assuming probability assessment at the level of the lower quartile, the impact value can be estimated at 0,0058 million PLN/year, which allows for estimating the expected value - risk assessment at the level of 0,0014 million PLN/year. Thus, with a probability of 25%, the expected value is less than 0,0014 million PLN/year. Assuming probability assessment at the upper quartile level, the impact value can be estimated at 0,0076 million PLN/year, which allows for estimating the expected value - risk assessment at the level of 0,0057 million PLN/year. Therefore, with a probability of 75%, the expected value is less than 0,0057 million PLN/year.

A histogram of the incidence of individual values of the *SFPZL-2* variable is presented in Table 2 and Figure 2.

The variable's value at the middle quartile level - 0,007 million PLN/year has been generated around 111 times, so the probability of occurrence is 11.1%. The variable's value at the lower quartile level - 0,006 million PLN/year has been generated approximately 92 times, so the probability of occurrence is 9.2%. The variable's value at the upper quartile level - 0,008 million PLN/year has been generated around 82 times, so the probability of occurrence is 8.2%.

The data in section 5 of the article assessed the risks using the Monte Carlo method described with the REKTAB variable. The simulations resulted in the following statistical parameter results:

- average value – m(REKTAB) = 0,06838427 million PLN/year,
- number of trials – n(REKTAB) = 1000,
- standard error – SE(REKTAB) = 0,000854593 million PLN/year,
- minimum value – min(REKTAB) = 0,003849992 million PLN/year,
- maximum value – max(REKTAB) = 0,133448467 million PLN/year,
- median – Me(REKTAB) = 0,068180725 million PLN/year,
- range – R(REKTAB) = 0,129598474 million PLN/year,
- standard deviation – SD(REKTAB) = 0,027038132 million PLN/year,
- variance – SD2(REKTAB) = 0,000731061 (million PLN/year)2,
- skewness – SKE(REKTAB) = 0,04,
- kurtosis – K(REKTAB) = 2,47.

The simulation (1,000 trials) produced a median value for the variable with the interpretation of the amount of compensation related to delays caused by causes grouped as "rolling stock" of approximately 0,068 million PLN/year, which varied by 0,00085 million PLN/year depending on the trial (standard error). The median value reached approximately 0,068 million PLN/year. The minimum value of the variable was recorded at around 0,0038 million PLN/year, and the maximum at 0,133 million PLN/year. The range was, therefore, approximately 0,1296 million PLN/year. The value of the standard deviation is relatively high, about 40% of the mean value. The variance takes on a low value, i.e. the results of individual observations are quite far from the mean value. The resulting distribution is right-handedly asymmetric and leptokurtic - the intensity of the extreme values is higher than for a triangular distribution.

The risk assessment for the *REKTAB* variable in rolling stock planning is shown in Table 3 and Figure 3.

Table 1. The risk assessment for the SFPZL-2 variable in rolling stock planning

No.	**Percentile (probability assessment)**	**Variable value [million PLN/year] (impact assessment)**	**Expected value[million PLN/year] (risk assessment)**
1	0%	0,003523	**0**
2	5%	0,004497	**0,00022**
3	10%	0,004894	**0,00049**
4	15%	0,005261	**0,00079**
5	20%	0,005508	**0,0011**
6	**25%**	**0,005756**	**0,00144**
7	30%	0,005972	**0,00179**
8	35%	0,006165	**0,00216**
9	40%	0,006334	**0,00253**
10	45%	0,006506	**0,00293**
11	**50%**	**0,00671**	**0,00336**
12	55%	0,006856	**0,00377**
13	60%	0,00707	**0,00424**
14	65%	0,00722	**0,00469**
15	70%	0,007455	**0,00522**
16	**75%**	**0,007614**	**0,00571**
17	80%	0,007854	**0,00628**
18	85%	0,008104	**0,00689**
19	90%	0,008418	**0,00758**
20	95%	0,008878	**0,00843**
21	100%	0,00985	**0,00985**

Source: own work using RiskAMP (Structured Data LLC, 2022)

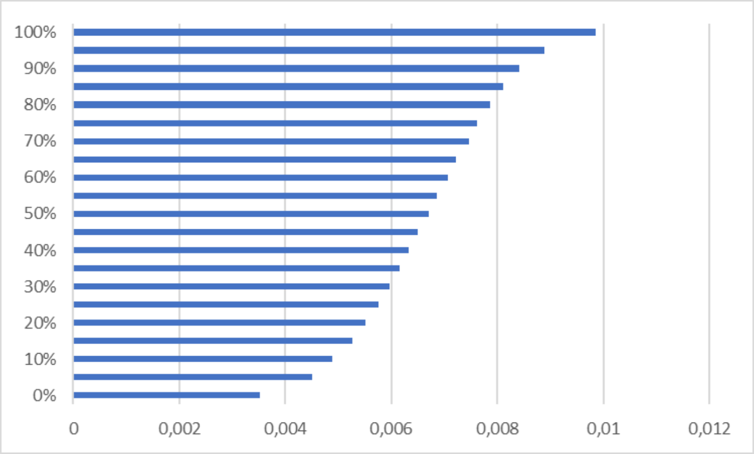

Fig. 1. Percentile distribution for variable *SFPZL-2* in rolling stock planning. Source: own work

Table 2. Histogram of the occurrence of individual values of the *SFPZL-2* variable in rolling stock planning

No.	**Variable value[million PLN/year] (impact assessment)**	**Frequency incidence of values**	**Probability of occurrence of a value**
1	0,0028	0	0,00%
2	0,0032	0	0,00%
3	0,0036	2	0,20%
4	0,004	16	1,60%
5	0,0044	22	2,20%
6	0,0048	45	4,50%
7	0,0052	56	5,60%
8	0,0056	77	7,70%
9	0,006	92	9,20%
10	0,0064	104	10,40%
11	0,0068	118	11,80%
12	0,0072	104	10,40%
13	0,0076	111	11,10%
14	0,008	82	8,20%
15	0,0084	65	6,50%
16	0,0088	49	4,90%
17	0,0092	35	3,50%
18	0,0096	19	1,90%
19	0,01	3	0,30%
20	0,0104	0	0,00%
21	0,0108	0	0,00%

Source: own work using RiskAMP (Structured Data LLC, 2022)

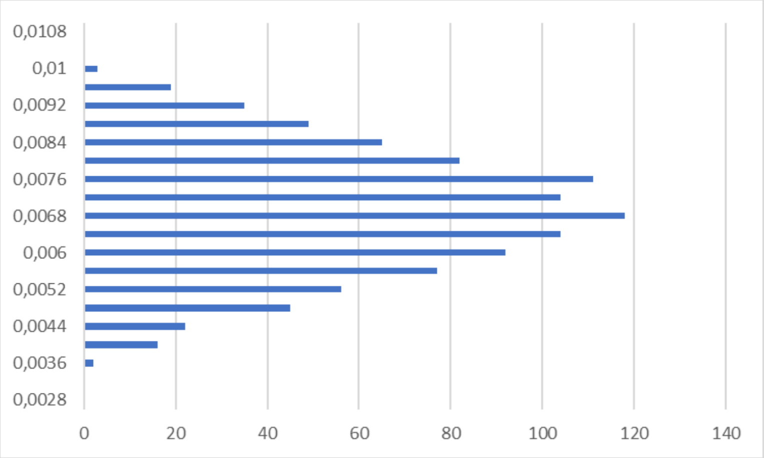

Fig. 2. Histogram of the occurrence of individual values of the SFPZL-2 variable in rolling stock planning. Source: own work

As can be seen from Fig. 7 and 8, with the same The minimum expected risk value assumes 0 million PLN/year (probability assessment 0%, impact assessment 0,0039 million PLN/year), and the maximum 0,1139 million PLN/year (probability assessment 100%, impact assessment 0,1139 million PLN/year). Assuming probability assessment at the level of the middle quartile, the impact value can be estimated at 0,0682 million PLN/year, which allows for an expected value - a risk assessment of 0,0341 million PLN/year. Thus, with a probability of 50%, the expected value is less than 0,0341 million PLN/year. Assuming probability assessment at the level of the lower quartile, the impact value can be estimated at 0,0491 million PLN/year, which allows for estimating the expected value - risk assessment at the level of 0,0123 million PLN/year. Thus, with a probability of 25%, the expected value is less than 0,0123 million PLN/year. Assuming probability assessment at the upper quartile level, the impact value can be estimated at 0,0868 million PLN/year, which allows for estimating the expected value - risk assessment at the level of 0,0651 million PLN/year. Therefore, with a probability of 75%, the expected value is less than 0,0651 million PLN/year.

A histogram of the incidence of individual values of the REKTAB variable is presented in Table 4 and Figure 4.

Table 3. The risk assessment for the REKTAB variable in rolling stock planning

No.	**Percentile (probabilityassessment)**	**Variable value [million PLN/year] (impact assessment)**	**Expected value [million PLN/year] (risk assessment)**
1	0%	0,00385	**0**
2	5%	0,022967	**0,00115**
3	10%	0,03128	**0,00313**
4	15%	0,039405	**0,00591**
5	20%	0,044926	**0,00899**
6	**25%**	**0,049086**	**0,01227**
7	30%	0,053579	**0,01607**
8	35%	0,057422	**0,0201**
9	40%	0,06125	**0,0245**
10	45%	0,064517	**0,02903**
11	**50%**	**0,068181**	**0,03409**
12	55%	0,07189	**0,03954**
13	60%	0,074624	**0,04477**
14	65%	0,077704	**0,05051**
15	70%	0,082093	**0,05747**
16	**75%**	**0,086818**	**0,06511**
17	80%	0,092697	**0,07416**
18	85%	0,099508	**0,08458**
19	90%	0,104966	**0,09447**
20	95%	0,113933	**0,10824**
21	100%	0,133448	**0,13345**

Source: own work using RiskAMP (Structured Data LLC, 2022)

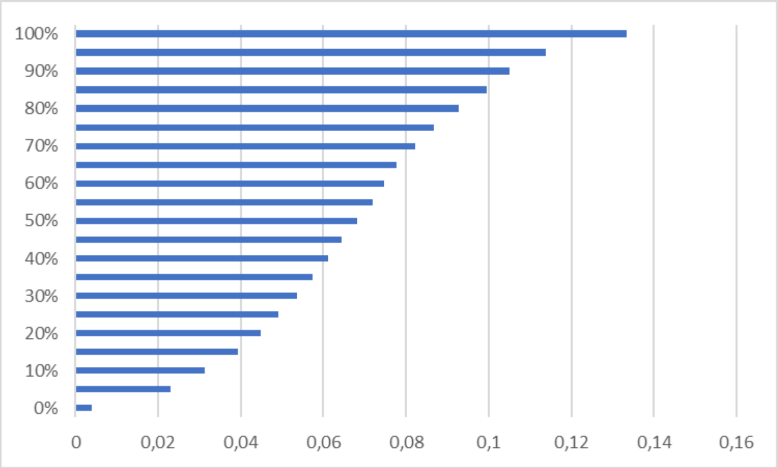

Fig. 3. Percentile distribution for variable *REKTAB* in rolling stock planning. Source: own work

Table 4. Histogram of the occurrence of individual values of the *REKTAB* variable in rolling stock planning

No.	**Variable value[million PLN/year] (impact assessment)**	**Frequency incidence of values**	**Probability of occurrence of a value**
1	0	0	0,00%
2	0,007	3	0,30%
3	0,014	11	1,10%
4	0,021	22	2,20%
5	0,028	44	4,40%
6	0,035	35	3,50%
7	0,042	55	5,50%
8	0,049	79	7,90%
9	0,056	79	7,90%
10	0,063	98	9,80%
11	0,07	97	9,70%
12	0,077	113	11,30%
13	0,084	90	9,00%
14	0,091	59	5,90%
15	0,098	55	5,50%
16	0,105	60	6,00%
17	0,112	40	4,00%
18	0,119	29	2,90%
19	0,126	21	2,10%
20	0,133	9	0,90%
21	0,14	1	0,10%

Source: own work using RiskAMP (Structured Data LLC, 2022)

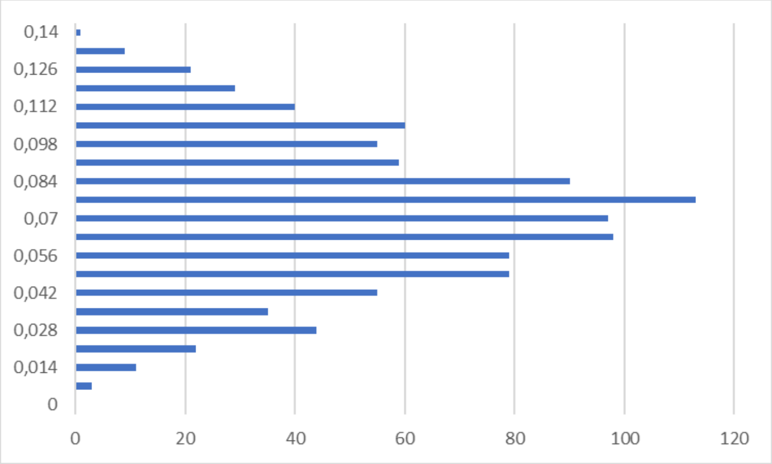

Fig. 4. Histogram of the occurrence of individual values of the REKTAB variable in rolling stock planning. Source: own work

The variable's value at the middle quartile level - 0,068 million PLN/year has been generated around 98 times, so the probability of occurrence is 11,2%. The variable's value at the lower quartile level - 0,049 million PLN/year has been generated approximately 79 times, so the probability of occurrence is 5,9%. The variable's value at the upper quartile level - 0,087 million PLN/year has been generated around 75 times, so the probability of occurrence is 6,9%.

7. Conclusions

Rolling stock planning is one of the steps in the traffic planning process considered from the railway undertaking's point of view. It is directly related to the efficiency of rolling stock utilisation, which, for railway undertakings, should be ensured at the highest possible level. The planning work stage is fraught with certain risks (threats and opportunities) which will affect it if they materialise. It, therefore, makes sense to carry out analyses that can anticipate specific events in good time and introduce appropriate countermeasures in advance.

Sixteen risks were identified as part of the work. All of them represent threats. The M_o_R methodology, which introduces the principle of risk description, was used to identify risks. It requires indicating for each risk the reason for its occurrence and the effect it has caused. The risks identified relate to, among other things, issues of circulation of a given rolling stock type, rolling stock constraints, maintenance levels, rolling stock transition times and seat supply. The effects of the occurrence of individual risks are expressed in monetary units. In the opinion of this article's authors, the essential risks have been identified to assess the risks of rolling stock planning.

As part of the risk estimation, variables were developed and used to assess the impact of individual risks on the process objectives. Publicly available statistical data were used to define the variables. Thus, the estimation method has no limitations regarding data access and forecasting the values of variables when new data are obtained for subsequent periods. The work identified five impact-describing variables, which were then assigned to individual risks. As a triangular probability distribution was used for the variability of the impact description, a minimum, most likely and maximum variable value was identified for each variable.

The risk assessment was carried out using the Monte Carlo simulation method. Due to the volume of article, an assessment was made for only two variables describing the impact (for those variables that were used the most times to describe the impact). For each variable, statistical parameters were indicated and analysed. Then, for each percentile, the obtained value of the variable describing the impact was read, and the expected risk value was calculated. A detailed risk assessment was made for the lower, middle and upper quartiles. A histogram of the incidence of each variable value was also presented and assessed.

The assessment method presented in this article is universal. It can be used to assess other stages of the railway traffic planning process and other processes in rail transport and beyond.

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