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Assessment actions for improving railway sector performance using intuitionistic fuzzy-rough multi-criteria decision-making model

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HIGHLIGHTS

- A novel integrated MCDM approach for improving railway sector performance is presented.
- Actions for improving the performance of the railway sector are identified and prioritized.
- A new weighted geometric Dombi Maclaurin Symmetric Mean (WGDMSM) operator is developed.
- The study combined the interval rough PIPRECIA and WGDMSM operator for the first time.
- The comparative study and sensitivity analysis are made to confirm the robustness of the obtained results.

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ABSTRACT

The selection and prioritization of appropriate actions to improve the performance of the railway sector pose a common challenge for policymakers and transport planners. This challenge is further complicated by factors such as political power shifts, policy changes, and socio-economic and environmental impacts, introducing various uncertainties. To address this issue, a novel multi-criteria decision-making framework was developed in this study. The framework introduces the weighted geometric Dombi Maclaurin Symmetric Mean operator within an intuitionistic fuzzy environment, enabling the identification of the most appropriate action from nine different alternatives to enhance the performance of railway sector. Moreover, the study makes an additional contribution by combining this approach with an interval rough PIvot Pairwise RElative Criteria Importance Assessment to determine the weight coefficients of the criteria. To assess the robustness of the proposed methodology, sensitivity analysis and a comparative study were conducted. The findings of the study indicate that "enhancing the governance of the transport sector" emerged as the most appropriate action to improve the performance of the railway sector.

1. Introduction

Railway transportation in Sub-Saharan Africa (SSA) has been in crisis for the past three decades, with a diminishing role in the transport subsector and a minimal contribution to the overall value of the transportation system [1]. According to statistics, railways in SSA region account for a meager 11.6% of freight volumes and 1.7% of passenger transport in Africa [2]. These figures indicate low levels of traffic and reveal the insufficient state of infrastructure in the region [3]. The small market share of railways in SSA region hinders their ability to benefit

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from substantial investments in infrastructure development and maintenance, making them less competitive compared to other modes of transportation. Ongoing neglect of maintenance has resulted in an estimated backlog investment of US$3 billion for the railway sector [4]. Generally, railways in SSA region prioritize the transportation of freight over passengers, reflecting the neglect of railways in favor of road infrastructure [5].

Multiple studies [2,6,7] have identified various factors contributing to the inadequate performance of railway transportation in SSA region. These factors encompass the absence of an effective transport policy, governmental negligence, and poor management. In response to these challenges, substantial reforms have been implemented in the railway sector since the mid-1990 s to tackle these issues and reinvigorate railway transportation [2]. While many railways have undergone private concessions, they have largely failed to meet expectations. In recent years, the revival of railways has gained significance in SSA region [3], with international participants, particularly the Chinese Government, taking the lead in financing numerous projects, often in collaboration with the World Bank [8]. However, the integration of the continent's railway systems encounters several obstacles. Furthermore, limited accessibility to and exchange of information regarding national railway master plans, policies, and legislation pose challenges to regional coordination efforts, ultimately leading to a decline in the performance of the railway system. Governments in SSA region are facing a growing challenge of determining the most suitable course of action to revive the railway sector amidst various options. Previous studies have put forth a series of recommendations aimed at facilitating constructive collaboration between public and private entities to rejuvenate the national and regional railway systems [6,9,10]. Nevertheless, these studies have overlooked the crucial task of evaluating appropriate actions in light of the obstacles that hinder the railway sector's performance.

Addressing the challenge of enhancing railway performance through the selection of appropriate actions is a complex task that involves multi-criteria decision-making (MCDM). This process necessitates the involvement of a group of experts. MCDM approaches have proven to be effective and adaptable in tackling transportation-related problems [10–31]. The experts engaged in the decision-making process are faced with a multitude of ambiguous, uncertain, and imprecise information. Regrettably, the existing studies on this subject do not adequately acknowledge and tackle this issue. Therefore, this study aims to introduce a novel integrated multi-criteria method for handling the subject under consideration. The proposed MCDM method incorporates the use of an Interval Rough PIvot Pairwise RElative Criteria Importance approach (IR-PIPRECIA), which eliminates the need for sorting criteria prior to expert evaluation. Additionally, it introduces a new operator called Weighted Geometric Dombi Maclaurin Symmetric Mean (WGDMSM) within an intuitionistic fuzzy (IF) framework, which take into account the interdependence among criteria to obtain a more suitable action for improving the performance of the railway sector through group decision-making.

The motivations for the proposed study are as follows.

- The IR-PIPRECIA method, after being transformed into an interval rough matrix, has a simple procedure. IR-PIPRECIA is an effective technique that determines the significance of criteria by comparing one criterion to the prior one, so experts in group decision-making do not have a complicated process to show their preferences [32]. Unfortunately, no previous research provided an IR-PIPRECIA- based model to determine the importance of evaluation criteria for the improvement of the performance of the railway sector.
- Archimedean operations surpass Algebraic, Einstein, Hamacher, and Frank operations by their capability to encompass those operations as special cases through the utilization of various t-norms and t-conorms [33]. This quality makes Archimedean operations more versatile and inclusive [33]. However, a drawback of Archimedean operators is their failure to account for the interdependencies among various criteria. While the geometric Bonferroni mean (BM) [34], Generalized extended Bonferroni mean [35], and Heronian mean (HM) [36] operators can address the dependency between two criteria, they lack the flexible nature of Archimedean operators, and none of these operators can consider the interrelationship between more than two criteria. In contrast, the geometric Maclaurin Symmetric mean (GMSM) operator [37] can handle the dependency between any number of criteria. This gives the MSM operators an advantage over the BM operator, generalized extended BM operator, and HM operator. Unfortunately, previous studies have not incorporated the Maclaurin symmetric mean (MSM) operator within the context of an IF environment. Additionally, the application of the weighted geometric Dombi Maclaurin Symmetric Mean (WGDMSM) operator in an IF environment to evaluate actions for improving the performance of the railway sector has not been explored.

The main contributions of this study are bellows.

- It proposes an advanced decision-making framework based on the integration of the PIPRECIA method and WGDMSM operator under an IF environment. Firstly, the interval rough PIPRECIA was used to determine the importance of the decision-making criteria. Secondly, the weighted geometric Dombi Maclaurin Symmetric Mean operator under an IF environment was developed to assess and rank the actions for the improvement of the performance of the railway sector and reveal the most appropriate action.
- The utilization of a novel MCDM framework, involving the weighted geometric Dombi Maclaurin Symmetric Mean operator within an IF environment, empowers policymakers to make informed choices in real-life decision-making scenarios. The primary objective of this framework is to enhance the performance of the railway sector, effectively addressing the current issue of low traffic and facilitating increased intra-African trade in transport services. Notably, although the research focuses on improving railway sector performance, the developed decision-making framework holds potential for solving complex decision-making problems in other domains as well.
- This study marks a significant milestone as it is the first instance where issues pertaining to enhancing railway sector performance in SSA region have been approached from the MCDM perspective. This contribution adds substantial value to the existing body of knowledge. Additionally, the research identified six key decision-making criteria, establishing a practical framework for evaluating alternative improvement actions within the context of SSA region. Lastly, by presenting a case study focused on the SSA region, the study provides tangible guidelines for selecting the most appropriate course of action to enhance railway sector performance.

The remaining article is structured as follows. **Section 2** provides a review of literature. **Section 3** presents the developed methodology for improving the performance of the railway sector. The case study is defined in **Section 4** . The overall results assessed by the presented model are evaluated together with the validation analysis in **Section 5** . **Section 6** presents the discussion and managerial and practical implications based on the proposed model. The conclusions with limitations and further research directions are given in the last section.

2. Literature

The literature review is organized into four sub-sections. The first sub-section overviews the approaches for the improvement of the performance of the railway sector. The second and third sub-sections provides the studies related to the application of the PIPRECIA method and the intuitionistic fuzzy set theory, respectively. The last sub-section provides the research gaps.

2.1. Approaches for railway sector performance improvement

Railway transportation has recently been subject to scrutiny due to its potential for significant social, economic, and environmental benefits [38]. This scrutiny is fueled by the African Continental Free Trade Area (AfCFTA) agreement, which calls for the strategic expansion of the railway network across the continent [39]. African countries are actively taking steps to improve their railway transportation by constructing new railway lines and renovating obsolete ones through international collaborations. The objective is to achieve regional connectivity and enhance regional trade. In Northern, Western, and Eastern Africa, the standard gauge railway is being embraced to establish new networks, primarily in response to the deterioration of existing railway lines. Conversely, Central and Southern African countries are focusing on expanding their networks by rehabilitating the existing cape gauge railways [40]. In addition to these redevelopment efforts, research contributions are being made to enhance the performance of the railway sector at both national and regional levels.

In their research paper centered around African railways, Blumenfeld, Wemakor, Azzouz and Roberts [38] investigated the existing state of railway infrastructure in low-income countries (LICs) and the level of operational performance achieved. Their objective was to pinpoint specific areas where the regional network lacks essential capabilities. To address this, they proposed a technical strategy that forms the basis for the implementation of continental technical strategy programs. These programs are designed to outline technology roadmaps that will effectively enhance the performance of the railway sector. Al-Douri, Tretten and Karim [41] conducted a study to examine the requirements of railway stakeholders involved in analyzing the condition of tracks and identifying the essential information needed to make informed decisions regarding maintenance. The objective of their research is to enhance the performance of railway sector by achieving higher availability, reliability, and safety, while simultaneously reducing maintenance expenses. Pisa [42] examined significant measurable advancements in railway freight transportation that have enhanced the efficiency of railway logistics in developed nations. The author emphasized that there are possibilities to introduce these innovations in emerging nations as well. Nevertheless, the effectiveness of these innovations in enhancing the performance of railway freight depends on careful consideration of the specific context and evidence-based evaluations of the challenges related to operational efficiency in various emerging economies. In reference [43], World Bank provides a convenient and accessible resource for understanding the railway industry. It offers a comprehensive collection of best practices based on real-world experiences, serving as a valuable guide for the effective planning and implementation of railway reforms. The resource draws insights from international cases involving different forms of railway organizations, such as state agencies, state-owned enterprises, and private companies. This resource is particularly relevant for those considering organizational transitions and individuals seeking to enhance railway performance through investment, reorganization, or changes in government policies. Stenström, Parida, Galar and Kumar [44] put forward a comprehensive model that specifically targets continuous improvement of the railway performance. This model serves as a valuable resource, providing detailed information on the performance of railway systems and components. It establishes clear connections between these components, as well as their alignment with overall objectives, thereby empowering decision-makers to take proactive measures. Beck, Bente and Schilling [45] focused on the notion of railway efficiency and explored a range of essential inquiries. These inquiries encompassed the definition and scope of "railway efficiency", the identification of additional evidence that supports the presence of gaps in railway efficiency, the examination of overarching factors that contribute to these gaps, and the exploration of potential measures that railway managers and regulators can implement to improve the performance of railway systems.

In Kenya, Chege, Wang, Suntu and Bishoge [46] used correlation and hierarchical models to determine how efficient technology transfer could improve the performance and sustainability of standard gauge railways. They advocated interdisciplinary initiatives to support regional institutions to improve regional railway sector through curriculum reviews and the creation of regional technology transfer offices. In South Africa, George, Mokoena and Rust [47] conducted an evaluation of the public railway networks, contributing to ongoing endeavors to raise awareness among the government and the general public about the existing condition of railway infrastructure. Their research emphasized the necessity for well-maintained infrastructure as a means to enhance the current performance of the national railway system. In their research, Bouraima, Qiu, Yusupov and Ndjegwes [48] explored the development strategy of the railway transportation system in the West African Economic and Monetary Union (WAEMU). Their findings highlighted that the primary factors contributing to the improvement of the performance of regional railway system are the potential for market growth and the efficient handling of high-capacity cargo over long distances. Ogochukwu, Ogochukwu, Ogorchukwu and Ebuka [49] evaluated the performance of railway transportation in Nigeria over 40 years using documentary analysis and data primarily sourced from archival records. Their study concluded that for Nigeria to improve the performance of railway transportation and maximize its benefits, the issue of poor management in this critical sub-sector of the transportation industry must be resolved. Bouraima, Alimo, Agyeman, Sumo, Lartey-Young, Ehebrecht and Qiu [3] assessed the current knowledge of the African railway network, challenges, economic prospects, and environmental sustainability. They emphasized research gaps that researchers can look into to improve railway performance and redevelopment. Using published articles, reports, and online data, Bouraima and Qiu [50] raised the development policies and Marshall's plan for improving the performance of the railway sector in the Benin Republic. A range of actions has been given by Olievschi [6] to assist both public and private interests in collaborating constructively to improve the performance of railway sector in the SSA region. Table 1 provides a widespread overview of the approaches for improving the performance of the railway transportation sector/system.

2.2. Applications and extensions of the PIPRECIA method

PIPRECIA is a method introduced by Stanujkic, Zavadskas, Karabasevic, Smarandache and Turskis [51] and denotes a better version of the SWARA method. The PIPRECIA method is applied to make easier the decision-making procedure in many real-world issues. The PIPRECIA method is utilized in a variety of applications in previous research. Jauković-Jocić, Karabašević and Jocić [52] employed the PIPRECIA to evaluate the quality of e-learning components. Stević, Bouraima, Subotić, Qiu, Buah, Ndiema and Ndjegwes [53] found the top five delays in road construction in the Benin Republic using the fuzzy PIPRECIA. Tomašević, Lapuh, Stević, Stanujkić and Karabašević [54] applied it under fuzzy environment to assess the criteria used to implement high-performance computing. Đalić, Stević, Karamasa and Puška [55] used the fuzzy PIPRECIA along with the interval rough SAW to choose a green supplier. Stević, Stjepanović, Božičković, Das and Stanujkić [56] used the fuzzy PIPRECIA and SWOT matrix method to evaluate the circumstances for implementation of the information technology in a warehouse system. The studies related to the applications and extensions of the PRIPRECIA method are shown in Table 2.

2.3. Applications of the intuitionistic fuzzy set theory

The IFS theory is introduced by Atanassov [57] as an extension of the fuzzy set concept. To address non-probabilistic uncertainty and non-determinism in the system, the theory has been proved to be more suitable than fuzzy sets. The intuitionistic fuzzy set is utilized in a variety of applications in previous research. In an intuitionistic fuzzy

Table 1
Survey of the available approaches for railway transportation performance improvement.

Author (s)	Empirical focus	GDM	SA	CA	Method (s)	Application	
						Country/ Region	Type
Bouraima, Alimo, Agyeman, Sumo, Lartey-Young, Ehebrecht and Qiu[3]	Proposing potential areas of research that can be explored to enhance railway performance and redevelopment	No	No	No	Published articles and reports	Africa	Literature review
Olievschi[6]	Addressing the issues affecting railway performance and possible improvements	No	No	No	Narratives based on periodical reports and bibliography	Sub-Saharan African	Real-life
Blumenfeld, Wemakor, Azzouz and Roberts[38]	Depicting technology roadmaps aimed at significantly improving the performance of the railway sector	No	No	No	Data from public repositories and reports	Asian and Sub-Saharan Africa	Literature review
Al-Douri, Tretten and Karim[41]	Facilitating the improvement of the railway sector's performance through the achievement of higher availability, reliability, and safety, while concurrently reducing maintenance expenses	Yes	No	No	Mix method research	Sweden	Real-life
Pisa[42]	Introducing innovative solutions that enhance the performance of railway freight based on the consideration of the specific context and evidence-based evaluations of the challenges	No	No	No	Systematic approach	Developed countries	Literature review
World Bank[43]	Provision of a convenient and accessible resource aiming to enhance railway performance through investment, reorganization, or changes in government policies.	No	No	No	Compilation of best practices derived from real-world experiences	Global	Real-life
Stenström, Parida, Galar and Kumar[44]	Putting forward a comprehensive model that specifically targets continuous improvement and strategic planning of the performance of railway systems and components	No	No	No	Link and effect model	Sweden	Real-life
Beck, Bente and Schilling [45]	Exploring of potential measures that railway managers and regulators can implement to improve the performance of railway systems	No	No	No	Benchmarking indicators, interviews	Europe	Real-life
Chege, Wang, Suntu and Bishoge[46]	Championing the implementation of interdisciplinary initiatives to offer support to regional institutions, thereby driving improvements in the regional railway sector performance	No	No	No	Survey-based method	Kenya	Real-life
George, Mokoena and Rust [47]	Underscoring the importance of maintaining infrastructure in order to improve the performance of the national railway system	No	No	No	National survey grading system	South-Africa	Real-life
Bouraima, Qiu, Yusupov and Ndjegwes[48]	Emphasizing main drivers for improving the performance of the regional railway system	No	No	No	SWOT & AHP	WAEMU member countries	Real-life
Ogochukwu, Ogochukwu, Ogorchukwu and Ebuka [49]	Addressing the problem of inadequate management in order to enhance the performance of railway transportation	No	No	No	Descriptive statistics and ANOVA	Nigeria	Real-life
Bouraima and Qiu[50]	Emphasizing the significance of development policies and Marshall's plan as means to bolster the performance of the railway sector	No	No	No	Narratives based on reports and archives	Benin-Republic	Real-life
Our study	**Identifying the most appropriate action for railway performance improvement**	**Yes**	**Yes**	**Yes**	**IR-PIPRECIA, IF, WGDMSM**	**Sub-Saharan African**	**Real-life**

Note: **AHP**- Analytic Hierarchy Process; **ANOVA**-Analysis of variance; **SWOT**- Strengths, Weaknesses, Opportunities, and Threats.

environment, Mukherjee [58] chose the best fuel technology for land transportation based on several criteria, creating a sustainable transportation system. Büyüközkan, Feyzioğlu and Göçer [59] suggested IFCI, together with group decision making approaches for the evaluation of urban transportation alternatives. Wang, Zhang and Sun [60] assessed consumer satisfaction in urban rail travel based on an intuitionistic fuzzy group decision model. Mahmoodirad, Allahviranloo and Niroomand [61] proposed a novel and efficient solution approach for the completely intuitive fuzzy transportation issue. Jingni, Junxiang and Zhenggang [62] developed a weighted scoring function and an intuitionistic fuzzy similarity model for the location choice of customer-equipped goods and materials assistance zone for the Sichuan-Tibet railway. Sun, Li, Wang and Yang [63] provided an intuitionistic fuzzy factorial analysis model in a random setting to choose a supplier for urban rail transit enterprises. Buran and Erçek [64] suggested a business model scheme for public transport via an integrated spherical fuzzy AHP and IF-AHP. Yan, Rong, Yu and Huang [65] applied an integrated intuitionistic fuzzy group decision structure for the choice of an urban rail transit system. The studies related to the applications of the intuitionistic fuzzy set theory are shown in Table 2.

2.4. Research gaps

The research gaps identified are as follows: a) The current approaches to improving railway transportation performance in SSA region are inadequate in determining the most appropriate actions for enhancing the railway sector's performance and categorizing the factors that pose challenges to its efficiency. Additionally, there is a notable absence of an implementation framework, specifically from the MCDM perspective, aimed at improving the performance of the railway sector in SSA region, as shown in Table 1; b) To date, there has been no prior research that combines the PIPRECIA approach and the weighted geometric Dombi Maclaurin Symmetric Mean (WGDMSM) operator within an unified methodological framework, specifically in the context of IF environment; c) Furthermore, the integration of the Maclaurin symmetric mean (MSM) operator with a geometric Dombi operator in an IF environment, as well as its application within the railway transportation sector, has not been explored or studied previously.

Table 2
Studies related to the application of the PIPRECIA method and the intuitionistic fuzzy set theory.

Authors	Empirical focus	Method	Country
Jauković-Jocić, Karabašević and Jocić[52]	e-learning materials quality assessment	PIPRECIA	-
Stević, Bouraima, Subotić, Qiu, Buah, Ndiema and Ndjegwes [53]	Causes of delays assessment in road construction projects	F-PIPRECIA	Benin Republic
Tomašević, Lapuh, Stević, Stanujkić and Karabašević[54]	Criteria assessment for high-performance computing	F-PIPRECIA	Danube region
Đalić, Stević, Karamasa and Puška[55]	Green supplier selection	F-PIPRECIA, R-SAW	-
Stević, Stjepanović, Božičković, Das and Stanujkić[56]	Information technology condition evaluation in warehouse system	F-PIPRECIA, SWOT	Europe
Mukherjee[58]	Alternative fuel selection for sustainable urban transport	IF-TOPSIS	-
Büyüközkan, Feyzioğlu and Göçer[59]	Sustainable urban transportation alternative choice	IFCI	Istanbul, Turkey
Wang, Zhang and Sun[60]	Customer satisfaction evaluation of urban rail transit	IF, Entropy	Tianjin, China
Mahmoodirad, Allahviranloo and Niroomand[61]	Transportation problem solution approach	FIFTP	-
Jingni, Junxiang and Zhenggang[62]	Choice of location of client-supplied goods	DIF-MADM	China
Sun, Li, Wang and Yang[63]	Supplier selection of urban rail transit	IF, FAM	China
Buran and Erçek[64]	Public transportation assessment	SF, IF, AHP	Turkey
Yan, Rong, Yu and Huang[65]	Urban transit system choice	IF, DEMATEL, CRITIC, COPRAS	China

Note: **COPRAS**- COmplex PRoportional ASsessment; **DEMATEL**- Decision Making Trial and Evaluation Laboratory; **DIF-MADM**- Dynamic Intuitionistic Fuzzy Multi-Attribute Decision-Making; **FAM**- Factorial Analysis Model; **FIFTP**-; **F**- Fuzzy; **IFCI**- Intuitionistic Fuzzy Choquet Integral; **R**- Rough; **SAW**- Simple Additive Weighting; **TOPSIS**- Technique for Order Preference by Similarity to Ideal Solution.

3. Proposed Methodology

This part of the study introduces a novel integrated model to prioritize the actions to be implemented to improve the performance of the railway sector in the SSA region. An outline of the novel established methodology is presented in Fig. 1.

3.1. Preliminaries

3.1.1. Intuitionistic fuzzy set theory

In fuzzy theory, an object's membership degree is typically denoted by a numerical value ranging from 0 to 1, whereas non-membership is essentially its opposite. However, this assumption fails to align with human intuition. Consequently, Atanassov [57] introduced the concept of IFSs by expressing membership and non-membership functions as a sum of values that does not exceed one.

Definition 1. **(Atanassov [57]).** An IFS S on $U = \{t_1,\ t_2,\ .,\ t_n\}$ is defined as.

$$S = \{\langle t_i,\ \mu_S(t_i),\ \nu_S(t_i)\rangle\ :\ t_i \in U\}, \tag{1}$$

where $\mu_S : U \to [0,\ 1]$ and $\nu_S : U \to [0,\ 1]$ indicate the membership degree and non-membership degree with the condition.

$0 \le \mu_S(t_i) \le 1, 0 \le \nu_S(t_i) \le 1$ and $0 \le \mu_S(t_i) + \nu_S(t_i) \le 1, \forall\, t_i \in U$. (2).

The intuitionistic index of an element $t_i \in U$ to S is defined by.

$\pi_S(t_i) = 1 - \mu_S(t_i) - \nu_S(t_i)$ and $0 \le \pi_S(t_i) \le 1, \quad \forall\, t_i\ \in U$..

For **simplicity**, Xu [66] characterized the intuitionistic fuzzy number (IFN) $\zeta = (\mu_\zeta,\ \nu_\zeta)$ which holds $\mu_\zeta,\ \nu_\zeta \in [0,\ 1]$ and $0 \le \mu_\zeta + \nu_\zeta \le 1$.

Definition 2. **(Xu [66])** Consider $\zeta_j = (\mu_j,\ \nu_j) j = 1(1)n,$ be IFN. Therefore,

$\mathbb{S}(\zeta_j) = (\mu_j - \nu_j),\ \hbar(\zeta_j) = (\mu_j + \nu_j)$, (3).

are the score and accuracy functions, respectively. Here, $\mathbb{S}(\zeta_j) \in [-1, 1]$ and $\hbar(\zeta_j) \in [0, 1]$..

Since $\mathbb{S}(\zeta_j) \in [-1, 1]$, when numerous score values are aggregated through linear weighted summation and the positive score values might be neutralized by the negative score values.

As $\mathbb{S}(\zeta_j) \in [-1, 1]$, Xu, Wan and Xie [67] therefore, developed an improved function, which is given by

Definition 3. **(Xu, Wan and Xie [67]).** Assume that $\zeta_j = (\mu_j,\ \nu_j)$ be an IFN. Then,

$\mathbb{S}^*(\zeta_j) = \frac{1}{2}(\mathbb{S}(\zeta_j) + 1), \hbar^\circ(\zeta_j) = \frac{1}{2}(\mu_j + \nu_j)$, (4).

are defined as normalized score and uncertainty functions, respectively. Here, $\mathbb{S}^*(\zeta_j) \in [0, 1]$ and $\hbar^\circ(\zeta_j) \in [0,\ 1]$..

Assume that $\zeta_1 = (\mu_1,\ \nu_1)$ and $\zeta_2 = (\mu_2,\ \nu_2)$ are two IFNs. To compare these IFNs, we have.

If $\mathbb{S}^*(\zeta_1) > \mathbb{S}^*(\zeta_2)$, then $\zeta_1 > \zeta_2$,.
If $\mathbb{S}^*(\zeta_1) = \mathbb{S}^*(\zeta_2)$, then.
if $\hbar^\circ(\zeta_1) > \hbar^\circ(\zeta_2)$, then $\zeta_1 < \zeta_2$;.
if $\hbar^\circ(\zeta_1) = \hbar^\circ(\zeta_2)$, then $\zeta_1 = \zeta_2$..

3.1.2. Dombi operators

Dombi operations have decent precedence of variation w.r.t parameter '$\mathcal{K}$' values.

Definition 4. Dombi [68] For μ_{ϑ_j}, the Dombi t-norm and Dombi t-conorm can be described by.

$HFDAOWAA : HFE^X \to HFE^X$

3.1.3. Geometric Maclaurin symmetric mean operator

The geometric Maclaurin Symmetric mean (GMSM) operator [37] is capable of considering the dependency between any number of criteria. This makes MSM operators superior compared to BM operator [34], generalized extended BM operator [35], and HM operator [36].

Definition 5. The GMSM operator [37] is defined by:

$$MSM^{(q)}\left(\xi_1, \xi_2,\ .,\ \xi_n\right) = \frac{1}{q}\left(\prod_{1 \le p_1 < p_2 < \ . < p_q \le n} \sum_{j=1}^{q} w_{p_j}\xi_{p_j}\right)^{\frac{1}{^{n}c_q}}, \tag{5}$$

where q is a parameter, $^{n}c_q$ stands for binomial coefficient, and $(p_1,\ p_2,\ .,\ p_q)$ denotes a q-tuple combination of $(1,\ 2,\ .,\ n)$..

The PIPRECIA technique and WGDMSM operator have been used with IRN and intuitionistic fuzzy environment respectively, which constitute a major contribution to our work. A comprehensive mathematical expression of both techniques is presented in the following section.

3.2. Interval Rough PIPRECIA

The mentioned section presents the implementation of PIPRECIA under IRN conditions. The subsequent analytical steps outline the procedure for assessing criteria weights using IR-PIPRECIA:

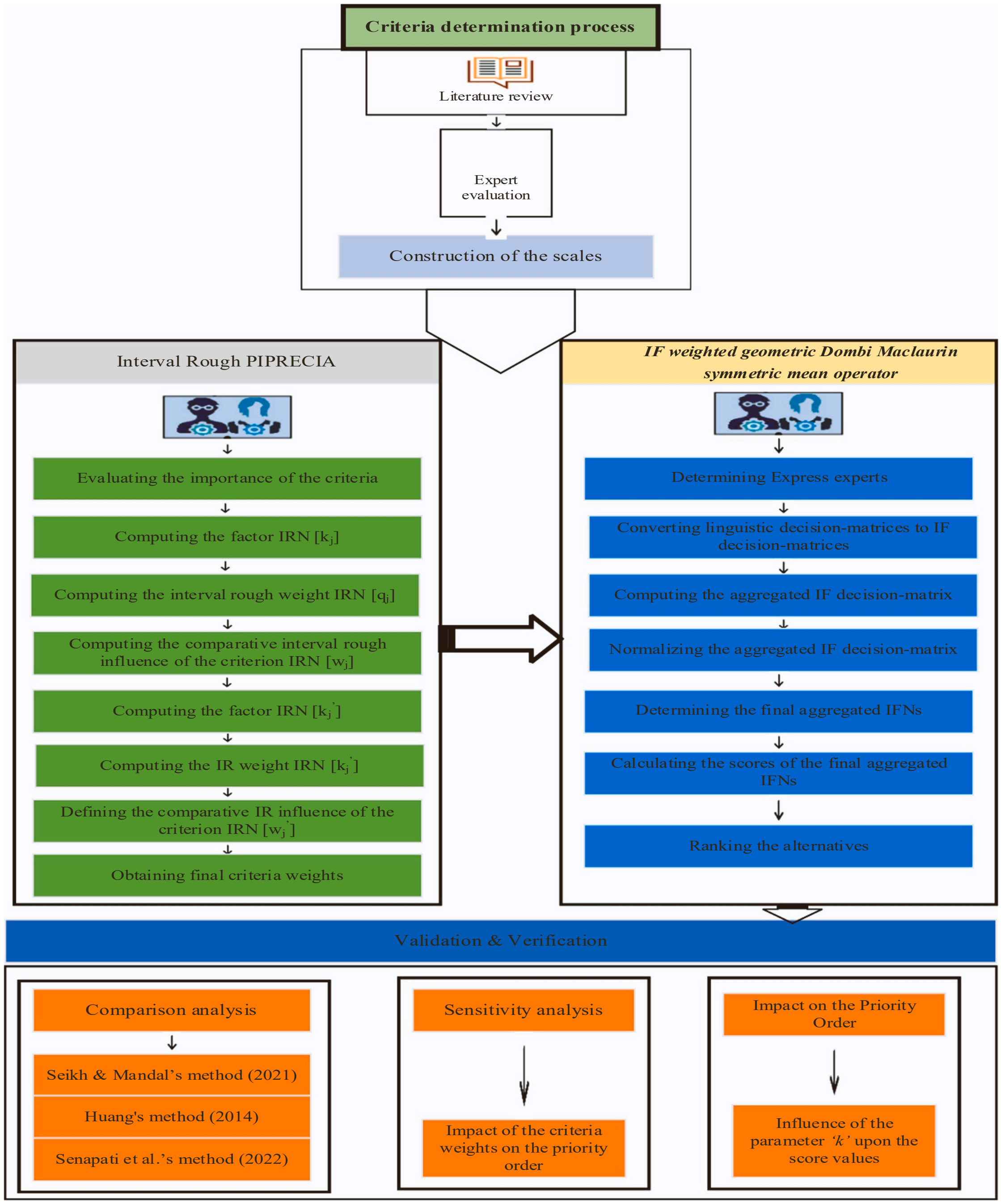

Fig. 1. Proposed methodology.

Step 1. The establishment of linguistic scales for evaluating the importance of criteria is first done since there is a difference between the IRN method and the crisp theory. Two scales are converted into IRNs due to the rough theory sets and the essence of the technique itself. Details of both linguistic scales are explained by Matić, Jovanović, Marinković, Sremac, Kumar Das and Stević [32].

Step 2. Characterizing all the components for establishing the MCDM model. Since group decision-making is the prerequisite for the implementation of such a method, it is important to determine a group of experts as well as the criteria. Additionally, it is essential to consider that the IR-PIPRECIA procedure doesn't necessitate any classification of criteria before their assessment by experts.

Step 3. Experts evaluated the significance of the criteria by beginning from the second criterion and checking its importance in correlation with the antecedent criterion using one of the aforementioned scales. Eq. (6) is used in this case to assess the condition that the criterion is approximately important in comparison to the antecedent one.

$$IRN\left[s_j^r\right] = \begin{cases} > & [1,1],[1,1] & if & C_j > C_{j-1} \\ = & [1,1],[1,1] & if & C_j = C_{j-1} \\ < & [1,1],[1,1] & if & C_j < C_{j-1} \end{cases} \tag{6}$$

$IRN[s_j^r]$ constitutes a comparative analysis of criteria by each expert r.

The merits of all experts are averaged via some of the operators due to the focus on the decision-making category. This aims to acquire a unique original IR decision-making matrix. In our work, an IRN Dombi weighted geometric averaging (IRNDWGA) aggregator, Eq. (7) according to the study performed in [69] is employed for average.

$$IRNDWGA\{IRN(\varphi_1),IRN(\varphi_2),.,IRN(\varphi_n)\}$$
$$= \left(\begin{bmatrix} \dfrac{\sum_{j=1}^{n}\underline{\varphi}_{lj}}{1+\left\{\sum_{j=1}^{n} w_j\left(\dfrac{1-f(\underline{\varphi}_{lj})}{f(\underline{\varphi}_{lj})}\right)^{\rho}\right\}^{1/\rho}}, \dfrac{\sum_{j=1}^{n}\overline{\varphi}_{lj}}{1+\left\{\sum_{j=1}^{n} w_j\left(\dfrac{1-f(\overline{\varphi}_{lj})}{f(\overline{\varphi}_{lj})}\right)^{\rho}\right\}^{1/\rho}} \end{bmatrix}, \begin{bmatrix} \dfrac{\sum_{j=1}^{n}\underline{\varphi}_{uj}}{1+\left\{\sum_{j=1}^{n} w_j\left(\dfrac{1-f(\underline{\varphi}_{uj})}{f(\underline{\varphi}_{uj})}\right)^{\rho}\right\}^{1/\rho}}, \dfrac{\sum_{j=1}^{n}\overline{\varphi}_{uj}}{1+\left\{\sum_{j=1}^{n} w_j\left(\dfrac{1-f(\overline{\varphi}_{uj})}{f(\overline{\varphi}_{uj})}\right)^{\rho}\right\}^{1/\rho}} \end{bmatrix}\right) \tag{7}$$

Step 4. Computation of the factor $IRN[k_j]$.

$$IRN[k_j] = \begin{cases} = [1,1],[1,1] & if \quad j=1 \\ 2-[s_j] & if \quad j>1 \end{cases} \tag{8}$$

Step 5. Computation of the interval rough weight $IRN[q_j]$

$$RN[q_j] = \begin{cases} = [1,1],[1,1] & if \quad j=1 \\ \dfrac{[q_{j-1}]}{[k_j]} & if \quad j>1 \end{cases} \tag{9}$$

Step 6. Computation of the comparative interval rough influence of the criterion $IRN[w_j]$

$$IRN[w_j] = \frac{[q_j]}{\sum_{j=1}^{n}[q_j]} \tag{10}$$

The implementation of the reversed IR-PIPRECIA technique, which is an essential portion of the process, is described in the following steps:

Step 7. Each expert evaluates the relative importance of the criteria beginning from the succeeding criterion, as bellows.

$$IRN[s_j^{r'}] = \begin{cases} > & [1,1],[1,1] & if \quad C_j > C_{j+1} \\ = & [1,1],[1,1] & if \quad C_j = C_{j+1} \\ < & [1,1],[1,1] & if \quad C_j < C_{j+1} \end{cases} \tag{11}$$

$IRN[s_j^{r'}]$denoted the criteria evaluation made by an expert r.

The identification of one of the proportioning operators is also necessary.

Step 8. Computation of the factor $IRN[k_j']$

$$IRN[k_j'] = \begin{cases} = [1,1],[1,1] & if \quad j=n \\ 2-[s_j'] & if \quad j>n \end{cases} \tag{12}$$

Step 9. Computation of the IR weight $IRN[q_j']$

$$\overline{q_j}' = \begin{cases} = [1,1],[1.1] & if \quad j=n \\ \dfrac{\overline{q_{j+1}}'}{\overline{k_j}'} & if \quad j>n \end{cases} \tag{13}$$

Step 10. Defining the comparative IR influence of the criterion $IRN[w_j']$

$$IRN[w_j'] = \frac{[q_j']}{\sum_{j=1}^{n}[q_j']} \tag{14}$$

Step 11. The subsequent equation is used for the obtaining final criteria weights.

$$[w_j''] = \frac{1}{2}\left(IRN[w_j] + IRN[w_j']\right) \tag{15}$$

Step 12. Both Spearman and Pearson correlation coefficients are used to check the results.

3.3. Weighted geometric Dombi Maclaurin symmetric mean (WGDMSM) operator under intuitionistic fuzzy environment

Motivated by the Dombi operations on IF data, we propose the WGDMSM operator which is flexible enough with the Dombi parameter and it can consider the interrelations between multi-input criteria.

Firstly, we recall the Dombi operations for IFNs.

Definition 6. [70]: For two IFNs $\varphi_j =< \mu_j,\ \nu_j >\ (j=1,2)$ and for $k>0$, we have.

$$(i)\ \varphi_1 \oplus \varphi_2 = \left\langle 1-\left(1+\left\{\sum_{q=1}^{2}\left(\frac{\mu_q}{1-\mu_q}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}, \left(1+\left\{\sum_{q=1}^{2}\left(\frac{1-\nu_q}{\nu_q}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle, \tag{16}$$

$$(ii)\ \varphi_1 \otimes \varphi_2 = \left\langle 1-\left(1+\left\{\sum_{q=1}^{2}\left(\frac{1-\mu_q}{\mu_q}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}, \left(1+\left\{\sum_{q=1}^{2}\left(\frac{\nu_q}{1-\nu_q}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle, \tag{17}$$

$$(iii)\ \zeta\varphi_1 = \left\langle 1-\left(1+\left\{\zeta\left(\frac{\mu_1}{1-\mu_1}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}, \left(1+\left\{\zeta\left(\frac{1-\nu_1}{\nu_1}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle (\zeta>0), \tag{18}$$

$$(iv)\ \varphi_1^{\zeta} = \left\langle 1-\left(1+\left\{\zeta\left(\frac{1-\mu_1}{\mu_1}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}, \left(1+\left\{\zeta\left(\frac{\nu_1}{1-\nu_1}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle\ (\zeta>0), \tag{19}$$

Theorem 1. [70]: For two IFNs $\varphi_j =< \mu_j,\ \nu_j >\ (j=1,2)$ and $\zeta,\ \zeta_1,\ \zeta_2>0$,

(i) $\varphi_1 \oplus \varphi_2 = \varphi_2 \oplus \varphi_1$,
(ii) $\varphi_1 \otimes \varphi_2 = \varphi_2 \otimes \varphi_1$,
(iii) $\zeta(\varphi_1 \oplus \varphi_2) = (\zeta\varphi_1) \oplus (\zeta\varphi_2)$,
(iv) $(\varphi_1 \otimes \varphi_2)^{\zeta} = (\varphi_1^{\zeta}) \otimes (\varphi_2^{\zeta})$,
(v) $(\zeta_1+\zeta_2)\varphi_1 = (\zeta_1\varphi_1) \oplus (\zeta_2\varphi_1)$,
(vi) $(\varphi_1 \otimes \varphi_2)^{\zeta_1+\zeta_2} = (\varphi_1^{\zeta_1}) \otimes (\varphi_2^{\zeta_2})$.

Definition 7. The IFDWGMSM operator on IFNs $\varphi_j =< \mu_j,\ \nu_j >\ (j=1(1)n)$ is defined as:

$$IFWDGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n) = \frac{1}{q}\left(\bigotimes_{1\le p_1<p_2<\cdots<p_q\le n}\left(\bigoplus_{j=1}^{q}\left(w_{p_j}\varphi_{p_j}\right)\right)\right)^{\frac{1}{n_{C_q}}}, \tag{20}$$

where $p_1,\ p_2,\ .,\ p_q \ge 0$, q is a parameter, and $(p_1, p_2, \ldots, p_r)$ stands for a q-tuple arrangement of natural numbers up to n.

Theorem 2. $IFWDGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n)$ is an aggregated FFN and.

$$IFWDGMSM\left(\varphi_1,\ \varphi_2,\ .,\ \varphi_n\right)$$

$$=\left\langle 1-\left(1+\left\{\frac{1}{q}\left(\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{\mu_{p_j}}{1-\mu_{p_j}}\right)^k\right)^{-1}\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1},\ \left(1+\left\{\frac{1}{q}\left(\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{1-\nu_{p_j}}{\nu_{p_j}}\right)^k\right)^{-1}\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle. \tag{21}$$

Proof of Theorem 2.

We have, $w_{p_j}\varphi_{p_j} = \langle 1 - \left(1+\left\{w_{p_j}\left(\frac{1-\mu_{p_j}}{\mu_{p_j}}\right)^k\right\}^{\frac{1}{k}}\right)^{-1},\ \left(1+\left\{w_{p_j}\left(\frac{\nu_{p_j}}{1-\nu_{p_j}}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\rangle$.

$$\therefore \bigoplus_{j=1}^{q}\left(w_{p_j}\varphi_{p_j}\right)=\left\langle 1-\left(1+\left\{\sum_{j=1}^{q}w_{p_j}\left(\frac{\mu_{p_j}}{1-\mu_{p_j}}\right)^k\right\}^{\frac{1}{k}}\right)^{-1},\ \left(1+\left\{\sum_{j=1}^{q}w_{p_j}\left(\frac{1-\nu_{p_j}}{\nu_{p_j}}\right)^k\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle.$$

So, $\bigotimes_{1\le p_1<p_2<\cdots<p_q\le n}\left(\oplus_{j=1}^{q}(w_{p_j}\varphi_{p_j})\right)$

$$=\left\langle\left(1+\left\{\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{\mu_{p_j}}{1-\mu_{p_j}}\right)^k\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1},1-\left(1+\left\{\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{1-\nu_{p_j}}{\nu_{p_j}}\right)^k\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle.$$

Then, $\left(\bigotimes_{1\le p_1<p_2<\cdots<p_q\le n}\left(\oplus_{j=1}^{q}(w_{p_j}\varphi_{p_j})\right)\right)^{\frac{1}{{}^nC_q}}$.

$= \langle\left(1+\left\{\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{\mu_{p_j}}{1-\mu_{p_j}}\right)^k\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1},\ 1-\left(1+\left\{\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{1-\nu_{p_j}}{\nu_{p_j}}\right)^k\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1}\rangle$Hence, $FWDGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n)$

$$=\left\langle 1-\left(1+\left\{\frac{1}{q}\left(\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{\mu_{p_j}}{1-\mu_{p_j}}\right)^k\right)^{-1}\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1},\left(1+\left\{\frac{1}{q}\left(\frac{1}{{}^nC_q}\sum_{1\le p_1<p_2<\cdots<p_q\le n}\left(\sum_{j=1}^{q}w_{p_j}\left(\frac{1-\nu_{p_j}}{\nu_{p_j}}\right)^k\right)^{-1}\right)^{-1}\right\}^{\frac{1}{k}}\right)^{-1}\right\rangle.$$

The FFDWGMSM operator obeys the following properties.

Theorem 3. (*Idempotency*): Let $\varphi_j = \varphi_0 =< \mu_0,\ \nu_0 >\ (j = 1(1)n)$. Then $FFDWGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n) = \varphi_0$..

Theorem 4. (*Boundedness*): $\varphi^- \prec FFDWGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n) \prec \varphi^+$, for$\varphi^- =< \min_j \mu_j,\ \max_j \nu_j >$ and $\wp^+ = < \max_j \mu_j,\ \min_j \nu_j >$ . .

Theorem 5. (*Monotonicity*): For another collection of FFNs $\varphi'_j =< \mu'_j,\ \nu'_j >\ (j = 1(1)n)$ satisfying $\mu_k \le \mu'_k$, and $\nu_k \ge \nu'_k$,$FFDWGMSM(\varphi_1,\ \varphi_2,\ .,\ \varphi_n) \prec FFDWGMSM(\varphi'_1,\ \varphi'_2,\ .,\ \varphi'_n)$..

4. Case study

In this part, the problem to be investigated, the criteria employed for dealing with this problem, and the results acquired by applying the suggested approach are given.

4.1. Problem definition

In recent decades, the need to enhance the performance of the railway sector, address low traffic issues, and boost intra-African trade in transport services has gained significant importance. This growing recognition of the social, economic, and environmental benefits of railway transportation has led African countries to gradually develop new railway lines and renovate existing ones through international partnerships. However, despite these efforts, the railway sector still faces numerous challenges that hinder its performance. To address this, a decision-making framework has been developed, drawing upon a literature review and the insights of experts, to identify and classify the factors that negatively impact the performance of the railway sector. In order to improve the sector's performance, it is crucial to propose appropriate actions in response to these challenges. This study involves the participation of eleven experts, including transportation specialists and academicians, whose detailed backgrounds are provided in Table 3.

4.2. Definition of alternatives

Owing to years of deficient infrastructure management, insufficient funding, and inadequate train operations, the railway sector has experienced a decline. In a report by Olievschi [6], nine distinct alternatives are proposed to facilitate proactive collaboration between governments and private entities, aimed at improving the performance of Sub-Saharan African railways. These alternatives seek to address the pressing needs and challenges faced by the sector, with the ultimate goal

Table 3
Demographic profile of participants.

Characteristics	Frequency
Category of age	
21–31	1
31–39	4
39–45	4
45–58	2
Gender	
Female	3
Male	8
Degree of Education	
Bachelor's	2
Master's	5
PhD	4
Role of participants	
Academic expert	5
Transport expert	6
Years of experience (Y)	
≥ 15	3
$10 \leq Y < 15$	6
$5 \leq Y < 10$	2
Total available number	11

Table 4
Interoperability of railways in SSA region.

Country	Interoperability of African railways	Country	Interoperability of African railways
West Africa		**East Africa**	
Benin	IS	Burundi	NOP
Burkina Faso	IN	Comoros	NOP
Cabo Verde/ Cape Verde	—	Djibouti	IN
Côte d'Ivoire	IN	Ethiopia	IN
Gambia	——	Eritrea	IS
Ghana	IS	Kenya	IN
Guinea	IS	Madagascar	IS
Guinea-Bissau	—	Malawi	IN
Liberia	IS	Mauritius	NOP
Mali	IN	Mozambique	IN
Mauritania	IS	Reunion	NOP
Niger	—	Rwanda	NOP
Nigeria	IS	Seychelles	—
Senegal	IN	Somalia	NOP
Sierra Leone	IS	South Sudan	IN
Togo	IS	Tanzania	IN
Central Africa		Uganda	IN
Angola	IN	Zambia	IN
Cameroon	IS	Zimbabwe	IN
Chad	—	**Southern Africa**	
Central African Republic	—	Botswana	IN
Congo Republic	IS	Lesotho	IN
Democratic Republic of Congo	IN	Namibia	IN
Equatorial Guinea	NOP	South Africa	IN
Gabon	IS	Swaziland	IN

Note: IS-isolated. IN-integrated. NOP-not operated. (—)-never had a railway.

of restoration.

A1*: Enhance the governance of the transport sector:* Highlighting the paramount importance of enhancing governance extends beyond the railway sector alone, encompassing the entire region and all sectors of society. It would be erroneous to assume that establishing a successful railway transport sector, characterized by robust governance, long-term vision, successful concessions, and amicable partner renegotiations for mutual benefit, can be achieved in a country where these practices are not ingrained as standard.

A2: *Develop long-term solutions for making the necessary investments in railway infrastructure:* In contrast to the substantial investment allocated to road infrastructure in the region, it becomes evident that collaborative efforts between governments and concessionaires can make the revitalization of the railway sector feasible. The key lies in implementing a sustainable program for rehabilitating railway infrastructure, which requires a fundamental shift in the prevailing financing paradigm. It is imperative to promptly introduce mechanisms that enable the allocation of public funds specifically for railway infrastructure investments, mirroring the established practices commonly employed for road projects.

A3*: Establish realistic traffic growth forecasts and set the duties of the concessionaire accordingly:* Establishing a fruitful partnership between governments and concessionaires requires a shared mindset of mutual benefit and long-term collaboration to accomplish their objectives. Accurate evaluations of traffic growth, regular assessments of progress, and updated predictions are integral for effective collaboration. These factors play a critical role in determining reasonable concession fees and taxes that governments should receive. Governments must remain committed to their long-term goals throughout their engagement with the private sector, ensuring a harmonious and successful partnership.

A4: *Address the issue of passenger transport services:* It is recommended to employ distinct concession agreements to address the concession of passenger transportation services. The existing practice of bundling freight and passenger services within the same concession agreement is not advisable.

A5*: Avoid undercapitalized concessions:* Governments must undertake a rigorous assessment of the capital bases of candidates during the concessionaire selection process. This evaluation is essential to determine their ability to effectively handle operational challenges. Accurate evaluations of market growth, the costs associated with updating the required rolling stock, and the operational expenses should form the basis of this assessment.

A6*: Enhance the regulatory environment for railway concessions*: The complete implementation of regulatory mechanisms can be a time-consuming process, often facing substantial challenges in many countries of SSA region. As a short-term measure, it is highly recommended to incorporate elements of regulatory frameworks into concession agreements. This inclusion serves to facilitate the effective management of relationships between governments and concessionaires.

A7*: Acting to create a friendlier business environment:* In order to stimulate private sector investment in SSA region, it is crucial for governments to demonstrate notable advancements in showcasing the competitiveness of their economies. Key factors in this regard include government effectiveness, social stability, the absence of violence, anti-corruption measures, and the accountability of public officials. By prioritizing these aspects, governments can enhance the reputation of the private sector and create an environment that fosters foreign investment.

A8*: Acting for developing the utilization of regional corridors in SSA region*: To bolster the increase in railway volumes and foster economic development in the region, it would be beneficial to develop coordinated regional policies. These policies should focus on facilitating the smooth flow of traffic along transportation corridors, addressing any issues related to border stations, and establishing well-suited logistic hubs.

A9*: Acting for better utilization of international financial support*: The railway transport sector relies heavily on international aid due to limited government revenues, as it necessitates substantial financial resources. To expand beyond the existing reliance on funding from international financial institutions for railway infrastructure rehabilitation, it is important to introduce new programs that offer assistance for the progressive achievement of goals.

In the SSA region, the operational railway network encompasses both passenger and freight transport. Among the 48 countries in the region, seven countries currently do not have any functioning railways, as indicated in Table 4.

Fig. 2 indicates the railway network in different SSA zones.

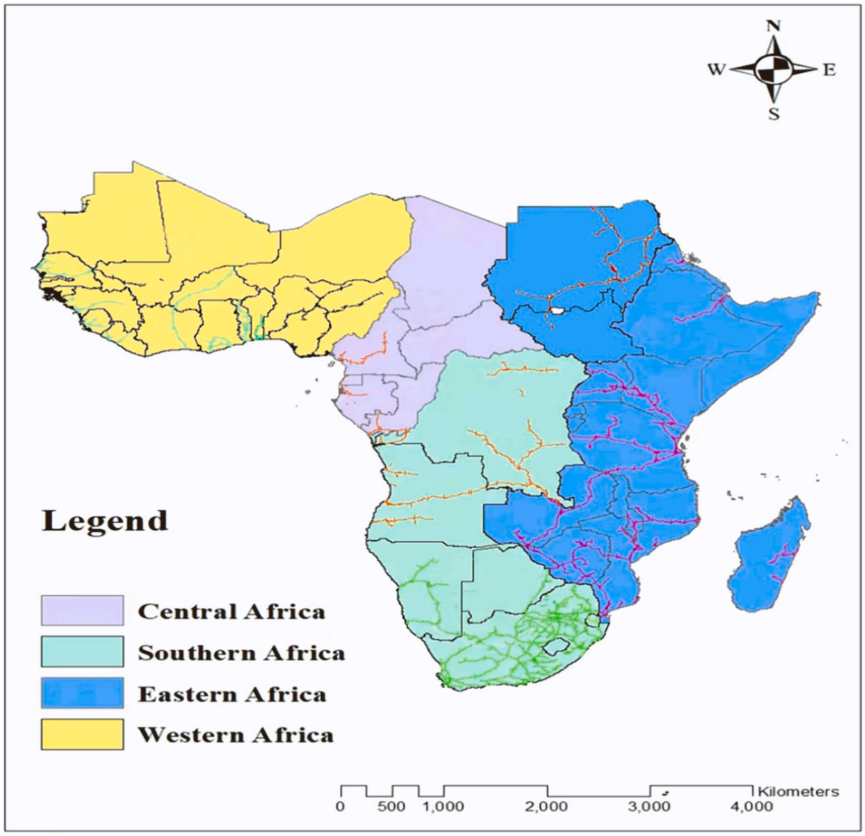

Fig. 2. Railway interoperability in SSA region.

Table 5
List of criteria (challenges).

Criteria	References (Sources)
Obsolete, non-functional infrastructure (**C1**)	[2,71,72]
Reduced connectivity between the countries in the region (**C2**)	[3,73]
Very low traffic for the existing railway network (**C3**)	[1,2,6]
Unsatisfactory agreements for operating passenger transport services (**C4**)	[2,6,74]
Chronic lack of resources to finance the maintenance and rehabilitation of infrastructure (**C5**)	[4]
Lack of competitiveness compared to road transport (**C6**)	[6,38]

4.3. Criteria definition

Based on the literature review and expert opinions, six key challenges have been identified and subsequently validated as can be seen in Table 5.

Fig. 3 illustrates the hierarchical decision-making process used to prioritize actions aimed at enhancing the railway sector's performance.

C1*: Obsolete, non-functional infrastructure:* Railway systems within SSA region are commonly associated with several challenges, including inadequate infrastructure, outdated technology, and substandard safety and operational performance. Insufficient investment and neglect over the years have resulted in a substantial number of railway sections in various countries becoming non-operational and requiring extensive refurbishment. Overall, the condition of railway infrastructure in SSA countries is notably deteriorated. For instance, the Benin Republic experiences non-functionality in 23% of its railways, while in Uganda, this number reaches a staggering 91% [2,71]. Similarly, a significant portion of Ghana's rail network, approximately 60%, remains idle [72].

C2*: Reduced connectivity between the countries in the region:* Insufficient length and substandard quality of railway routes are currently posing significant challenges in ensuring effective regional connectivity for landlocked countries [3]. The majority of existing railway lines are single tracks that predominantly connect inland destinations to coastal areas, resulting in limited opportunities for interconnection. In Northern Africa, apart from Algeria and Sudan, which maintain railway connections with Tunisia and South Sudan respectively, the remaining networks are either isolated (Morocco and Egypt) or non-operationalized (Libya and Western Sahara). In West Africa, two international networks (Bamako-Dakar and Ouagadougou-Abidjan) facilitate the transportation needs of landlocked countries [73]. East Africa features two distinct networks: (1) Tanzania, Kenya, and Uganda, and (2) a network linking Addis Ababa in Ethiopia to Djibouti. In Southern and Central Africa, the railway infrastructure exhibits interconnectivity through the Democratic Republic of Congo and southern Tanzania.

C3*: Very low traffic for the existing railway network:* Within SSA region, the railway network operates with significant limitations, accounting for a mere 11.6% of freight volumes and a mere 1.7% of passenger transportation across the entire continent [2]. By operating within such a small market, SSA's railways struggle to capitalize on the economies of scale that typically characterize this mode of transportation. Furthermore, the average traffic density achieved within the region was less than 1 million traffic units per rail-route-kilometer, which is four times

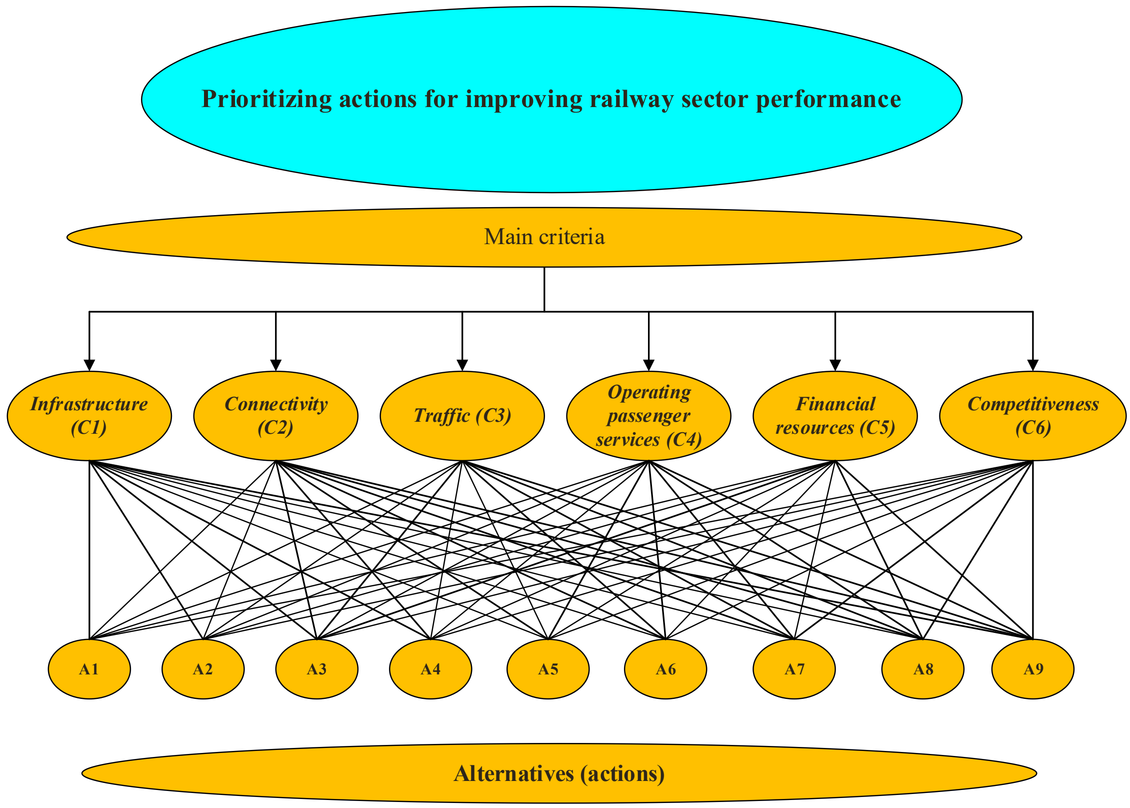

Fig. 3. The decision hierarchy of prioritizing actions for improving railway performance.

lower than the continental average and six times lower than the traffic intensity observed in South Africa's robust railway system. This prevailing situation can be attributed to a historical prioritization of road infrastructure development at the expense of railway infrastructure [1, 6].

***C4**: Unsatisfactory agreements for operating passenger transport services*: Despite sustained economic growth in the majority of sub-Saharan countries over the past decade, there has been a lack of observable progress in the expansion of railway passenger services [2,6]. Most railways have experienced stagnation or decline in passenger traffic, as road transportation continues to outpace them [74]. Furthermore, these passenger services often rely on cross-subsidies from freight transport, which presents an additional obstacle to the growth of freight transportation. The lack of clarity in concession agreements and governments' failure to fulfill compensation commitments have resulted in concessionaires showing little interest in operating passenger services. Consequently, the quality of these services has steadily deteriorated, leading to a contraction in the market.

***C5**: Chronic lack of resources to finance the maintenance and rehabilitation of infrastructure:* The considerable funding shortfall confronting African infrastructures has long been recognized, prompting extensive efforts by national governments, bilateral and multilateral donors, and private investors to mitigate it. Prior to considering new projects, it has been estimated that inadequate long-term maintenance, particularly in the railway sector, has led to an accumulated investment backlog of up to $3 billion [4].

***C6**: Lack of competitiveness compared to road transport:* The railway network in the SSA region spans approximately 56,000 km, which represents a mere 2% of the total length of operating railway lines worldwide. However, the majority of railway infrastructure in SSA region is outdated and ill-suited to meet the demands of modern traffic operations. Many structures and track components have surpassed the century

Table 6
Calculation and outcomes of the application of IR-PIPRECIA and inverse IR-PIPRECIA for criteria.

PIPR.	s_j				k_j				q_j				w_j			
C1					1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.070	0.175	0.135	0.232
C2	1.10	1.28	1.26	1.52	0.480	0.740	0.720	0.900	1.111	1.389	1.351	2.083	0.078	0.243	0.182	0.483
C3	0.51	0.88	0.64	1.03	0.970	1.360	1.120	1.490	0.746	1.240	0.994	2.148	0.052	0.217	0.134	0.498
C4	0.62	0.98	0.75	1.11	0.890	1.250	1.020	1.380	0.540	1.216	0.795	2.413	0.038	0.213	0.107	0.559
C5	1.02	1.11	1.13	1.27	0.730	0.870	0.890	0.980	0.551	1.366	0.914	3.306	0.039	0.239	0.123	0.766
C6	0.49	0.87	0.61	1.00	1.000	1.390	1.130	1.510	0.365	1.209	0.657	3.306	0.026	0.212	0.089	0.766
SUM									4.314	7.420	5.711	14.256				
PIPR-I	s_j				k_j				q_j				w_j			
C1	0.54	0.77	0.70	0.92	1.080	1.300	1.230	1.460	0.159	0.503	0.252	0.958	0.027	0.140	0.057	0.315
C2	0.58	1.03	0.67	1.16	0.840	1.330	0.970	1.420	0.233	0.619	0.327	1.034	0.039	0.172	0.074	0.340
C3	0.51	0.92	0.60	1.04	0.960	1.400	1.080	1.490	0.330	0.600	0.435	0.869	0.056	0.167	0.099	0.286
C4	0.32	0.41	0.39	0.52	1.480	1.610	1.590	1.680	0.492	0.648	0.609	0.834	0.083	0.180	0.138	0.274
C5	0.79	1.03	0.98	1.19	0.810	1.020	0.970	1.210	0.826	1.031	0.980	1.235	0.139	0.286	0.223	0.406
C6					1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.169	0.278	0.227	0.329
									3.040	4.402	3.603	5.930				

Table 7
Initial assessment data by experts'.

	E1						**E2**						**E3**					
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6
A1	9	7	3	1	8	7	8	9	8	9	9	7	5	8	2	2	8	4
A2	9	9	8	4	6	7	9	9	7	6	8	8	9	9	7	4	9	6
A3	7	7	4	5	9	5	4	4	9	8	5	6	2	2	8	1	2	8
A4	2	3	3	7	8	8	8	8	9	9	7	7	3	3	6	3	1	9
A5	7	6	6	7	4	8	6	7	4	5	7	6	4	2	2	3	6	3
A6	8	8	8	7	9	5	7	7	5	6	7	6	8	6	6	7	4	4
A7	8	8	8	8	8	8	5	5	7	8	8	7	4	2	3	4	3	4
A8	9	9	6	5	6	5	6	6	7	8	8	8	8	9	8	3	5	8
A9	9	9	9	7	8	6	6	6	4	4	6	6	5	3	2	1	2	2
	E4						E5						E6					
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6
A1	7	7	7	7	8	7	9	9	3	9	9	3	7	8	5	7	8	8
A2	8	7	7	5	8	7	9	9	1	1	9	9	7	8	6	7	8	8
A3	6	5	7	7	5	5	4	3	9	3	3	9	5	5	8	5	3	5
A4	5	5	7	7	5	5	1	9	9	1	2	9	3	3	7	7	5	8
A5	5	5	4	5	6	5	1	1	2	9	9	2	3	5	7	7	8	8
A6	6	5	5	7	6	5	1	2	2	9	9	1	8	9	7	5	5	8
A7	5	5	5	6	6	5	4	5	5	9	9	9	3	4	7	5	5	5
A8	5	7	7	5	5	5	1	9	8	6	7	7	5	8	3	3	4	7
A9	7	6	5	5	8	6	7	8	4	9	9	9	8	9	5	7	8	8
	E7						E8						E9					
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6
A1	5	7	6	7	8	8	6	5	6	5	8	6	8	9	7	6	9	7
A2	6	7	7	7	7	8	8	4	7	5	8	7	9	7	8	6	9	6
A3	7	8	6	6	5	8	3	6	8	5	3	6	5	5	9	7	4	7
A4	8	8	7	7	6	7	5	3	4	7	5	5	7	7	9	9	9	5
A5	5	6	6	7	7	7	6	5	8	5	8	6	8	8	5	5	7	5
A6	4	7	6	6	7	6	5	3	6	6	6	7	9	9	7	7	9	5
A7	8	7	6	7	8	7	6	6	7	6	7	6	8	8	7	8	9	7
A8	8	8	8	7	8	8	7	9	6	4	6	8	8	9	8	9	9	5
A9	7	7	6	5	8	7	7	6	6	5	7	6	9	9	9	7	9	5
	E10						E11											
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6						
A1	9	8	7	8	9	8	5	1	8	2	8	3						
A2	9	9	8	8	9	8	7	5	5	2	8	2						
A3	8	7	7	5	5	8	4	3	5	2	1	8						
A4	5	7	5	8	8	8	1	7	4	8	2	5						
A5	8	8	5	7	8	8	7	3	2	5	9	2						
A6	9	7	5	5	8	7	6	3	5	4	8	1						
A7	8	8	5	8	9	8	4	8	2	5	3	1						
A8	8	8	5	5	8	8	5	5	8	6	2	1						
A9	9	9	8	5	9	8	8	3	4	1	2	2						

Table 8
Ranks of criteria by using the IR-PIPRECIA.

Criteria	Final w_j	Rank
C1	[0.084, 0.245] [0.163,0.389]	6
C2	[0.098, 0.329] [0.219,0.653]	3
C3	[0.080, 0.300] [0.183,0.641]	5
C4	[0.079, 0.303] [0.176,0.697]	4
C5	[0.108, 0.382] [0.235,0.969]	1
C6	[0.110, 0.350] [0.202,0.931]	2

mark, indicating the obsolete nature of the railways. This aging infrastructure faces significant issues such as deteriorating tracks, poorly maintained structures, outdated signaling and telecommunication systems, and a lack of available spare parts. The imposition of speed limits on longer sections further hampers the productivity of rolling stock and diminishes the overall competitiveness of the railway sector. Moreover, with the expansion of modern road networks along major transportation corridors, the railways encounter serious challenges in their struggle to remain competitive [6,38].

Table 9
Aggregated IF decision matrix.

	C1	**C2**	**C3**	**C4**	**C5**	**C6**
A1	< 0.647, 0.259 >	< 0.266, 0.617 >	< 0.382, 0.511 >	< 0.263, 0.622 >	< 0.860,0.0929 >	< 0.462,0.4369 >
A2	< 0.775, 0.147 >	< 0.601, 0.305 >	< 0.267, 0.614 >	< 0.266, 0.617 >	< 0.770, 0.149 >	< 0.383, 0.508 >
A3	< 0.385, 0.507 >	< 0.382, 0.511 >	< 0.587, 0.317 >	< 0.268, 0.615 >	< 0.264, 0.619 >	< 0.653, 0.254 >
A4	< 0.244, 0.644 >	< 0.442, 0.457 >	< 0.485, 0.414 >	< 0.267, 0.615 >	< 0.244, 0.617 >	< 0.244, 0.264 >
A5	< 0.267,0.615 >	< 0.266, 0.617 >	< 0.343, 0.552 >	< 0.495, 0.404 >	< 0.591, 0.315 >	< 0.356, 0.537 >
A6	< 0.267, 0.614 >	< 0.381, 0.512 >	< 0.385, 0.506 >	< 0.585, 0.319 >	< 0.593, 0.313 >	< 0.245, 0.643 >
A7	< 0.493, 0.406 >	< 0.387, 0.504 >	< 0.380, 0.512 >	< 0.589, 0.315 >	< 0.465, 0.434 >	< 0.266, 0.617 >
A8	< 0.267, 0.614 >	< 0.683, 0.229 >	< 0.506, 0.394 >	< 0.470, 0.428 >	< 0.383, 0.509 >	< 0.266, 0.617 >
A9	< 0.686, 0.226 >	< 0.465, 0.434 >	< 0.387, 0.504 >	< 0.245, 0.642 >	< 0.358, 0.535 >	< 0.358, 0.535 >

5. Results and validation analysis

5.1. Results of the case study

The following decision-making steps are performed to obtain the results.

Step 1*:* Express experts' assessments in terms of linguistic decision-matrices and obtain criteria weights by the IR-PIPRECIA method.

Step 2*:* Determine express experts' using the technique described

and Bullock [2] which put the financial issues among the major parameters driving the poor maintenance and operation status of the regional railway system. The second-ranked challenge is a lack of competitiveness, which supports a study by Olievschi [6] that found that most railways are experiencing stagnation or a decline in passenger traffic, losing ground to road transportation.

We utilize Eq. (22) and obtain the followings:

$$r_1 = 0.95 \times (2 - 0.95 - 0.05) = 0.95.$$

$$\text{Similarly,} \quad r_2 = 0.77, r_3 = 0.84, r_4 = 0.55, r_5 = 0.8925, r_6 = 0.66, r_7 = 0.77, r_8 = 0.66,$$

$$r_9 = 0.84, r_{10} = 0.8925, r_{11} = 0.95.$$

$$\therefore \; w_1 = \frac{0.95}{0.95 + 0.77 + 0.84 + 0.55 + 0.8925 + 0.66 + 0.77 + 0.66 + 0.84 + 0.8925 + 0.95} = 0.1083.$$

below:

Suppose $r_k = \langle \mu_k, \nu_k \rangle$ be an IFN for the rating of the k-th expert. Then the weight w_k of the k-th expert can be formulated as:

$$w_k = \frac{r_k}{\sum_{k=1}^{l} r_k}, \quad \text{where } r_k = \mu_k \times \left(2 - \mu_k - \nu_k \right) \tag{22}$$

Step 3*:* Convert linguistic decision-matrices to IF decision-matrices.

Step 4*:* Compute the aggregated IF decision matrix using the IFWGD operator.

Step 5*:* Normalize the aggregated IF decision-matrix if any cost attribute is present.

Step 6*:* Determine the final aggregated IFNs using the proposed WGDMSM operator under IF environment.

Step 7*:* Calculate the scores of the final aggregated IFNs and rank the alternatives according to their descending order of scores.

The Calculation and outcomes of the application of IR-PIPRECIA and inverse IR-PIPRECIA for criteria are provided in Table 6. Table 7 shows the evaluation of the importance of criteria by eleven experts who took part in the decision-making category. The evaluation was carried out according to the established scales explained in reference [32].

The significance of the above ratings in terms of IFNs is as follows:

1: (0.2, 0.7), **2**: (0.3, 0.6), **3**: (0.4, 0.5), **4**: (0.5, 0.4), **5**: (0.6, 0.3), **6**: (0.7, 0.2), **7**: (0.8, 0.15),

8: (0.85, 0.10), **9**: (0.95, 0.05).

Table 8 indicates the ranks of criteria by using the IR-PIPRECIA. Six criteria that characterized the challenges to the performance of the railway sector were investigated. Based on the weight obtained, we have the ranking order C5 > C6 > C2 > C4 > C3 > C1. The most critical challenge is the lack of financial resources. Our findings are consistent with prior studies by Blumenfeld, Wemakor, Azzouz and Roberts [38]

Similarly, the other experts' weights are:

w_2= 0.0877, w_3= 0.0957, w_4= 0.0627, w_5= 0.1017, w_6= 0.0752, w_7= 0.0877, w_8= 0.0752, w_9= 0.0957, w_{10}= 0.1017, and w_{11}= 0.1083. Converting the linguistic elements to IFNs and using the IFWGD operator, the aggregated IF decision-making matrix is obtained (Table 9). The aggregated IFNs of this matrix are:

Aggregated IFN for A_1 under C_1.

= <1/(1 +((0.1083 *(((1–0.95)/0.95)ˆ6)+ 0.0877 * (((1–0.85)/0.85)ˆ6)+ 0.0957 * (((1–0.6)/0.6)ˆ6)+ 0.0627 * (((1–0.8)/0.8)ˆ6) + 0.1017 * (((1–0.95)/0.95)ˆ6)+ 0.0752 * (((1–0.8)/0.8)ˆ6)+ 0.0877 * (((1–0.6)/0.6)ˆ6)+ 0.0752 * (((1–0.7)/0.7)ˆ6)+ 0.0957 * (((1–0.85)/0.85)ˆ6)+ 0.1017 * (((1–0.95)/0.95)ˆ6)+ 0.1083 * (((1–0.6)/0.6)ˆ6))ˆ(1/6))), 1-(1/(1 +((0.1083 *((0.05/(1–0.05))ˆ6)+ 0.0877 * ((0.1/(1 –0.1)) ˆ6) + 0.0957 * ((0.3/(1–0.3))ˆ6)+ 0.0627 * ((0.15/(1–0.15))ˆ6)+ 0.1017 * ((0.05/(1–0.05))ˆ6)+ 0.0752 * ((0.15/(1–0.15))ˆ6)+ 0.0877 * ((0.3/(1–0.3))ˆ6)+ 0.0752 * ((0.2/(1–0.2))ˆ6) + 0.0957 * ((0.1/ (1–0.1))ˆ 6)+ 0.1017 * ((0.05/(1–0.05))ˆ6)+ 0.1083 * ((0.3/(1–0.3))ˆ6))ˆ(1/6))))> .

= <0647, 0.259 > .

Similarly, we can obtain the other aggregated IFNs. As no cost attribute is present, we skip the step of normalization.

The final aggregated IFNs are computed using the WGDMSM operator under IF environment and their corresponding scores are noted (Table 10). As an instance, the computational step for the final aggregated IFN corresponding to A_1 is:

< 1-(1/(1 +(((1/6)* (0.22 *((0.647/(1–0.647))ˆ6)+ 0.325 * ((0.266/(1–0.266))ˆ6)+ 0.301 * ((0.382/(1–0.382))ˆ6)+ 0.314 * ((0.263/(1–0.263))ˆ6)+ 0.424 * ((0.860/(1–0.860))ˆ6)+ 0.398 * ((0.462/(1–0.462))ˆ6)))ˆ(1/6)))), 1/(1 +(((1/6)* (0.22 *(((1–0.259)/0.259)ˆ6)+ 0.325 * (((1–0.617)/0.617)ˆ6) + 0.301 * (((1–0.511)/0.511)ˆ6)+ 0.314 * (((1–0.622)/0.622)ˆ6)+ 0.424 * (((1–0.093)/0.093) ˆ6)+ 0.398 * (((1–0.437)/0.437)ˆ6)))ˆ(1/6)))> .

i.e.; < 0.798, 0.137 > .

Based on the scores obtained in Table 10, we have the ranking order $A_1 \succ A_2 \succ A_8 \succ A_9 \succ A_3 \succ A_6 \succ A_5 \succ A_7 \succ A_4$, where "$>$ " means "superior to". The most suitable action for improving the performance of the railway sector is "enhancing the governance of the transport sector (A1) with a score of 0.830. Focusing on the aspect of passenger transportation services (A4) is determined as the least suitable action for improving the performance of the railway sector.

Table 10
Final Aggregated matrix.

	Aggregated IFNs	Scores
A1	< 0.798, 0.137 >	0.830
A2	< 0.700, 0.202 >	0.748
A3	< 0.550, 0.344 >	0.603
A4	< 0.376, 0.359 >	0.508
A5	< 0.485, 0.414 >	0.535
A6	< 0.504, 0.395 >	0.554
A7	< 0.474, 0.424 >	0.525
A8	< 0.570, 0.325 >	0.622
A9	< 0.558, 0.336 >	0.611

5.2. Validation analysis and Discussion

This section is divided into three parts, as described below.

Table 11
Various weights set for criteria.

	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
G1	0.22	0.325	0.301	0.314	0.424	0.398	G13	0.22	0.325	0.424	0.314	0.398	0.301
G2	0.22	0.325	0.301	0.314	0.398	0.424	G14	0.22	0.398	0.424	0.314	0.325	0.301
G3	0.325	0.22	0.301	0.314	0.424	0.398	G15	0.424	0.398	0.22	0.314	0.325	0.301
G4	0.325	0.22	0.301	0.424	0.314	0.398	G16	0.424	0.398	0.22	0.314	0.301	0.325
G5	0.325	0.301	0.22	0.424	0.314	0.398	G17	0.424	0.325	0.22	0.314	0.301	0.398
G6	0.325	0.301	0.424	0.22	0.314	0.398	G18	0.424	0.325	0.22	0.398	0.301	0.314
G7	0.325	0.424	0.301	0.22	0.314	0.398	G19	0.424	0.325	0.22	0.301	0.398	0.314
G8	0.325	0.424	0.22	0.301	0.314	0.398	G20	0.314	0.325	0.22	0.301	0.398	0.424
G9	0.398	0.424	0.22	0.301	0.314	0.325	G21	0.314	0.325	0.22	0.301	0.424	0.398
G10	0.398	0.424	0.22	0.301	0.325	0.314	G22	0.314	0.325	0.398	0.301	0.424	0.22
G11	0.22	0.325	0.301	0.424	0.398	0.314	G23	0.314	0.325	0.398	0.424	0.301	0.22
G12	0.22	0.325	0.301	0.314	0.398	0.424	G24	0.314	0.325	0.301	0.424	0.398	0.22

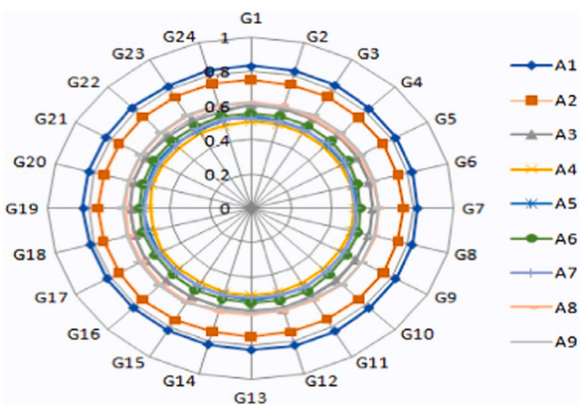

Fig. 4. Sensitivity analysis of criteria weights.

5.2.1. *Sensitivity Analysis of the Criteria Weights*

We consider different criteria weight sets, namely G1, G2, …, and G24 (Table 11) to verify the impact of the criteria weights on the priority order. These weights' sets are developed through different arrangements of the criteria weights; i.e.,$w_1 = 0.220$, $w_2 = 0.325$, $w_3 = 0.301$ $w_4 = 0.314$, $w_5 = 0.424$, and $w_6 = 0.398$. The results of the performed sensitivity analysis are depicted in Fig. 4.

The ranking order obtained in each scenario is given in Table 11 according to which the alternative "Enhance the governance of the transport sector" (A_1) holds the first place in all scenarios when the WGDMSM operator under IF environment is applied.

Then, we calculate Spearman's rank correlation coefficient (SRCC) values (Table 12), the average of which is found to be 0.9805. This signifies a "strong correlation" among different priority ordering [75]. Thus, the ranking order obtained is credible.

5.2.2. *Impact on the priority order*

To illustrate the influence of the parameter 'k' upon the score values, the operator WGDMSM under IF environment is used for $k \in \{1, 2, ., 24\}$. We utilize diverse parameter values $k \in \{1, 2, ., 24\}$ to illustrate its impact. The related score values of the investigated alternatives are depicted in Fig. 5.

The ranking order in each case is given in Table 13. Clearly, from Table 13, it follows that there is a slight change in the ranking position of alternatives, but the best alternative (A_1) remains the same except for the first case. Then, we calculate Spearman's rank correlation coefficient (SRCC) values (Table 13), the average of which is found to be 0.9882. This signifies a "strong correlation" among different priority ordering [76]. So, the ranking order obtained is credible.

5.2.3. *Comparative study*

To validate our developed model with the WDGMSM operator under IF environment, we present the comparative study with existing models namely- Huang [77] using the IFHWA operator, Seikh and Mandal [70] using the IFDWA operator, and Senapati, Chen and Yager [78] using the IFAAWA operator. Outcomes are presented in Fig. 6 and corresponding ranking orders are given in Table 14.

In practical multi-criteria group decision making (MCGDM)

Table 12
Ranking positions and SRCC values.

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
A1	1	1	1	1	1	1	1	1	1	1	1	1
A2	2	2	2	2	2	2	2	2	2	2	2	2
A3	5	5	5	5	5	5	5	5	5	5	5	5
A4	9	9	9	9	9	8	9	9	9	9	9	9
A5	7	7	7	8	8	7	7	8	8	7	8	7
A6	6	6	6	6	6	6	6	6	6	6	6	6
A7	8	8	8	7	7	9	8	7	7	8	7	8
A8	3	3	4	4	4	4	3	3	4	4	3	3
A9	4	4	3	3	3	3	4	4	3	3	4	4
SRCC value	1	1	0.983	1	1	1	1	1	1	1	1	1
	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24
A1	1	1	1	1	1	1	1	1	1	1	1	1
A2	2	2	2	2	2	2	2	2	2	2	2	2
A3	5	5	5	5	5	5	5	5	5	5	5	5
A4	9	9	8	9	9	9	9	9	9	9	9	9
A5	7	7	8	8	8	8	7	7	7	7	8	8
A6	6	6	6	6	6	6	6	6	6	6	6	6
A7	8	8	7	7	7	7	8	8	8	8	7	7
A8	3	3	4	4	4	4	4	4	4	4	4	4
A9	4	4	3	3	3	3	3	3	3	3	3	3
SRCC value	1	1	0.96	0.97	0.97	1	1	1	1	1	0.97	1

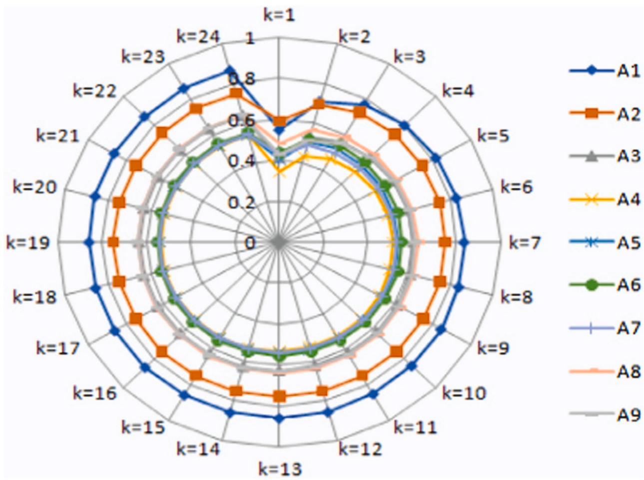

Fig. 5. Effects of the parameter 'k′ upon scores of alternatives.

problems, the interdependence among various criteria is evident. For example, let's consider an MCGDM problem that involves assessing five OSS-LMS packages (alternatives) - ATutor, Dokeos, Moodle, Sakai, and efront - based on different criteria such as activity tracking, assessment, maintenance and upgrading, course development, error reporting, efficiency, backup and recovery, and troubleshooting. In this case, there is a connection between activity tracking, assessment, backup and recovery. Consequently, it becomes crucial to consider the interrelationships among multiple criteria to arrive at a more reasonable decision. Unfortunately, the existing methods [70,77,79] are unable to address this particular situation.

In practical scenarios, not all criteria carry equal importance, and it is crucial to assess their weights in a logical manner. However, existing decision-making methodologies [70,77,79] often assign criteria weights arbitrarily during the aggregation of criteria values. As a result, the final ranking is influenced, and these methods fail to mitigate the impact of extreme assessment criteria values provided by biased experts with different perspectives. This hidden issue adversely affects decision outcomes in any decision-making process. To address this problem, it is essential to consider a robust and objective method for determining criteria weights.

The main advantages of our method are as follows:

1. The WDGMSM operator, proposed under IF environment, offers enhanced flexibility in aggregating IF data. It also considers the interrelationships among multiple input criteria. By combining the Dombi operator and geometric MSM operator, these operators have

Table 13
Ranking positions and SRCC values for different values of 'k′.

	k = 1	k = 2	k = 3	k = 4	k = 5	k = 6	k = 7	k = 8	k = 9	k = 10	k = 11	k = 12
A1	2	1	1	1	1	1	1	1	1	1	1	1
A2	1	2	2	2	2	2	2	2	2	2	2	2
A3	7	4	4	5	5	5	5	5	5	5	5	5
A4	9	9	9	9	9	9	9	9	9	8	9	9
A5	8	7	7	7	7	7	7	7	7	7	7	7
A6	4	5	6	6	6	6	6	6	6	6	6	6
A7	5	8	8	8	8	8	8	8	8	7	8	8
A8	3	3	3	3	3	3	3	3	3	3	3	3
A9	6	6	5	4	4	4	4	4	4	4	4	4
SRCC value	0.8	0.95	1	1	1	1	1	1	1	0.98	1	1
	k = 13	k = 14	k = 15	k = 16	k = 17	k = 18	k = 19	k = 20	k = 21	k = 22	k = 23	k = 24
A1	1	1	1	1	1	1	1	1	1	1	1	1
A2	2	2	2	2	2	2	2	2	2	2	2	2
A3	5	5	5	5	5	5	5	5	5	5	5	5
A4	9	9	9	9	9	9	9	9	9	9	9	9
A5	7	7	7	7	7	7	7	7	7	7	7	7
A6	6	6	6	6	6	6	6	6	6	6	6	6
A7	8	8	8	8	8	8	8	8	8	8	8	8
A8	3	3	3	3	3	3	3	3	3	3	3	3
A9	4	4	4	4	4	4	4	4	4	4	4	4
SRCC value	1	1	1	1	1	1	1	1	1	1	1	1

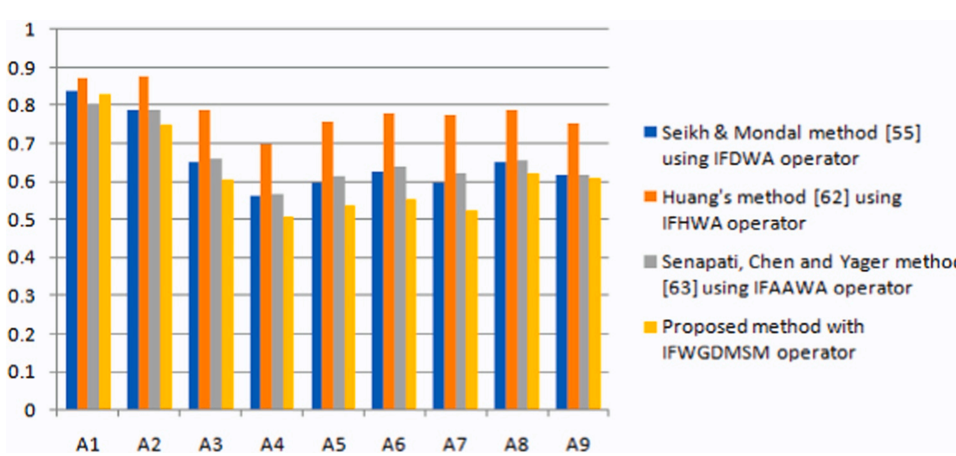

Fig. 6. Comparative study: Existing Vs. Proposed.

Table 14
Ranking positions and SRCC values.

	Seikh and Mandal[70] method using IFDWA operator	Huang[77] method using the IFHWA operator	Senapati, Chen and Yager[78] method using IFAAWA operator	Proposed method
A1	1	2	1	1
A2	2	1	2	2
A3	3	4	3	5
A4	9	9	9	9
A5	8	7	8	7
A6	5	5	5	6
A7	7	6	6	8
A8	4	3	4	3
A9	6	8	7	4
SRCC Value	0.9	0.8	0.833333333	

been developed to prevent any loss of information during the aggregation process.

2. The interval rough PIPRECIA method, as an objective weighting scheme, mitigates the influence of priority order from experts. Additionally, the systematic assessment of criteria weights minimizes imprecision and biases in the decision-making process. As a result, this makes the decision-making procedure more rational and meaningful.

By examining the SRCC values provided in Table 14, we observe that the average SRCC value among the existing methods [70,77,79] is 0.844, despite their varied computational approaches. This consistency affirms the validity of our proposed method.

6. Discussion, managerial and practical implications

The study focuses on a real case where unfavorable operating conditions (as mentioned in Section 4.3) have resulted in a continuous deterioration of service quality in the railway sector. Initially, a criteria evaluation is carried out, wherein specific criteria are identified. The weights for these criteria are determined using the PIPRECIA method, which leverages interval rough numbers to handle ambiguous information effectively [32]. Moreover, considering the interdependence among the criteria, a weighted geometric Dombi Maclaurin Symmetric Mean (WGDMSM) operator is developed within an IF environment. Consequently, an integrated approach combining IR-PIPRECIA and WGDMSM is proposed, operating within an IF environment, to select the most appropriate course of action for enhancing the railway sector's performance. The proposed integrated approach incorporates the evaluation of criteria and alternatives, based on expert opinions, to improve the performance of the railway sector. By analyzing the challenges that hinder performance improvement, this approach strategically determines the appropriate action to be implemented. This is especially valuable for fostering constructive partnerships between the public and private sectors in revitalizing the Sub-Saharan African railway network. The proposed integrated approach proves instrumental in identifying critical challenges and selecting the most appropriate action to enhance the performance of the railway sector.

The study highlights that the most critical challenges hindering the performance improvement of the railway sector are the chronic lack of resources for infrastructure maintenance and rehabilitation, as well as the lack of competitiveness when compared to road transport. To address these challenges, it is essential to identify remedial solutions that focus on financial and competitiveness issues. To tackle the financial aspect, a crucial step is to establish an appropriate legal framework that ensures long-term public financing for railway infrastructure, similar to the financing mechanisms in place for roads. Governments can also consider the development of railway funds, similar to existing road funds, to achieve a fair and balanced approach in financing both road and rail infrastructures. Moreover, the revenue generated from fuel excise imposed on users of road and railway fuel can be utilized to fund the land transport infrastructure fund. This can be achieved by implementing novel initiatives, such as allocating funds for infrastructure maintenance as part of a long-term strategy, supporting the establishment of a rolling stock leasing industry, and providing political risk insurance for private investments in railways. These measures have the potential to change the current trend of relying solely on financial resources from international financial institutions to directly rehabilitate railway infrastructure. To facilitate private investments in railways in Sub-Saharan Africa, it would be beneficial to employ financing tools that promote the development of capacities for formulating transportation strategies, establishing appropriate regulations, implementing safety standards, and creating sufficient public service contracts. To achieve the goal of enhancing competitiveness, it is crucial to rehabilitate the existing narrow-gauge network with a minimum axle load of 18 tons/axle. This upgrade would adequately cater to the current and projected traffic in Sub-Saharan Africa. While there are ongoing discussions in various countries regarding the potential transition from narrow to standard gauge, it is important to note that these debates lack sufficient financial backing and fail to consider the economic implications of such substantial investments. The transition to a new gauge would entail the complete replacement of existing infrastructure and the entire rolling stock fleet, resulting in higher operational costs during the transition period of two to three decades when both gauges would be in use. Furthermore, changing the rail gauge would lead to the isolation of the system from neighboring networks and the loss of the economic leverage provided by a regional market, unless a comprehensive global and regional approach is adopted.

The experts have unanimously selected the alternative "*A1 - enhance the governance of the transport sector*" as the most appropriate course of action to improve the performance of the railway sector. This outcome aligns with expectations, considering the inherent challenges involved in enhancing railway performance in Sub-Saharan Africa. It is crucial for the political leadership to prioritize establishing long-term confidence in the socio-political system and fostering stable commitment from the private sector for long-term investments in the region. While international financial institutions and the private sector can provide support, it is essential for governments to take on the primary role and demonstrate their unwavering commitment to completing a complex agenda. The respondents have been duly informed of the study's findings, which coincide with the expectations of all the experts regarding the ranking of alternatives to enhance the performance of the railway sector.

The assessment of actions to enhance railway sector performance in the SSA region has not been previously explored from an MCDM perspective in the existing literature. Therefore, the proposed methodology brings forth significant theoretical and practical contributions to the field of railway sector studies. The main implications, both theoretical and practical, derived from this study are outlined below:

The integration of an interval rough PIvot Pairwise Relative Criteria Importance Assessment, along with a novel weighted geometric Dombi Maclaurin Symmetric Mean operator, within an intuitionistic fuzzy environment is a unique approach that has not been previously explored in the literature. This methodology is specifically applied for the assessment of actions aimed at enhancing railway sector performance in the SSA region, marking a significant contribution to the existing body of knowledge on this subject.

Through a meticulous examination of existing literature and the invaluable input of experts, a set of criteria is established to evaluate the actions undertaken to enhance the performance of the railway sector in the SSA region. This endeavor results in the formulation of a comprehensive framework that effectively assesses the challenges encountered in this domain. To ensure a well-informed and diverse perspective, an expert group is formed, comprising transportation specialists and academicians who possess extensive knowledge and expertise in the field. Their collective insights and experience greatly contribute to the robustness and credibility of the assessment framework.

This model is developed in a manner that allows for extension and adaptability on a continental scale, making it applicable and adaptable to various contexts. Railway corporations can utilize this model to assess the performance of their railway systems within each nation, while it can also serve as a tutorial for evaluating the challenges associated with declining railway sector performance. Thus, the proposed model holds significant potential for addressing the complexities involved in improving railway sector performance.

7. Conclusion

This study proposes the integrated interval rough PIvot Pairwise RElative Criteria Importance Assessment and weighted geometric Dombi Maclaurin Symmetric Mean operator, specifically designed for evaluating the most appropriate course of action to enhance the performance of the railway sector. By applying this model to a case scenario in Sub-Saharan Africa, the study demonstrates its effectiveness in a real-world context. The findings of the research highlight two primary challenges that significantly impede the improvement of the railway sector's performance: a chronic lack of resources to fund infrastructure maintenance and rehabilitation, and the sector's limited competitiveness compared to road transport. The results also indicate that improving the governance of the transport sector is the most appropriate action to address these challenges and enhance railway performance, given the complex nature of the task in Sub-Saharan Africa.

While this study has certainly made valuable contributions, it is essential to acknowledge its limitations. Firstly, our research did not encompass the criteria across the three dimensions of sustainability. To gain a more comprehensive understanding of these criteria, future research should adopt a multidimensional perspective. This approach can assist in pinpointing critical areas that require greater attention. Secondly, our study exclusively focused on the sub-Saharan Africa region, omitting consideration of the North Africa region or the entire African continent. Consequently, it is imperative to either replicate the research framework utilized in this study across the entire African continent or approach the five African regions individually. This approach takes into account the diverse conditions and circumstances prevailing in each region, allowing for meaningful comparisons of the results obtained. At last, while the intuitionistic fuzzy approach with interval rough PIPRECIA and weighted geometric Dombi MSM operator offers several benefits, it does have a limitation. Although this approach can handle various multi-expert decision-making problems effectively, it encounters challenges when dealing with a large number of experts due to the lack of a consensus-reaching process. Therefore, it is necessary to extend the proposed methodology and develop a consensus-based model that incorporates a consensus coefficient, which would require further research. Furthermore, the current multi-criteria framework can be applied to address other complex decision-making issues, such as selecting renewable energy sources, assessing sustainability, achieving transportation decarbonization, and implementing the circular economy. These areas offer valuable opportunities for future exploration and application of the proposed methodology.

CRediT authorship contribution statement

Mouhamed Bayane Bouraima: Conceptualization, Data curation, Formal analysis, Investigation, Writing-original draft, Editing, Final draft preparation; **Abhijit Saha:** Methodology, Formal analysis, Editing; **Željko Stević**: Methodology, Formal analysis, Editing; **Jurgita Antuchevičienė**: Data curation, Formal analysis, Investigation, Final draft preparation; **Yanjun Qiu**: Data curation, Formal analysis, Investigation; **Peter Marton:** Supervision, Review, Validation.

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

Data will be made available on request.

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