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Decoding rail derailments: Unraveling the weighted factors influencing safety and sustainability using the best-worst method

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ABSTRACT

The rail network is essential for sustainable transportation, offering various advantages such as reduced greenhouse gas emissions and congestion relief. However, ensuring safety within the rail network is crucial for its long-term viability and public acceptance. Derailment incidents have significant implications for safety, efficiency, and sustainability. This study employs the Best-Worst Method (BWM) to identify and weigh the parameters affecting derailment incidents. The research methodology involved conducting an extensive literature review to extract influential parameters, which were subsequently classified. Additionally, a rigorous data collection process was undertaken to ensure the reliability of the findings. The BWM was then applied, utilizing the expertise of five carefully selected domain experts who met specific selection criteria based on their experience and reputation in the field of railway safety. This expert panel provided valuable insights to determine the relative importance of the identified parameters. The calculated weights revealed the criticality of factors such as fractures in railway lines, illegal rail width, unauthorized locomotive speed, and defects in wagon wheels. Conversely, falling cargo train parts, improper load distribution, and subsidence of the railway line had relatively lesser influence. The results of this study offer valuable information for decision-makers and stakeholders in the rail industry, facilitating resource allocation and the implementation of targeted strategies to enhance rail safety.

1. Introduction

The rail network plays a crucial role in sustainable transportation, offering numerous benefits such as reduced greenhouse gas emissions [1], energy efficiency [2,3], and congestion relief [4]. It provides an efficient mode of transportation for passengers and freight, contributing to the overall sustainability and resilience of the transportation system [5–7]. However, it is paramount to maintain safety within the rail network to ensure the long-term viability and public acceptance of this mode of transportation [8]. Safety measures protect the lives of passengers and workers, safeguard infrastructure investments, and maintain public confidence in rail travel [9]. Freight accidents such as the Neishabur Line (Iran, 2004) [10], Fukuyama Line (Japan, 2012) [11], and Jiao-Ji Line (China, 2015) [11] demonstrate the importance of maintaining safety and integrity in railway lines. By prioritizing safety and implementing robust safety management systems, it can be ensured that the rail network continues to serve as a sustainable and reliable mode of transportation for generations to come.

Derailment incidents pose significant threats to transportation systems' safety, efficiency, and sustainability [12]. Understanding the factors leading to derailments and accurately assessing these variables is crucial for implementing effective preventive measures [13]. Derailment occurs when train wheels unintentionally leave the tracks, resulting in accidents and disruptions within the transportation system, with potential consequences such as loss of life, injuries, property damage, and economic losses. Statistical data from 2020 reveals that the

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Canadian rail transportation system experienced 965 derailment accidents, causing 38 injuries [14]. Similarly, in 2022, the United States witnessed a notable 1164 train derailments, resulting in 5871 injuries [15]. These figures underscore the significant toll of derailments on lives, property, and the economy of affected countries. Given their profound impact, it is important to analyze the contributing factors to derailments. By identifying and comprehending these factors, policymakers, engineers, and transportation authorities can implement targeted measures to prevent derailments, enhance safety, and improve the overall efficiency and sustainability of transportation networks [16].

In this regard, a systematic and quantitative approach is essential for prioritizing factors affecting derailment incidents [17]. Assigning appropriate weights to parameters associated with derailment enables decision-makers to allocate resources effectively and focus on the most influential factors. These parameters might be track conditions, train speed, maintenance practices, crew training, weather conditions, and cargo characteristics within the railway system [18]. In the past decades, utilizing multi-criteria decision-making (MCDM) methods applied various decision making problems [19–23] and offer a robust framework for parameter weighting in complex decision problems [24–26]. The MCDM techniques such as the Chang method [27–29], Analytic Hierarchy Process (AHP) [30,31], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [32,33], and best-worst method (BWM) [34] enable decision-makers to evaluate multiple criteria concurrently and establish priority rankings. MCDM methods integrate expert judgments and quantitative data, providing a comprehensive and objective approach to parameter weighting [35].

Several studies have explored factors influencing accidents in railway systems [36–39]. These studies utilize various MCDM methods to evaluate factors like track conditions, train speed, crew training, and weather conditions. Their findings contribute to understanding derailment prevention and prioritizing risk mitigation strategies. However, it's important to justify this further by noting gaps in current literature. While existing research has examined factors contributing to derailments, there's still a need for more comprehensive investigations. This includes applying MCDM methods specifically to derailment incidents and considering the impact of emerging technologies on derailment risks. Additionally, a more thorough evaluation of human, technical, and infrastructure factors is warranted. Addressing these gaps will enhance understanding of derailment parameters and improve preventive measures.

The present study employed the BWM for (MCDM due to its numerous advantages over other methods. Furthermore, BWM was chosen because it excels in handling complex decision problems involving a large number of criteria and alternatives. The BWM is a prominent MCDM approach that offers advantages in parameter weighting [40]. The BWM allows decision-makers to identify the best and worst parameters regarding their impact on derailment incidents. By focusing on both extremes, the BWM provides a more comprehensive perspective and avoids potential biases that may arise in other weighting methods [41]. Moreover, the BWM enables accurate calculation of weights, enhancing the reliability and validity of the results [42].

In comparison to the AHP, BWM offers a more comprehensive comparison by explicitly capturing the best and worst options, which is especially beneficial when dealing with a high number of criteria and alternatives [43]. Additionally, when compared to the TOPSIS, BWM provides a more balanced perspective by considering both the best and worst alternatives, thus reducing potential bias [44]. Moreover, BWM surpasses methods like Elimination and Choice Translating Reality (ELECTRE) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) by incorporating extreme values, allowing for a more precise assessment of the best and worst options and yielding more reliable rankings [45]. Similarly, in contrast to VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), which does not differentiate between the best and worst alternatives, BWM's explicit consideration of both extreme options provides decision-makers with a more comprehensive understanding of the decision problem, enhancing decision quality [46]. Finally, when compared to the Analytic Network Process (ANP), BWM stands out as a more straightforward and computationally efficient method, capable of handling complex decision problems by explicitly capturing the best and worst options [35].

This study utilizes the Best-Worst Method (BWM) to identify and weigh parameters affecting derailment incidents, aiming to overcome previous limitations and offer valuable insights for enhancing rail transportation safety. By comprehensively analyzing factors like infrastructure conditions, equipment failures, and human errors, the research contributes significantly to prioritizing preventive measures and advancing sustainable transportation systems. Through objective evaluation and consideration of emerging technologies, it addresses scientific gaps and provides crucial inputs for decision-making processes in ensuring safe and sustainable rail networks.

The paper is organized into five sections. Section 2.1 explains the process of gathering influential factors, including the literature review and classification of parameters. Section 2.2 describes the application of the BWM for parameter weighting, while Section 2.3 discusses the use of the Lingo 17 software for accurate calculations. Section 3 presents the results, including the identified influential parameters and their computed weights. The conclusion summarizes the findings and suggests future research directions.

2. Materials and methods

Fig. 1 demonstrates the steps of the study. The methodology employed in this study encompassed essential steps for a comprehensive analysis and prioritization of influential parameters. Initially, a thorough literature review was conducted utilizing prominent databases such as Scopus, Science Direct, and Google Scholar to identify and categorize these parameters. Through this process, parameters were extracted and classified based on expert opinions to ensure a comprehensive understanding of their significance. Subsequently, parameters underwent further analysis by being weighed and prioritized. This involved formulating a questionnaire based on the BWM and disseminating it among five rail safety experts. Using Lingo 17 software in conjunction with the BWM equations, the parameters were assigned weights, facilitating a quantitative assessment of their importance. Finally, the parameters were ranked based on their weighted scores, providing valuable insights into their relative significance in the context of rail safety.

The integration of Lingo 17 software into this research methodology proves highly fitting for several reasons. Firstly, its robust optimization capabilities are adept at solving the intricate mathematical models inherent in this study. Lingo 17's capacity to handle various programming types, including linear, integer, and nonlinear programming, ensures effective modeling and analysis of the diverse factors impacting the research outcomes. Moreover, the software's user-friendly interface and strong solver algorithms enable efficient and precise calculations. Its compatibility with different data formats and seamless integration with other software tools further enhance its suitability for the research needs. Additionally, Lingo 17 facilitates sensitivity analysis, allowing for the evaluation of the influence of different parameters on the results and enabling well-informed decisions.

2.1. Parameter extraction and classification methodology

In this study, the goal was to identify and classify influential parameters impacting derailment incidents. To achieve this, an extensive literature review was conducted, employing specific inclusion and exclusion criteria to select relevant articles. The search encompassed various academic databases, including Scopus, ScienceDirect, and Google Scholar, using appropriate keywords such as "derailment," "rail accidents," "causes of derailment," and "influential parameters."

The inclusion criteria involved selecting studies published between

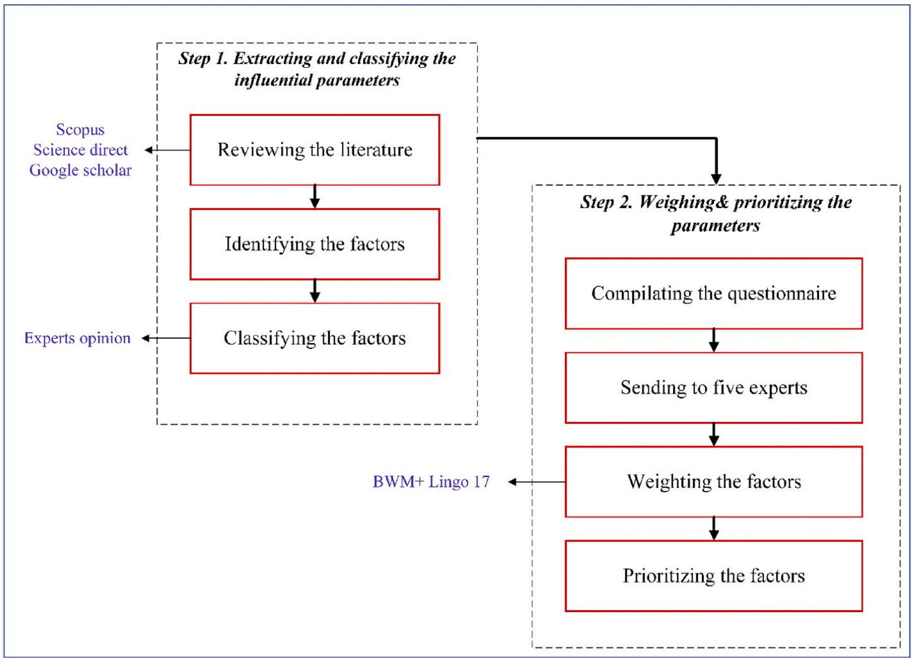

Fig. 1. The steps of the study.

1990 and 2021 to ensure the inclusion of recent findings while maintaining a comprehensive perspective. Additionally, references within relevant articles were thoroughly examined to identify additional sources that could provide valuable insights. After the initial screening, a systematic approach was adopted to identify and classify the influential parameters. The parameters were extracted based on their frequency of occurrence in the literature and their significance in contributing to derailment incidents. Priority was given to parameters that consistently appeared and were highlighted as critical factors in multiple studies during the classification process. The identified influential parameters were carefully categorized into different groups based on their nature and characteristics. This classification aimed to organize the parameters systematically, enabling a clearer understanding of their individual contributions to derailments. The parameters were grouped into categories such as environmental factors, railway conditions, wagon characteristics, loading situation, operational aspects, and human factors.

By incorporating specific inclusion and exclusion criteria in the literature review process, the study ensures the selection of relevant articles that contribute to the identification of influential parameters. This approach enhances the credibility and validity of the research findings, providing a comprehensive understanding of the factors influencing derailment incidents.

2.2. Parameter weighting utilizing the best-worst method

A rigorous evaluation was conducted using the BWM to determine the relative importance of the identified influential parameters. In this study, the opinions of five domain experts with extensive experience in the field of railway safety and derailment analysis were sought. Experts were selected based on their expertise, publications, and professional reputation in the field. These experts were provided with a carefully prepared questionnaire containing identified influential parameters. Table 1 presents a summary of the qualifications and expertise of five railway safety engineering experts. Notably, all experts involved in the study were of Iranian nationality. As can be inferred, all the experts have had sufficient qualifications to express their opinion regarding the questionnaire.

It is noteworthy that the questionnaire was thoroughly reviewed and approved by the Research Committee of Hamadan University of Medical Sciences (RC-UMSHA). This approval process ensured adherence to the ethical standards and regulations governing studies involving human participants in the country. The oversight of RC-UMSHA protected the welfare of both the participants and the researchers, ensuring compliance with all relevant ethical guidelines and legal requirements. Furthermore, the questionnaire employed in our study was designed to adhere to the principles of the BWM, known for its effectiveness in discerning preferences and priorities. Structured as a series of pairwise comparisons, experts were presented with scenarios featuring pairs of rail system defects and asked to indicate the most significant (best) and least significant (worst) defects within each pair. This approach allowed for a nuanced assessment of the relative importance of different defects, capturing the diverse perspectives of the experts involved. In addition to the comparative aspect, the questionnaire included demographic questions to gather information about the experts' backgrounds, such as job roles, work experience, and educational qualifications, ensuring a comprehensive understanding of their viewpoints. Through this meticulously structured questionnaire, systematic capture and analysis of the experts' opinions were conducted, culminating in robust insights into the prioritization of rail system defects.

The best-case scenario represents the most favorable outcome for

Table 1
Characteristics of railway experts.

Expert NO.	Job	Work experience (years)	Degree of education	Field of education
EX-1	Faculty Member	18	Ph.D.	Transportation engineering
EX-2	Chief Maintenance Engineer	13	Master of science	Mechanical Engineering
EX-3	Railway Safety Inspector	14	Bachelor	Safety Engineering
EX-4	Railway operator	17	Bachelor	Transportation management
EX-5	Railway Freight Management	23	Master of science	Logistics and Supply Chain Management

each criterion, while the worst-case scenario represents the least favorable outcome, with values determined through expert opinion and literature review. This study specifies the interpretation of the range for both cases, outlining the significance of each criterion's placement within the spectrum of best and worst scenarios.

The BWM is a multi-criteria decision-making technique introduced by Rezaei (2015) [47] that provides a structured approach to determining the significance of various factors in a given context. The BWM process involved two distinct steps: best and worst selection. In the best selection step, the experts were asked to identify the most critical parameter from each criterion's provided list. On the other hand, in the worst selection step, they were asked to identify the least critical parameter for each criterion. The experts assigned weights to the parameters based on their perceived importance by performing these pairwise comparisons [48]. The BWM algorithm then aggregated these weights to determine the overall priority of each parameter relative to the others. The BWM has proven to be an effective method for decision-making in various fields. Its strengths lie in its ability to handle complex and multi-dimensional problems by capturing the experts' subjective judgments [49]. Additionally, the BWM provides a transparent and systematic framework for assessing the relative importance of different parameters, thus aiding in informed decision-making [50, 51]. The calculations and equations of the best-worst method are given below [47].

Section 1- ***Determining the Decision Criteria Set:*** In the first step, we consider a set of decision criteria $[c_1, c_2, \ldots, c_n]$ that are used to decide on the study.

Section 2- ***Identifying the Best and Worst Criteria:*** In this step, the decision-maker determines the best (e.g., most desirable, most important) and worst (e.g., least important, least desirable) criteria. The decision-maker specifies the best and worst criteria in a general manner without conducting any comparisons at this stage.

Section 3- ***Determining the Preference of the Best Criterion:*** The preference of the best criterion relative to the other criteria is determined using numbers ranging from 1 to 9. The preference vector of the best criterion compared to others can be represented as Eq. (1).

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \tag{1}$$

where a_{Bj} represents the superiority of the best criterion B over criterion j. It is evident that the following relationship holds as $a_{BB} = 1$.

Section 4- ***Determining the Preference of All Criteria Relative to the Worst Criterion:*** The preference of all criteria relative to the worst criterion is determined using numbers ranging from 1 to 9. The superiority vector of the other criteria relative to the worst criterion (W) is as follows Eq. (2).

$$A_w = (a_{1w}, a_{2w}, \ldots, a_{nw})^T \tag{2}$$

where a_{jw} represents the superiority of criterion j over the worst criterion W. It is evident that the following relationship holds as $a_{ww} = 1$.

Section 5- ***Finding the Optimal Weights [w_1*, w_2*, …, w_n*]:*** The optimal weights for the criteria, i.e., the weights for which the ratios $\frac{w_b}{w_j}$ and $\frac{w_j}{w_w}$ satisfy Eq. (3) and Eq. (4).

$$\frac{w_b}{w_j} = a_{Bj} \tag{3}$$

$$\frac{w_j}{w_w} = a_{jw} \tag{4}$$

To satisfy these conditions for all j, we must find a solution where the absolute differences $\left| \frac{w_b}{w_j} - a_{Bj} \right|$ and $\left| \frac{w_j}{w_w} - a_{jw} \right|$ are minimized for all j. Considering the non-negativity and sum-to-one constraints on the weights, Eq. (5) is formulated.

$$[min, max_J] = \left[\left| \frac{w_b}{w_j} - a_{Bj} \right| \cdot \left| \frac{w_j}{w_w} - a_{jw} \right| \right], s.t. \begin{bmatrix} \sum_j \mathrm{w}_j = 1, for\ all\ j \\ \mathrm{W_j} \geq 0, \text{for all j} \end{bmatrix} \tag{5}$$

The problem described by Eq. (5) is a nonlinear problem and may have multiple optimal solutions. Therefore, it can be transformed into a linear model for optimization purposes, as presented in Eq. (6), adapted from the model proposed by Rezaei (2016) (considering $\sum_j \mathrm{w}_j = 1$, $for\ all\ j$).

$$\min \xi, s.t. \begin{bmatrix} \left| \frac{w_b}{w_j} - a_{Bj} \right| \leq \xi, \text{for all j} \\ \left| \frac{w_j}{w_w} - a_{jw} \right| \leq \xi, \text{for all j} \\ \mathrm{W_j} \geq 0, \text{for all j} \end{bmatrix} \tag{6}$$

By solving the above optimization problem, the optimal weights *[w_1*, w_2*, …, w_n*]* and ξ^* are obtained. It is worth mentioning that by using ξ^*, we introduce the concept of consistency ratio. A higher value of ξ^* indicates a higher level of inconsistency, implying that the comparisons have less reliability.

2.3. Software for calculation

To ensure maximum accuracy in the calculations, all BWM calculations were performed using the *Lingo 17* software. The *Lingo 17* software was employed to execute the necessary computations, leveraging its built-in formulas and algorithms. By utilizing this software, the required equations and constraints were effectively implemented. The use of Lingo 17 allowed for precise and reliable results to be obtained, enhancing the credibility and validity of the study's findings. The adoption of Lingo 17 underscores a commitment to rigorous methodology, emphasizing accurate calculations throughout the research process [52].

2.4. Global applicability and adaptation

The applicability of this study extends beyond national boundaries, addressing a global audience. Railway systems are governed by diverse legal and regulatory frameworks worldwide, and this research acknowledges these variations by incorporating a comprehensive analysis that considers these differences. The findings, while broadly applicable, recognize that specific implementations may vary depending on each country's unique legislative environment, technological infrastructure, and the maturity of their railway sector. This variation underscores the importance of contextual adaptation, enabling stakeholders to tailor the insights and recommendations to their specific national or regional contexts.

The study's methodology and conclusions are designed to be versatile, offering a foundation that supports customized applications in different countries. By understanding the local legal requirements, operational standards, and developmental stages of railway systems, the research provides a robust framework for adaptation. For instance, in countries with advanced railway infrastructures, the focus might be on optimizing existing systems, whereas in developing regions, the emphasis could be on foundational development and regulatory alignment. Moreover, the research highlights best practices and innovative solutions that can be universally applied, fostering cross-border collaborations and knowledge sharing. This approach not only enhances the relevance of the study in various national contexts but also contributes to the global discourse on railway development and modernization. By providing a detailed and adaptable set of insights, the study ensures its practical applicability and value across different geopolitical and economic landscapes.

3. Results and analysis

3.1. Identified the influential parameters

Table 2 presents the primary parameters influencing derailment incidents alongside their corresponding sub-factors. These parameters are categorized into eight main factors denoted by letters (A) through (H), each encompassing multiple sub-factors. Factor (A) relates to the subsidence of the railway line, with sub-factors including improper infrastructure and pavement as well as the absence of speed limits in affected areas. Factor (B) addresses the illegal width of the rail line, comprising sub-factors such as non-standard construction, lack of measuring tools, and delayed replacement of rail lines, particularly in curves. Similarly, factors (C) through (H) encompass various aspects contributing to derailment incidents, including fracture and escaping railway lines, unauthorized locomotive speed, improper distribution of load on wagons, defects in wagon wheels, and falling cargo train parts. Each sub-factor is accompanied by references denoting its significance in the literature, with 'B' indicating it as the best group/sub-factor related to derailment and 'W' as the worst. From infrastructure deficiencies like subsidence and illegal width to operational issues such as unauthorized locomotive speed and improper load distribution, the table highlights various aspects that can potentially lead to derailments. Each parameter is accompanied by specific sub-factors, offering a detailed understanding of the multifaceted nature of derailment risk factors. The inclusion of references provides further context and validation for the significance of these factors in ensuring railway safety and underscores the importance of addressing these issues to mitigate derailment incidents effectively.

Table 2
The main parameters affecting derailment incidents and their corresponding sub-factors.

Main factors	Sub-factors	Reference
(A) Subsidence of the railway line	A1: Improper infrastructure and pavement of the railway line[W]	[53]
	A2: Not applying speed limits in places with subsidence[B]	[5]
(B) Illegal width of the rail line	B1: Non-standard construction of railway lines[W]	[54]
	B2: Non-use of measuring tools for railway lines	[55]
	B3: Late replacement of rail lines, especially in curves[B]	[56]
(C) Fracture in railway lines[B]	C1: Implementation of rail lines at the wrong time	[57]
	C2: Using the wrong alloy	[58]
	C3: Improper repairs of railway lines[B]	[59]
	C4: Failure to report by the operator	[60]
	C5: Failure to report a fracture signal[W]	[61]
(D) Escaping railway lines	D1: Implementation of rail lines at the wrong time[W]	[57]
	D2: Using the wrong alloy	[58]
	D3: Improper repairs of railway lines[B]	[62]
	D4: Failure to report by the operator	[63]
	D5: Defects in periodic inspection	[64]
(E) Unauthorized locomotive speed	E1: Malfunction in the locomotive control system[W]	[65]
	E2: Malfunction in the locomotive braking system[B]	[66]
	E3: Failure of the emergency brake	[7]
	E4: Inexperience and incompetence of the operator	[67]
(F) Improper distribution of the load on the wagon	F1: Failure to comply with the loading limit[B]	[68]
	F2: Improper loading arrangement[W]	[69]
	F3: Improper loading	[70]
	F4: The mismatch between wagons and loading	[71]
(G) Defects in wagon wheels	G1: Defects in periodic inspection	[72]
	G2: Failure to report by the operator[B]	[63]
	G3: Improper operation of grease sprayer and oil sprayer[W]	[73]
(H) Falling cargo train parts[W]	H1: Defects in periodic inspection[W]	[74]
	H2: Lack of daily visual inspections[B]	[75]
	H3: No use of mechanical glue and lock	[76]

[B]Best group/sub-factor related to the derailment/group.
[W]Worst group/sub-factor related to the derailment/group.

3.2. Computed weights

3.2.1. Best and worst subfactors related to each group

The application of the BWM served as a crucial step in the research process, aimed at identifying the most influential sub-factors within each main group. By engaging in a collaborative effort with five domain experts, a brainstorming session was conducted to evaluate and determine the best and worst sub-factors. The insights and expertise of the experts were instrumental in reaching a consensus and identifying the sub-factors with the highest and lowest impact on derailment incidents. The outcomes of this collaborative endeavor, as presented in Table 2, provide valuable insights into the relative significance and priority of the sub-factors within their respective main groups. This informed selection of the best and worst sub-factors enables a comprehensive understanding of the critical factors contributing to derailment incidents, thereby guiding further analysis.

3.2.2. Weighting results

Analyzing the calculated weights for Groups A to H provides insightful findings regarding the relative importance and ranking of each group concerning derailment incidents (Fig. 2). Group C, which focuses on "fracture in railway lines," emerged as the highest-ranking group with a weight of 0.3143. This indicates its significant impact on derailment occurrences, highlighting the criticality of addressing fracture-related issues in railway lines to ensure safety and prevent derailments. Following closely behind, Groups B, E, and G obtained the second and third ranks, with equal weights of 0.1542, 0.1342, and 0.1342, respectively. Group B is associated with the "illegal width of the rail line," emphasizing the importance of adhering to standard rail dimensions to maintain rail system stability. Group E focuses on "unauthorized locomotive speed," highlighting the significance of controlling locomotive speeds within permissible limits to mitigate derailment risks effectively. Similarly, Group G pertains to "defects in wagon wheels," emphasizing the importance of regular inspection and maintenance of wagon wheels to ensure their proper functioning and reduce the risk of derailments.

On the other end of the spectrum, Group H, focusing on "falling cargo train parts," obtained the lowest weight of 0.0295, indicating its relatively lesser impact on derailment incidents. Similarly, Group F, associated with the "improper distribution of the load on the wagon," and

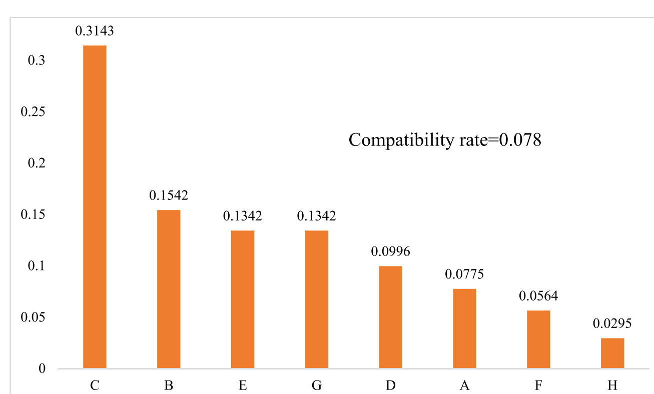

Fig. 2. The calculated weights for each group.

Group A, addressing "subsidence of the railway line," obtained relatively lower ranks, suggesting their lesser influence compared to other groups. In the calculations using a linear model within the best-worst method, a lower compatibility rate indicates higher accuracy. In this study, the calculated compatibility rate of 0.078 demonstrates a reasonable level of agreement among the rankings provided by the experts. This finding suggests that there is a degree of consistency in the assessments made by the experts regarding the weights assigned to the sub-factors.

The findings also reveal that fractures in railway lines (Group C) carry the highest weight, indicating their significant impact on derailment occurrences. This underscores the importance of addressing railway line fracture issues to enhance safety and prevent derailments. Additionally, factors such as illegal rail line width (Group B), unauthorized locomotive speed (Group E), and wagon wheel defects (Group G) also hold notable weights, emphasizing their role in mitigating derailment risks and ensuring overall safety. Conversely, factors like falling cargo train parts (Group H) have lower weights, suggesting a relatively lesser impact on derailment incidents. Nonetheless, factors with lower weights, such as railway line subsidence (Group A) and improper load distribution on the wagon (Group F), still demand attention and improvement, as they can contribute to derailments and compromise safety.

To enhance the clarity of calculations, an example of a calculation is presented. For instance, pairwise comparisons were conducted between the best sub-factor, "fracture in railway lines," and other main factors, as presented in Table 3. Similarly, pairwise comparisons were also performed between the remaining sub-factors and the worst sub-factor, "falling cargo train parts," as shown in Table 4.

Based on Tables 3 and 4 and utilizing Eq. (6), a linear model for the BWM was formulated for the main factors. Subsequently, the model was solved using Lingo 17 software, allowing for the calculation of the weights of the factors and the compatibility rate. Additionally, the compatibility rate of this model was determined to be 0.024, indicating an acceptable level of compatibility.

The linear model was represented by the equations shown below:

$$
\begin{aligned}
&\text{Min } Z\\
&|W3-5.073 \times w1| \le Z\\
&|W3-2.551 \times w2| \le Z\\
&|W3-3.949 \times w4| \le Z\\
&|W3-2.93 \times w5| \le Z\\
&|W3-6.971 \times w6| \le Z\\
&|W3-2.93 \times w7| \le Z\\
&|W3-7.975 \times w8| \le Z\\
&|w1-5.305 \times W8| \le Z\\
&|w2-3.565 \times W8| \le Z\\
&|w4-3.104 \times W8| \le Z\\
&|w5-3.728 \times W8| \le Z\\
&|w6-3.288 \times W8| \le Z\\
&|w7-1.888 \times W8| \le Z\\
&w1+w2+w3+w4+w5+w6+w7+w8 = 1
\end{aligned}
$$

The findings presented in Table 5 and Fig. 3 highlight the weights and priority assigned to various subfactors associated with railway line safety. These weights indicate each subfactor's relative importance or influence in contributing to the overall safety concerns. The subfactors with higher weights are deemed more critical and require greater attention and mitigation efforts, while those with lower weights are comparatively less influential. Among the subfactors, "improper repairs of railway lines" (C3) had the greatest impact on safety concerns, with a weight of 0.1458. This subfactor highlights the significance of proper maintenance and repair practices to ensure the integrity and safety of railway lines. Following closely is the subfactor "late replacement of rail lines, especially in curves" (B3) with a weight of 0.1027. This finding underscores the importance of timely replacement of worn-out rail lines, particularly in curved sections, to mitigate safety risks associated with derailments or accidents. Another influential subfactor is "failure to

Table 3
Pairwise comparisons of the best sub-factor with main factors (BO).

BO	A	B	C	D	E	F	G	H
C	5.073	2.551	1	3.949	2.93	6.971	2.93	7.975

Table 4
Pairwise comparisons of other sub-factors with the worst sub-factor (OW).

OW	A	B	C	D	E	F	G	H
H	5.305	3.565	7.975	3.104	3.728	3.288	1.888	1

Table 5
The calculated weights for each sub-factor.

Main factors	Sub-factors	WRSG	WRAA
(A) Subsidence of the railway line	A1: Improper infrastructure and pavement of the railway line	0.1586	0.0123
	A2: Not applying speed limits in places with subsidence	0.8414	0.0652
(B) Illegal width of the rail line	B1: Non-standard construction of railway lines	0.2462	0.0380
	B2: Non-use of measuring tools for railway lines	0.0877	0.0135
	B3: Late replacement of rail lines, especially in curves	0.6662	0.1027
(C) Fracture in railway lines B	C1: Implementation of rail lines at the right time	0.0622	0.0196
	C2: Using the wrong alloy	0.1450	0.0456
	C3: Improper repairs of railway lines	0.4640	0.1458
	C4: Failure to report by the operator	0.1481	0.0465
	C5: Failure to report a fracture signal	0.1807	0.0568
(D) Escaping railway lines	D1: Implementation of rail lines at the wrong time	0.0589	0.0059
	D2: Using the wrong alloy	0.1539	0.0153
	D3: Improper repairs of railway lines	0.4685	0.0467
	D4: Failure to report by the operator	0.1419	0.0141
	D5: Defects in periodic inspection	0.1768	0.0176
(E) Unauthorized locomotive speed	E1: Malfunction in the locomotive control system	0.0808	0.0108
	E2: Malfunction in the locomotive braking system	0.5052	0.0678
	E3: Failure of the emergency brake	0.1785	0.0240
	E4: Inexperience and incompetence of the operator	0.2355	0.0316
(F) Improper distribution of the load on the wagon	F1: Failure to comply with the loading limit	0.5132	0.0290
	F2: Improper loading arrangement	0.0780	0.0044
	F3: Improper loading	0.2103	0.0119
	F4: The mismatch between wagons and loading	0.1985	0.0112
(G) Defects in wagon wheels	G1: Defects in periodic inspection	0.2115	0.0284
	G2: Failure to report by the operator	0.6732	0.0904
	G3: Improper operation of grease sprayer and oil sprayer	0.1153	0.0155
(H) Falling cargo train parts	H1: Defects in periodic inspection	0.1110	0.0033
	H2: Lack of daily visual inspections	0.6623	0.0195
	H3: No use of mechanical glue and lock	0.2267	0.0067

WRSG: Weight relative to other subfactor(s) in the group
WRAA: Weight relative to all subfactors in all groups

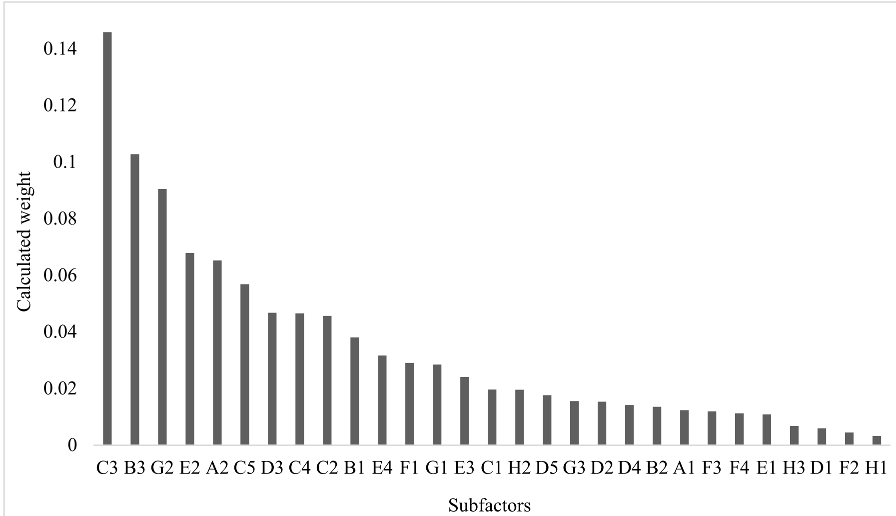

Fig. 3. Prioritizing sub-factors based on their impact on derailment.

report by the operator" (G2) with a weight of 0.0904. This emphasizes the crucial role of operators in promptly reporting any safety-related issues or incidents, and facilitating timely interventions and preventive measures. Additionally, the subfactor "malfunction in the locomotive braking system" (E2) carries significant weight with a value of 0.0678. This highlights the critical role of well-functioning braking systems in ensuring effective control and safe operation of locomotives.

On the other hand, the factor "defects in periodic inspection" (H1) had the least impact on safety concerns, with a weight of 0.0033. This indicates that while periodic inspection defects should still be considered, they have a relatively lower influence on overall safety compared to other subfactors. Similarly, the subfactor "improper loading arrangement" (F2) carries a weight of 0.0044, suggesting a relatively lower impact on safety concerns. Additionally, the subfactor "implementation of rail lines at the wrong time" (D1) has a weight of 0.0059, indicating a lesser influence on safety considerations. Lastly, the subfactor "non-use of measuring tools for railway lines" (B2) carries a weight of 0.0135, highlighting its relatively lower impact on safety concerns. While these subfactors still require attention and improvements, their lower weights suggest that they have a lesser overall influence on safety when compared to other factors.

These findings suggest that addressing the subfactors with higher weights, such as improper repairs of railway lines, late replacement of rail lines, failure to report by the operator, and malfunction in the locomotive braking system, should be prioritized in order to enhance railway line safety. Conversely, the subfactors with lower weights, such as defects in periodic inspection, improper loading arrangement, implementation of rail lines at the wrong time, and non-use of measuring tools for railway lines, may be of relatively lesser concern in terms of safety and may warrant less immediate attention.

4. Discussion

The present study has made significant contributions by identifying and weighing the factors contributing to derailment incidents in rail transportation systems. The findings provide computational insights into the main parameters and corresponding sub-factors that significantly impact derailments. Understanding these factors is crucial for preventing derailments and ensuring rail systems' safety, efficiency, and sustainability. The results of this study hold implications for decision-makers, engineers, and policymakers in the rail industry as they help guide the allocation of resources and the implementation of targeted measures to mitigate the risks associated with derailments. The computed weights have revealed the relative importance and ranking of each group and sub-factor concerning derailment incidents.

Group C, which focuses on "fracture in railway lines," emerged as the highest-ranking group, indicating its substantial impact on derailment occurrences. This finding underscores the criticality of addressing issues related to fractures in railway lines to ensure safety and prevent derailments. Similarly, Groups B, E, and G obtained high ranks, highlighting the importance of adhering to standard rail dimensions, controlling locomotive speeds within permissible limits, and regularly inspecting and maintaining wagon wheels, respectively. These results emphasize the significance of these factors in minimizing derailment risks and ensuring the overall safety of rail transportation systems. On the other hand, Group H, addressing "falling cargo train parts," obtained the lowest weight among the groups, suggesting its relatively lesser impact on derailment incidents. Similarly, Group F, associated with the "improper distribution of the load on the wagon," and Group A, addressing "subsidence of the railway line," obtained lower ranks than other groups. Although these factors still require attention and improvements, their lower weights indicate that they have a lesser overall influence on derailment incidents.

Nonetheless, it is important to recognize that addressing these factors should not be overlooked, as even relatively less influential factors can contribute to derailments and compromise safety. The pairwise comparisons and the BWM application have played a crucial role in calculating the weights for each sub-factor. The findings provide insights into the relative importance of each sub-factor in contributing to overall safety concerns. Sub-factors such as "improper repairs of railway lines," "late replacement of rail lines, especially in curves," "failure to report by the operator," and "malfunction in the locomotive braking system" carried higher weights, highlighting their critical role in ensuring the safety of railway lines. Conversely, sub-factors such as "defects in periodic inspection," "improper loading arrangement," "implementation of rail lines at the wrong time," and "non-use of measuring tools for railway lines" had lower weights, suggesting their relatively lesser influence on safety concerns.

The prioritization of sub-factors based on their weights provides valuable guidance for decision-makers and stakeholders in resource allocation and implementing targeted strategies to enhance rail safety. The findings underscore the importance of proper maintenance and repair practices, timely replacement of worn-out rail lines, prompt reporting of operator safety-related issues, and the effective functioning of locomotive braking systems. By addressing these critical sub-factors, rail industry stakeholders can effectively mitigate derailment risks and ensure safer rail transportation. Finally, the calculated compatibility rate suggests a reasonable level of agreement among the rankings provided by the experts. This finding indicates a degree of consistency in the assessments made by the experts regarding the weights assigned to the sub-factors. The consistency in the rankings adds credibility and reliability to the study's findings, enhancing their applicability and usefulness in real-world decision-making processes.

The significance of the identified factors contributing to derailment incidents in rail transportation systems cannot be overstated. These factors provide critical insights into the underlying causes of derailments, offering valuable guidance for decision-makers, engineers, and policymakers in the rail industry. Understanding the relative importance and impact of each factor enables stakeholders to prioritize resource allocation and implement targeted interventions to effectively mitigate derailment risks. Addressing factors such as fractures in railway lines, adherence to standard rail dimensions, control of locomotive speeds, and maintenance of wagon wheels is crucial for ensuring the safety, efficiency, and sustainability of rail systems. Furthermore, recognizing the importance of even relatively less influential factors, such as falling cargo train parts and improper load distribution, underscores the holistic approach needed to enhance rail safety. Ultimately, the insights gleaned from these factors contribute to the development of informed strategies aimed at preventing derailments and safeguarding the integrity of rail transportation systems.

It is essential to compare the findings of the present study with other similar studies. The study by Wang et al. (2020) [16]highlights significant reductions in broken rails, welds, track geometry issues, and other axle and journal defects. Notably, extreme weather emerged as one of the few causes that increased during the study period. Moreover, the development of a statistical model to understand the relationship between track class, traffic density, method of operation, and derailment rate provides a systematic approach to analyzing derailment risks. In comparison, the present study aimed to identify and weigh factors contributing to derailment incidents in rail transportation systems. Our findings corroborate the importance of addressing issues such as fractures in railway lines and adhering to standard rail dimensions to mitigate derailment risks effectively. Similarly, the study by Chadwick et al. (2012) [77] focused on three specific factors impacting train derailments at highway-rail grade crossings, emphasizing the role of highway vehicle type, particularly large vehicles like tractor-semitrailers, in contributing to derailment occurrences. This study provided valuable insights into the unique challenges associated with highway-rail grade crossings. In contrast, the present study did not specifically analyze highway-rail grade crossings but instead provided insights into broader factors contributing to derailment incidents in rail transportation systems.

Additionally, while the analysis conducted by Barkan et al. (2003) [78] delves into the correlation between derailment speed, the number of derailed cars, and hazardous materials releases, the present study did not specifically focus on hazardous materials transportation. Nonetheless, our study underscores the importance of proper maintenance and repair practices, timely replacement of worn-out rail lines, and effective functioning of locomotive braking systems to mitigate derailment risks effectively, indirectly contributing to ensuring the safe transportation of hazardous materials and protecting public safety. Furthermore, Chung et al. (2019) [79] emphasize the importance of considering train derailment risk in train operation to ensure safety. While their study does not directly compare factors contributing to derailments, it contributes to understanding overall risk and safety measures in rail transportation systems. In contrast, the present study focused on identifying and weighing factors contributing to derailment incidents in rail transportation systems.

The study made valuable contributions by identifying and weighing factors contributing to derailment incidents. However, there are limitations and areas for future research to consider. The study focused only on identifying factors and did not explore their interrelationships or complex interactions, which could inform more effective preventive strategies. Moreover, this study solely focused on derailment incidents in rail transportation systems, and future research should include other types of incidents to gain a comprehensive understanding of overall safety challenges. Additionally, the present study did not quantify the actual impact of identified sub-factors or establish their correlation with specific derailment events. Statistical analysis and data-driven approaches would strengthen the findings by establishing direct links between factors [80]. Lastly, the study did not provide specific recommendations or interventions, and future research should evaluate the effectiveness of mitigation strategies to enhance rail safety and guide resource allocation. Addressing these limitations and pursuing further research will improve understanding and aid in mitigating derailment risks in rail transportation systems.

5. Conclusion

This study aimed to identify and weigh the factors contributing to derailment incidents in rail transportation systems, providing significant insights into these factors. The findings underscore the importance of addressing fracture-related issues, adhering to standard rail dimensions, controlling locomotive speeds, and maintaining wagon wheels to effectively mitigate derailment risks. However, falling cargo train parts, improper load distribution, and subsidence of the railway line had relatively lesser influence on derailment incidents. Emphasizing the criticality of proper maintenance, timely replacements, operator reporting, and functioning locomotive braking systems for railway line safety, the study highlights key measures for enhancing rail safety. Future research should explore interrelationships between factors, consider a broader range of incidents, quantify actual impact, and evaluate the effectiveness of interventions. These findings hold implications for decision-makers and stakeholders in resource allocation and targeted strategies to enhance rail safety. Ultimately, this study contributes to preventing derailments and ensuring the long-term safety and sustainability of rail transportation systems.

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CRediT authorship contribution statement

Kamran Gholamizadeh: Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization. **Dragan Pamucar:** Writing – review & editing, Visualization, Validation, Conceptualization. **Sarbast Moslem:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Parastou Basiri:** Writing – original draft, Methodology, Conceptualization. **Domokos Esztergár-Kiss:** Writing – review & editing, Visualization, Supervision. **Iraj Mohammadfam:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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