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RESEARCH

An Interval-valued Intuitionistic Fuzzy Group Decision Model for Evaluation of Cross-border Railway Development

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Abstract

This paper presents a novel approach to prioritize cross-border railway transportation development alternatives using an interval-valued intuitionistic fuzzy group decision model. This model combines Step-Wise Weight Assessment Ratio Analysis (SWARA) and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) within an interval-valued intuitionistic fuzzy (IVIF) framework. The study considers nine alternatives and identifies seven barriers in the initial stage to rank these alternatives. The IVIF-SWARA method is then used to determine barrier weights, followed by the IVIF-VIKOR method to rank the alternatives. The key barriers identified include inefficient funding mechanisms, regulatory gaps, and unfavorable concessioning arrangements. Proposed strategies include conducting a legal review and establishing supranational institutions. Furthermore, the study conducts a thorough sensitivity analysis to assess the reliability of the model. This proposed model can provide valuable guidance to East African Community member states and policymakers looking to improve cross-border railway transportation.

Keywords Interval-valued intuitionistic fuzzy sets · Cross-border railway transportation · SWARA · VIKOR

Introduction

As international trade across borders increases, the importance of cross-border transportation infrastructure for promoting regional integration [1] and enabling trade [2] is becoming increasingly critical. Currently, the East African Community (EAC) is prioritizing the improvement of five transportation corridors to address regional transportation challenges. With the African Continental Free Trade Area (AfCFTA) agreement, infrastructure development and connectivity have become a top priority for the continent, offering numerous opportunities for cross-border transportation projects [3].

In the railway sector, there is an ongoing effort to enhance transportation by rehabilitating existing networks and establishing new connections with neighboring regions [4]. Previous research has indicated that the institutional and legal frameworks established in East Africa to regulate railway development may not be conducive to regional railway development [5]. However, to establish operational and sustainable railway systems, the presence of a robust institutional and legal framework is essential. The laws and organizations overseeing railway development in the community face challenges due to factors like differing

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legal systems and inadequate frameworks. Additionally, the development of regional transportation is hindered by weak institutional capabilities and fragmented operations [6]. The regional bodies responsible for EAC's cross-border railways lack the autonomy and capacity needed to achieve their goals. Furthermore, each EAC state's national railway system operates independently without adequate cross-border connections, and national institutions struggle due to limited funds and resources [7].

A growing concern for the EAC's member states is the need to overcome institutional and legal barriers that are impeding the development of cross-border railway transportation. Despite prior attempts to improve the situation, these barriers persist due to the absence of a well-defined and effective strategy. In response to this challenge, there is a need to form a team of specialists assigned with the intricate task of choosing the most appropriate alternative through the multi-criteria decision-making (MCDM) method, which has been recommended in earlier research studies [8, 9]. It is important to note that while the MCDM approach proves effective in addressing transportation issues [10], the experts engaged in this process face the substantial challenge of dealing with a significant amount of uncertain and imprecise information. Remarkably, there is currently a lack of comprehensive studies aimed at resolving this specific problem.

The motivations for the proposed study are as follows.

- In situations where we need to make decisions based on multiple criteria, the goal is usually to choose the best option from a set of choices. However, traditional fuzzy set theory has limitations in handling complexities and uncertainties in such scenarios. To address these challenges, researchers have turned to intuitionistic fuzzy sets (IFSs), which are valuable tools for dealing with uncertainty in MCDM-related problems [11]. The IFSs excel in representing imprecise or less than completely reliable judgments. These sets can express not only affirmation and negation but also hesitation, all through the utilization of membership definitions [12, 13]. One of the key problems in the realm of IFS theory is finding ways to broaden the definition of IFS and its operations [14, 15]. To address the challenge, Atanassov and Gargov [11] extended the concept of IVIFS from interval fuzzy sets (IFS). They introduced the fundamental IVIFS algorithm, which offers distinct advantages over IFS in handling complexity and imprecise information. Using IVIFS allows us to effectively represent uncertainty and incorporate expert insights into our decision-making processes. In the case of EAC's cross border railway development, these benefits are very important. In fact, various stakeholders from distinct countries are engaged in this development. Each of them has various pollical interests, infrastructure abilities, and socio-economic priorities. This results in often conflicting, sometimes inadequate experts' evaluations, and great uncertainty. Fundamental fuzzy MCDM models and even traditional crisps have difficulty apprehending incomplete accord, hesitation, and ambiguity immanent from multinational decision-making situations.
- Criteria weighting methods rely on decision-makers' judgments and comparisons among criteria [16]. One such method, the Level Based Weight Assessment (LBWA), offers flexibility for decision-makers to express preferences and resolve inconsistencies logically without being limited to predefined integer scales [17]. Another method, the FUll Consistency Method (FUCOM) developed by Pamučar, Stević [18], has shown better results than the Best–Worst Method (BWM) when considering the relationship between consistency and the number of criteria comparisons [19, 20]. However, it is important to note that FUCOM lacks extensive validation studies. In contrast, the BWM method is a comparison-based approach that involves fewer pairwise comparisons and matrices, making it quicker to implement [21, 22]. However, it may become less suitable for complex non-linear models due to the large number of required pairwise comparisons. Unlike other MCDM methods like LBWA, FUCOM, and BWM, the computation process of the SWARA method is straightforward and easy to understand [23]. The SWARA method showed its capability to identify the subjective weights of the criteria [24]. It allows experts to select their primary priorities based on current conditions [25]. In the case of EAC railway, where regional accords, funding cycles, and political variations can affect the prerogatives of stakeholders, SWARA method provides the resilience to powerfully modernize weighting process in the absence of extreme data requests. However, despite SWARA's notable success in various domains, there exists a research gap in its application within the context of an IVIF framework for evaluating the barriers that impede the development of cross-border railway transportation. Our study aims to fill this gap.
- The Measurement of Alternatives and Ranking according to the COmpromise Solution (MARCOS) technique is known for providing reliable results in dynamic environments. However, one drawback of MARCOS is that it relies on a single normalization technique [26]. Pamučar and Ćirović [27] introduced the Multi-Attributive Border Approximation Area Comparison (MABAC) method, which produces consistent outcomes, even when there are changes in the units of measurement and maintains stable solutions when criteria formulations

are altered [28]. However, there is a need to improve the method, especially in addressing its structural restrictions. The VIšeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method was developed to optimize complex systems with multiple criteria. It aims to rank and select alternatives when there are conflicting criteria, seeking a compromise solution. The VIKOR method employs its own aggregation function and normalization method. The VIKOR method is suitable for situations where profit maximization takes precedence over decision risk. Its key advantage lies in balancing the maximum group utility and minimum individual regret [31]. In the EAC situation, this is especially beneficial because cross border railway development necessitates compromise or adjustment between each country-specific concerns like infrastructure compatibility, sovereignty, cost and collective regional benefits. Despite the method's widespread use in various fields, there is a lack of studies exploring its integration into an IVIF framework for evaluating alternative solutions to overcome the barriers to the development of cross-border railway transportation. This study bridges this gap by addressing this integration.

The main contributions of this paper are as follows.

- The authors gathered primary data by administering SWARA and VIKOR questionnaires to experts with a minimum of 10 years of experience, either in academia or industry, and who have a track record of publishing papers in the field of railway transportation.
- The authors of this study have effectively addressed a significant gap in the literature concerning cross-border railway development. Despite conducting an extensive search, no prior research has delved into this specific topic, examining the challenges to cross-border railway development and offering insights through managerial techniques. Consequently, this paper conducts an in-depth assessment of these challenges for cross-border railway development in the East Africa community. The findings and recommendations derived from this model can serve as a valuable resource for scientists and researchers seeking to gain a comprehensive understanding of cross-border railway development within the domain of management science.
- This study is new since it differs from existing literature by applying an interval-valued intuitionistic fuzzy group decision model to assess the alternatives for the development of cross-border railway transportation in the East Africa Community.
- The outcomes of this study can benefit the East African Community member states and policymakers in overcoming legal and institutional barriers by selecting the most appropriate strategies in real-world decision-making.
- The applied methodology can be extended to other types of infrastructures in the region.

Following are the research objectives: (i) provide an interval-valued intuitionistic fuzzy group decision model for the development of cross-border railway transportation; (ii) presenting the most appropriate alternatives to promote this development, and (iii) investigating the application of an interval-valued intuitionistic fuzzy group decision model to identify the main institutional and legal barriers to this development and evaluates alternatives for overcoming them. By pursuing these goals, the following questions are answered: (*) Which kind of framework needs to be applied for the promotion of this development (**) What are those barriers hindering this development? (***) Which are the most appropriate alternatives to overcome these barriers?

Following the introduction, Sect. "Literature review" provides a literature review. While the problem definition is presented in **Sect. 3**, the fundamental principles of IVIFS are detailed in Sect. "Basics principles of the IVIFS". Sects. "Proposed Methodology" and "Application" deal with the proposed methodology and its application, respectively. The sensitivity analysis is performed in Sect. "Sensitivity Analysis". Sect. "Findings and discussion" presents the findings and discussions. The conclusions along with further rec

ommendations are stated in the last section.

Literature Review

Four sub-sections are presented below.

Decision-Making Procedures Related to Cross-border Transportation Infrastructures

Cross-border projects must often demonstrate added value beyond what can be achieved by simply connecting markets and bringing populations together through large infrastructure projects. Research has shown that upgrading infrastructure in border regions can have positive impacts on trade and economic growth. This increased demand for connectivity can also lead to new investment opportunities. Additionally, there have been studies conducted on the benefits of improved transportation infrastructure across borders. For instance, Dimitriou and Sartzetaki [29] created a strategic decision framework for upgrading railway corridors. Li, Zhang [30] developed a methodology for evaluating risk in projects that considers multiple interconnected factors.

Brauweiler, Yerimpasheva [31] examined issues related to the construction of a model to effectively manage cross-border projects. Lopez, Monzón [32] created a method to determine the impact of transportation infrastructure on the integration of European countries. Medeiros [33] evaluated the current state of transportation within European union (**EU**) cross-borders and introduced an index to evaluate the ease of movement across them. Vulevic, Castanho [34] discussed the important elements of accessibility and evaluated ways to remove barriers to sustainable transportation in areas along the Portuguese Spanish border. Dörry and Decoville [35] explored the transnational governance networks in Europe. Walther and Reitel [36] demonstrated how internal borders shape the policy network framework. Medeiros, Ferreira [37] presented policies and practices that can enhance border permeability through cross-border public transportation, including several case studies from various parts of Europe. Sirotić, Žuškin [38] suggested a method for creating practical and cross-border passenger services by implementing a six-stage process that encourages stakeholder collaboration. Renner, Meijerink [39] evaluated the effectiveness of cross-border cooperation using a long-term study. Christodoulou and Christidis [40] developed a method for measuring and assessing the availability of European borders within regions. Tebagana [5] reviewed the existent legal and institutional structure for the development of cross-border railway transportation. Table 1 provides an overview of the cross-border transportation infrastructure-related approaches.

DEMATEL Decision-Making Trail and Evaluating Laboratory, *GDM* Group Decision Making; *RL* Real-life; *SA* Sensitivity Analysis; *SWOT* Strength Weakness Opportunity Threat, *TACI* Two-Additive Choquet Integral.

Applications and Extensions of the SWARA Method

Several studies have effectively addressed a range of decision-making problems using the SWARA method [41]. For instance, Deveci, Varouchakis [42] assessed the significance of risks that could hinder sustainable mining. Alrasheedi, Mishra [43] determined the most suitable renewable energy source based on various sustainability criteria. Norouzzadeh [44] identified and prioritized factors affecting medical tourism. Tripathi, Nigam [45] evaluated alternative food waste treatment technologies in uncertain environments. Moslem, Stević [46] determined the importance of supplying quality elements in urban bus transport services. Jafarzadeh Ghoushchi, Shaffiee Haghshenas [47] applied an integrated approach to assess road safety and prioritize risks. Chusi, Qian [48] ranked strategies to tap into the potential of Africa's carbon credit market. Ghoushchi, Garg [49] examined barriers to the development of clean energy. Qiu, Bouraima [50] explored strategies to promote the adoption of Industry 4.0. Its available applications and extensions are indicated in Table 2.

Applications and Extensions of the VIKOR Method

The VIKOR method is becoming increasingly significant in the process of decision-making [51, 52]. For instance, Chatterjee and Chakraborty [53] compared the VIKOR approach and its extensions in the selection of grinding wheel abrasive material. Yazici and Kahraman [54] developed a fuzzy technique model for personnel selection. Rostamzadeh, Govindan [55] provided a tool for assessing ambiguity in management activities in the green supply chain. Büyüközkan, Feyzioğlu [56] introduced a new perspective for evaluating the performance of web services. Zhao, Tang [57] provided a method for selecting partners in emerging market opportunities. Tan and Chen [58] proposed a group decision-making model for selecting an investment company. Park, Cho [59] used it for a faculty promotion at a university. Jiang and Yao [60] selected the suppliers of automobile parts in the railway station. Krishankumar, Premaladha [61] solved the issue related to personnel choice. Wu, Gao [62] evaluated the funding risk associated with tourism projects in rural areas. Qi, Huang [63] examined the viability of the energy sector of developing countries. Salimian, Mousavi [64] selected a viable supplier in the organ transplantation network for medical implements. Öztürk, Yildizbasi [65] assessed the performance of vaccines based on several factors. Tian and Zhang [66] evaluated the traffic safety of the urban road. Büyüközkan, Havle [67] proposed a new model to assess the digital capability of airlines. Table 3 illustrates the various applications and expansions of the VIKOR method that are available.

Research Gaps

The following are the research gaps: a) This study is the first to focus on this issue related to the development of cross-border railway transportation in East Africa. It aims to identify and address the main institutional and legal barriers that are hindering the progress of this development, and it offers the most appropriate strategies to overcome these barriers, as can be shown in Table 1. Before this study, these strategies had not been fully examined and prioritized; b) The study is unique in that it combines the SWARA and VIKOR methods into a single framework within the IVIF context. This integration of the two methods has not been done previously in this specific context (Table 2**,** Table 3); c) The SWARA and VIKOR methods have not been utilized in

Table 1 Cross-border transportation infrastructures related approaches

Author (s)	Target	Empirical focus	GDM	SA	Method (s)	Application	
						Country/Region	Type
Dimitriou and Sartzetaki [29]	Effectively evaluating the necessity and prospects for establishing a cross-border railway connection	Strategic railway project decision framework	No	No	System of System approach	Greece, Turkey, and Bulgaria	RL
Li, Zhang [30]	Establishing a fuzzy decision analysis method for assessing risk in cross-border transportation infrastructure projects	Risk assessment	Yes	No	DEMATEL, TACI, fuzzy reasoning approach	China, Laos	RL
Brauweiler, Yerimpasheva [31]	Analysis of critical success parameters within borders	Project management success model	Yes	No	Survey-based method	Europe and China through Kazakhstan	RL
Lopez, Monzón [32]	Evaluation of cross-border spillover influences of the transportation infrastructure plan	Network efficiency estimation	No	No	Accessibility-based approach	Spain, Portugal, France	RL
Medeiros [33]	Comparing the cross-border permeability among EU border regions	Cross-border transport permeability index	Yes	No	Survey-based method	EU	RL
Vulevic, Castanho [34]	Presenting an overview of relevant accessibility indicators	Accessibility of cross-border cooperation scenarios	No	No	Case study research method	Alto Alentejo (Portugal) and Badajoz (Spain)	RL
Dörry and Decoville [35]	Governance frame analysis of public transportation within borders	Governance and transportation policy networks	No	No	Mixed methods	Europe	RL
Walther and Reitel [36]	Information on how the structure of policy networks is influenced by national borders	Policy network	Yes	No	Social network analysis	Switzerland, France, and Germany	RL
Medeiros, Ferreira [37]	Presenting relevant policy tools to increase border permeability	Cross-border transport services	No	No	Survey-based method	EU	RL
Sirotić, Žuškin [38]	Contribution to the enhancement of transport macro-management	Cross-border transport services	No	No	SWOT, gap analysis, methodological framework	Italy, Croatia	RL
Renner, Meijerink [39]	Assessing the cross-border water regime	Cross-border cooperation performance	No	No	Qualitative analysis	Netherlands, Germany	RL
Christodoulou and Christidis [40]	Measuring and evaluating the accessibility of border regions	Cross-border accessibility	No	No	Accessibility concept-based method	Norway, Switzerland	RL
Tebagana [5]	Reviewing the existent legal and institutional structure	Development of cross-border railway	No	No	Desk and library-based survey	EAC	RL
Our study	Selecting the most appropriate strategies to overcome the legal and institutional barriers to the development of cross-border railway transportation	Cross-border railway development assessment	Yes	Yes	IVIF-SWARA-VIKOR	EAC	RL

the IVIF context to recognize and classify institutional and legal barriers, nor to suggest effective strategies for overcoming them, in the development of cross-border railway infrastructure at regional level (Tables 1, 2, and 3).

Problem Definition

In recent times, there has been a growing focus on resolving significant issues within the legal and institutional aspects of the EAC railways infrastructure. This heightened attention is driven by the recognition that establishing a robust legal and institutional framework and ensuring its effective implementation are vital steps towards fostering the growth of efficient, harmonized, and environmentally sustainable cross-border railway systems. Consequently, numerous strategies have been put forth to address the challenges associated with cross-border railways. This study underscores the need to engage experts to evaluate diverse approaches aimed at enhancing the legal and institutional foundation of cross-border railways.

Table 2 Applications and extensions of the SWARA

Authors	Aims	GDM	Env	Method(s)	Appl	Crit	Alt
Deveci, Varouchakis [42]	Sustainable mining risk assessment	Yes	FF	SWARA	Global	49	-
Alrasheedi, Mishra [43]	Renewable energy source	Yes	IF	SWARA, WASPAS	India	15	6
Norouzzadeh [44]	Health medical tourism parameters	Yes		Fuzzy Delphi method, SWARA	Iran	15	-
Tripathi, Nigam [45]	Waste treatment technology choice	Yes	IF	SWARA, COPRAS	-	4	13
Moslem, Stević [46]	Public transportation development strategies	Yes	Fuzzy	Fuzzy Bonferroni, IMF SWARA	Turkey	3	11
Jafarzadeh Ghoushchi, Shaffiee Haghshenas [47]	Road safety evaluation	Yes	SF	SWARA, MARCOS	Italy	16	-
Chusi, Qian [48]	Carbon credit market prioritization strategies	Yes	IVSF	SWARA	Africa	6	-
Ghoushchi, Garg [49]	Clean energy barrier assessment	Yes	SF	SWARA, CODAS	-	19	5
Qiu, Bouraima [50]	Industry 4.0 improvement strategies	Yes	SF	SWARA, WASPAS	East Africa	7	2
Our study	Cross-border railway development assessment	Yes	IVIF	SWARA, VIKOR	RL	7	9

Alt Alternative; *Appl* Application; *Crit* Criteria; *CODAS* COmbinative Distance-based Assessment; *COPRAS* Complex Proportional Assessment; *Env* Environment; *FF* Fermatean Fuzzy; *GDM* Group Decision Making; *IF* Intuitionistic Fuzzy; *IVIF* Interval Valued Intuitionistic Fuzzy; *IVSF* Interval Valued Spherical Fuzzy; *MARCOS* Measurement of Alternatives and Ranking according to COmpromise Solution; *SF* Spherical Fuzzy; *VIKOR* Vlsekriterijumska Optimizacija I KOmpromisno Resenje; *WASPAS* Weighted Aggregated Sum Product Assessment

Definition of Alternatives

Nine alternatives have been identified to constitute realistic and pragmatic strategies to handle these criteria, considering both documented best practices and recommendations.

S1: ***Legal review***: It is important to evaluate current legal frameworks to determine the rights and responsibilities of the government, implement preventative measures, and resolve any inconsistencies [68]. Additionally, it is crucial to address cross-border environmental concerns. To facilitate private sector participation in infrastructure investments, it is recommended that nations adopt laws promoting public–private partnerships.

S2: ***Harmonization of legal frameworks***: To effectively manage all aspects of railway development, it

Table 3 Applications and extensions of the VIKOR

Authors	Aims	GDM	Env	Method(s)	Appl	Crit	Alt
Chatterjee and Chakraborty [53]	Material selection issue	No	Crisp	VIKOR	IE	7	8
Yazici and Kahraman [54]	Personnel evaluation	Yes	IT2FS	VIKOR	IE	5	3
Rostamzadeh, Govindan [55]	Green supply chain assessment	Yes	Fuzzy	VIKOR	RL	30	4
Büyüközkan, Feyzioğlu [56]	Medical web services assessment	Yes	IF	AHP, VIKOR	RL	15	10
Zhao, Tang [57]	Partner selection	Yes	IVIF	Cross-entropy, VIKOR	IE	5	4
Tan and Chen [58]	Selection of investment company	Yes	IVIF	CI, VIKOR	IE	4	5
Park, Cho [59]	University faculty assessment	Yes	DIF	VIKOR	IE	3	5
Jiang and Yao [60]	Supplier selection	Yes	Fuzzy, IVIF	AHP, VIKOR	IE	5	5
Krishankumar, Premaladha [61]	Personnel selection	Yes	IF	VIKOR	RL	4	5
Wu, Gao [62]	Financial risk evaluation	Yes	IVIF	VIKOR	IE	4	5
Qi, Huang [63]	Sustainable production of the energy sector	Yes	IVIF	DEMATEL, VIKOR	RL	9	7
Salimian, Mousavi [64]	Sustainable supplier selection	Yes	IVIF	E-VIKOR, MARCOS	RL	17	4
Öztürk, Yildizbasi [65]	Vaccine selection	Yes	IVIF	VIKOR	RL	8	5
Tian and Zhang [66]	Traffic safety assessment	**Yes**	IVIF	VIKOR	RL	4	5
Büyüközkan, Havle [67]	Digital competency assessment	**Yes**	IVIF	AHP, VIKOR	RL	30	4
Our study	Cross-border railway development assessment	Yes	IVIF	SWARA, VIKOR	RL	7	9

AHP Analytical Hierarchy Process; *CI* Choquet Integral; *DIF* Dynamic Intuitionistic Fuzzy; *IE*: Illustrative Example; *IT2FS*: Interval Type-2 Fuzzy Set

is necessary to standardize laws across partner nations [69]. Furthermore, to simplify collaboration on joint projects, it is essential to align procurement rules and procedures.

S3*: **Harmonize railway operations**:* To improve efficiency and optimize resource distribution, coordination and homogeneity in railway operations should be established within a specific region [70, 71]. This includes implementing a standard gauge railway among partner nations and creating a comprehensive implementation program. Additionally, it is important to establish common safety, technical, and operational standards to facilitate cross-border railway operations. To move beyond current limitations, a multilateral regional economic contract among railways should be established.

S4*: **Establish supranational institutions*** [72]: For an effective operation of the East African Community Railways Authority (EARA) in the region, it is necessary to grant it supranational powers. This includes the ability to impose legally binding laws and regulations on member nations and their national railway regulators. The EARA should also be given the authority to make decisions that benefit the entire region, particularly on issues that fall outside the jurisdiction of national railway authorities. All member states should be willing to abide by the EARA's ruling.

S5*: **Establish a dedicated regional infrastructure fund (expert opinion)**:* To support regional infrastructure development, it is necessary to establish a dedicated regional infrastructure fund [5]. This fund should be open to contributions from both public and private sector partners and should be managed by external auditors to ensure transparency and integrity.

S6*: **Address issues of a multiplicity of memberships*** [73]: The participants in the Tripartite Free Trade Area should pay attention to the issue of diverse membership during their discussions and collaborate in identifying shared interests in infrastructure development within each sector.

S7*: **Human capital development (expert opinion)**:* Adero and Aligula [6] suggested that the number of cooperative training sessions for employees working in organizations involved in regional initiatives should increase. Alternatively, setting up one-stop centers where individuals can provide services to multiple institutions may help to address any human resource shortages that may exist within partner nations.

S8*: **Explore multimodal transport development**:* To improve the transportation system, it is important to connect the road and railway networks. This can lead to cost savings, increased efficiency, and more options for customers [71]. To achieve this, it is suggested that joint administration be established to oversee both road and railway transportation or that connections be established between operators of both types of transportation. This approach can also help to reduce competition and monopolistic behaviors.

S9*: **Renegotiate or terminate failing concessions**:* When private companies are given the right to operate and maintain certain infrastructure, they must fulfill their obligations. If they do not, the agreements with them should be reassessed or terminated [73]. To ensure this, the responsibilities of the private companies and the government should be clearly outlined in the agreements. Also, the agreements should specify under which circumstances the government can allow other private companies to operate on the same infrastructure.

Definition of Criteria

Seven criteria (barriers) have been selected according to challenges pinpointed in the development of cross-border railway infrastructure and following the consultation of experts and a review of pertinent literature. The seven criteria are selected to apprehend the major financial, operational, institutional, and legal barriers impeding this development.

C1: ***Absence of clarity of duties and rights:*** The EAC treaty is not clear about the specific roles and rights of each partner nation in jointly implemented infrastructure projects [5]. This can lead to confusion and difficulties in collaboration. However, the treaty serves as a general framework for nations to work together on infrastructure projects.

C2: ***Regulation gaps*** [74]: In the EAC, there are a lack of regulations regarding certain important aspects of railway development. Many landlocked nations within the EAC do not have sufficient laws to effectively regulate private–public partnerships (PPP) as a means of generating revenue and facilitating private sector involvement in infrastructure building.

C3: ***Absence of legal harmonization*** *(expert opinion)**:*** Within the EAC partner nations, two main legal systems in operation can conflict with each other, common law and civil law. These different legal systems have different norms and procedures that can slow down or hinder the efficient execution of projects [69].

C4: ***Poor institutional capacity:*** The main problem identified in the institution is the lack of capability. This is primarily caused by poor decision-making abilities, lack of funding, and lack of technological knowledge [75]. The institutions that have been set up recently do not have enough power to carry out their intended functions.

C5: *Diversified operations:* The ability of cross-border railway systems to connect different nations in the region is hindered by the diverse way in which the region's railways operate [76]. This includes the fact that railway companies from Kenya, Tanzania, and Uganda each operate independently, despite having a regional focus. Additionally, there are different railway gauges used in the region, which makes it challenging to connect the railway systems.

C6: *Inappropriate concession arrangements:* The use of concession procedures as a method of funding and managing the EAC's railways has put the participating nations at a disadvantage [5]. Furthermore, there were no thorough evaluations made to determine if the companies granted concessions were capable of fulfilling their duties.

C7: *Unsuitable funding mechanisms (expert opinion):* There is currently no coordinated plan in place for allocating funds specifically for infrastructure development, where partner nations, aid agencies, and the private sector can come together and set aside money [5, 77]. Governments and development partners usually make contributions after this fact. Additionally, funding from donors may not match the requirements of the recipient nations.

The criteria used in the study have been confirmed as independent by experts in the field. Each criterion addresses distinct aspects of the decision-making problem, ranging from funding procedures (C7) to legal and regulatory concerns (C1, C2, C3) and operational issues (C4, C5, C6). The independent nature of these criteria ensures that they capture different dimensions of the problem without overlapping.

Basics Principles of the IVIFS

The definitions and fundamental notions about IVIFS are provided.

Definition 1: The IFSs can be presented as $\widetilde{I}$:

$$\widetilde{I} \cong \left\{ x, \widetilde{I}(\mu_{\widetilde{I}}(x), v_{\widetilde{I}}(x)); x \in X \right\} \tag{1}$$

X is a predetermined set in the function.$\mu_{\widetilde{I}}(x) : X \mapsto [0,1]$ define the membership degree and $v_{\widetilde{I}}(x) : X \mapsto [0,1]$ define the non-membership degree of a parameter $x \in X$ to $\widetilde{I}$.

$$0 \leq \mu_{\widetilde{I}}(x) + v_{\widetilde{I}}(x) \leq 1; x \in X \tag{2}$$

The indeterminacy level is determined:

$$\pi_{\widetilde{I}}(x) = \sqrt{1 - \mu_{\widetilde{I}}(x) + v_{\widetilde{I}}(x)} \tag{3}$$

Interval numbers are favorable in conveying ambiguity when assessing criteria and options [78]. In this study, IVIF numbers are used to address fuzziness and ambiguity in the data. The authors of the study provide preliminary definitions for IVIFSs, as established by Kahraman, Öztayşi [79].

Definition 2: An IVIF number $\widetilde{I}$ is explained in X and provided [80].

$$\widetilde{I} = \left\{ \langle x \left[\mu_{\widetilde{I}}^{-}(x), \mu_{\widetilde{I}}^{+}(x) \right], \left[v_{\widetilde{I}}^{-}(x), v_{\widetilde{I}}^{+}(x) \right] \rangle; x \in X \right\} \tag{4}$$

where,

$$0 \leq \mu_{\widetilde{I}}^{-}(x), \mu_{\widetilde{I}}^{+}(x), v_{\widetilde{I}}^{-}(x), v_{\widetilde{I}}^{+}(x) \leq 1 \tag{5}$$

$$\mu_{\widetilde{I}}^{-}(x) \leq \mu_{\widetilde{I}}^{+}(x) \text{ and } v_{\widetilde{I}}^{-}(x) \leq v_{\widetilde{I}}^{+}(x) \tag{6}$$

$$\mu_{\widetilde{I}}^{+}(x) + v_{\widetilde{I}}^{+}(x) \leq 1 \tag{7}$$

Definition 3: Fundamental operations of two IVIF numbers ($\widetilde{\alpha} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+} \right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+} \right]$ and $\widetilde{\beta} = \left[\mu_{\widetilde{\beta}}^{-}, \mu_{\widetilde{\beta}}^{+} \right], \left[v_{\widetilde{\beta}}^{-}, v_{\widetilde{\beta}}^{+} \right]$) can be shown [81]:

$$\widetilde{\alpha} \oplus \widetilde{\beta} = \left[\mu_{\widetilde{\alpha}}^{-} + \mu_{\widetilde{\beta}}^{-} - \mu_{\widetilde{\alpha}}^{-}\mu_{\widetilde{\beta}}^{-}, \mu_{\widetilde{\alpha}}^{+} + \mu_{\widetilde{\beta}}^{+} - \mu_{\widetilde{\alpha}}^{+}\mu_{\widetilde{\beta}}^{+} \right], \left[v_{\widetilde{\alpha}}^{-}v_{\widetilde{\beta}}^{-}, v_{\widetilde{\alpha}}^{+}v_{\widetilde{\beta}}^{+} \right] \tag{8}$$

$$\widetilde{\alpha} \otimes \widetilde{\beta} = \left[\mu_{\widetilde{\alpha}}^{-}\mu_{\widetilde{\beta}}^{-}, \mu_{\widetilde{\alpha}}^{+}\mu_{\widetilde{\beta}}^{+} \right], \left[v_{\widetilde{\alpha}}^{-} + v_{\widetilde{\beta}}^{-} - v_{\widetilde{\alpha}}^{-}v_{\widetilde{\beta}}^{-}, v_{\widetilde{\alpha}}^{+} + v_{\widetilde{\beta}}^{+} - v_{\widetilde{\alpha}}^{+}v_{\widetilde{\beta}}^{+} \right] \tag{9}$$

$$\lambda\widetilde{\alpha} = \left[1 - \left(1 - \mu_{\widetilde{\alpha}}^{-}\right)^{\lambda}, 1 - \left(1 - \mu_{\widetilde{\alpha}}^{+}\right)^{\lambda} \right], \left[\left(v_{\widetilde{\alpha}}^{-}\right)^{\lambda}, \left(v_{\widetilde{\alpha}}^{+}\right)^{\lambda} \right] \tag{10}$$

$$(\widetilde{\alpha})^{\lambda} = \left[\left(\mu_{\widetilde{\alpha}}^{-}\right)^{\lambda}, \left(\mu_{\widetilde{\alpha}}^{+}\right)^{\lambda} \right], \left[1 - \left(1 - v_{\widetilde{\alpha}}^{-}\right)^{\lambda}, 1 - \left(1 - v_{\widetilde{\alpha}}^{+}\right)^{\lambda} \right] \tag{11}$$

$$\frac{\widetilde{\alpha}}{\widetilde{\beta}} = \left[min\left(\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\beta}}^{-}\right), min\left(\mu_{\widetilde{\alpha}}^{+}, \mu_{\widetilde{\beta}}^{+}\right) \right], \left[max\left(v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\beta}}^{-}\right), max\left(v_{\widetilde{\alpha}}^{+}, v_{\widetilde{\beta}}^{+}\right) \right] \tag{12}$$

Definition 4: Score function $S(\widetilde{\alpha}) \in [-1,1]$ for an IVIF number ($\widetilde{\alpha} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+} \right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+} \right]$) is given [82]:

$$S(\widetilde{\alpha}) = \frac{\mu_{\widetilde{\alpha}}^{-} - v_{\widetilde{\alpha}}^{-} + \mu_{\widetilde{\alpha}}^{+} - v_{\widetilde{\alpha}}^{+}}{2} \tag{13}$$

Definition 5: Reliable function $H(\widetilde{\alpha})$ for an IVIF number ($\widetilde{\alpha} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+} \right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+} \right]$) is provided [82]:

$$H(\widetilde{\alpha}) = \frac{\mu_{\widetilde{\alpha}}^{-} + v_{\widetilde{\alpha}}^{-} + \mu_{\widetilde{\alpha}}^{+} + v_{\widetilde{\alpha}}^{+}}{2} \tag{14}$$

Definition 6: A comparison between two IVIF numbers $\widetilde{\alpha}$ and $\widetilde{\beta}$ as bellows.

i. If

$$S(\widetilde{\alpha}) < S\left(\widetilde{\beta}\right) \quad \text{, then } \widetilde{\alpha} < \widetilde{\beta} \tag{15}$$

ii. If

$$S(\widetilde{\alpha}) > S\left(\widetilde{\beta}\right) \quad \text{, then } \widetilde{\alpha} > \widetilde{\beta} \tag{16}$$

iii. If

$$S(\widetilde{\alpha}) = S\left(\widetilde{\beta}\right), \tag{17}$$

a. If

$$S(\widetilde{\alpha}) < S\left(\widetilde{\beta}\right) \quad \text{, then } \widetilde{\alpha} < \widetilde{\beta} \tag{18}$$

b. If

$$S(\widetilde{\alpha}) > S\left(\widetilde{\beta}\right) \quad \text{, then } \widetilde{\alpha} > \widetilde{\beta} \tag{19}$$

c. If

$$S(\widetilde{\alpha}) = S\left(\widetilde{\beta}\right) \quad \text{, then } \widetilde{\alpha} \sim \widetilde{\beta} \tag{20}$$

Definition 7: Let $\widetilde{\alpha} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+}\right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+}\right]$ be an IVIF number. $\widetilde{\alpha}$ is defuzzified as the formula bellows [81]:

$$\mathcal{D}(\widetilde{\alpha}) = \frac{\mu_{\alpha}^{-} + \mu_{\alpha}^{+} + \left(1 - v_{\alpha}^{-}\right) + \left(1 - v_{\alpha}^{+}\right) + \mu_{\alpha}^{-}\mu_{\alpha}^{+} - \sqrt{\left(1 - v_{\alpha}^{-}\right)\left(1 - v_{\alpha}^{+}\right)}}{4} \tag{21}$$

Definition 8: Let $\widetilde{a}_{ij}^{k} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+}\right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+}\right]$ be the IVIF numbers where $k = 1,2,\ldots,t$. IVIF Hybrid Geometric (IVIFHG) operator is defined [83].

$$IVIFHG(\widetilde{\alpha}_1, \widetilde{\alpha}_2, \ldots, t) = \sum_{k=1}^{t} \psi_k \widetilde{\alpha}_k = \left(\left[\prod_{k=1}^{t} \left(\mu_k^{-}\right)^{\psi_k}, \prod_{k=1}^{t} \left(\mu_k^{+}\right)^{\psi_k}\right] \left[1 - \prod_{k=1}^{t} \left(1 - v_k^{-}\right)^{\psi_k}, 1 - \prod_{k=1}^{t} \left(1 - v_k^{+}\right)^{\psi_k}\right]\right) \tag{22}$$

where ψ_k is the importance of expert k.

Definition 9: The Euclidean distance between two IVIF numbers $\widetilde{\alpha} = \left[\mu_{\widetilde{\alpha}}^{-}, \mu_{\widetilde{\alpha}}^{+}\right], \left[v_{\widetilde{\alpha}}^{-}, v_{\widetilde{\alpha}}^{+}\right]$ and $\widetilde{\beta} = \left[\mu_{\widetilde{\beta}}^{-}, \mu_{\widetilde{\beta}}^{+}\right], \left[v_{\widetilde{\beta}}^{-}, v_{\widetilde{\beta}}^{+}\right]$) can be calculated [84]:

$$\mathcal{D}_j = \sqrt{0.5 \sum_{i=1}^{n} \left[\left(\mu_{\alpha}^{-} - \mu_{\beta}^{-}\right)^2 + \left(\mu_{\alpha}^{+} - \mu_{\beta}^{+}\right)^2 + \left(v_{\alpha}^{-} - v_{\beta}^{-}\right)^2 + \left(v_{\alpha}^{+} - \mu_{\beta}^{+}\right)^2 + \left(\pi_{\alpha}^{-} - \pi_{\beta}^{-}\right)^2 + \left(\pi_{\alpha}^{+} - \pi_{\beta}^{+}\right)^2\right]} \tag{23}$$

Proposed Methodology

The proposed methodology utilizes both the SWARA and VIKOR MCDM approaches. It is explained in detail in the following steps, starting with the criteria weighing process using the SWARA methodology under an IVIF setup (steps 1 to 8). When using the pairwise comparison-based methods to solve decision-making problems with a large number of criteria, the number of pairwise comparisons increases substantially, which can negatively affect the consistency of these comparisons. However, these methods usually include a built-in procedure to check the consistency of the comparisons, making it easy to identify and discard unreliable responses, such as inconsistent questionnaires [85]. Many studies have critiqued and improved the AHP's aggregation and irregularity of individual evaluations required for group decision making [86]. In contrast, the SWARA method does not include a similar consistency-checking mechanism. This is because the SWARA method inherently ensures consistency by requiring criteria to be ranked in descending order of importance [41].

Then, the alternative ranking process is determined using the IVIF VIKOR approach (steps 9 to 13).

Step 1: A group of experts (Es) is assembled, and the significance of each member is assessed. The group consists of academicians and transport experts who will be responsible for rating the strategies according to the criteria.

Step 2: The criteria are sorted by their relative importance. Each expert uses their expertise and judgments to arrange them in order of importance, using linguistic evaluation and a fuzzy rating derived from Table A1 **(see Appendix)**.

Step 3: The aggregated expert assessments are constructed. Once the significance scores of all experts have been calculated, the IVIFHG operator is applied for the aggregating score.

Step 4: Using Definition 4, the calculation of the score value is made.

Step 5: Each criterion's average relative weight (S_j) is found by establishing the weight of criterion j with criterion (j-1) beginning from the second criterion. The most important criterion, j in proportion to the antecedent criterion, (j-1), is first positioned, and the least important criterion, j is placed last.

Step 6. Find the (k_j) coefficient. The coefficient is calculated using Eq. (24).

$$k_j = \begin{cases} 1 & j = 1 \\ S_{j+1} & j > 1 \end{cases} \tag{24}$$

Step 7. Determine the weights (q_j).

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases} \tag{25}$$

Step 8. The assessment criteria's comparative weights are determined and shown in Eq. (26).

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{26}$$

where w_j and n, are the weight of the jth criterion and criteria numbers, respectively.

Step 9. Gather the alternative language assessment. The conversion of linguistic evaluations for the decision matrix to IVIF sets is seen below.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_m \end{array} \begin{pmatrix} \mathrm{C}_1 & \mathrm{C}_2 & \mathrm{C}_1 & \cdots & \mathrm{C}_\mathrm{n} \\ h_{12} & h_{12} & h_{13} & \cdots & h_{1n} \\ h_{21} & h_{22} & h_{23} & \cdots & h_{2n} \\ h_{31} & h_{32} & h_{33} & \cdots & h_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ h_{m1} & h_{m2} & h_{m3} & \cdots & h_{mn} \end{pmatrix}$$

where A represents the alternatives and C represents the criteria. h_{ij} is the assessment of alternatives concerning the criteria by using IVIF. Averaged evaluations are utilized for the decision matrix with the following Eq. (27).

$$h_{ij} = \frac{1}{k}\left[\sum_{e=1}^{n} h_{ij}^{e}\right], i = 1,2,3,\cdots,m \tag{27}$$

Step 10. Calculate the fuzzy best fj ∗and worst fj- values.

$$f_J^* = \underset{i}{maxx}_{ij}, \text{ and } f_j^- = \mathrm{minx}_{ij} \tag{28}$$

Step 11. Determine the mean group utility (Eq. 29) and maximal regret (Eq. 30).

$$S_i = \sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{w_j} \frac{\mathcal{D}\left(\widetilde{\mathrm{X}}_{\mathrm{ij}}, \widetilde{\mathrm{X}}_{\mathrm{j}}^*\right)}{\mathcal{D}\left(\widetilde{\mathrm{X}}_{\mathrm{j}}^-, \widetilde{\mathrm{X}}_{\mathrm{j}}^*\right)} \tag{29}$$

$$R_i = \underset{j}{max}\left(w_j \frac{\mathcal{D}\left(\widetilde{X}_{ij}, \widetilde{X}_j^*\right)}{\mathcal{D}\left(\widetilde{X}_j^-, \widetilde{X}_j^*\right)}\right) \tag{30}$$

The variable S_i represents the overall evaluation of criteria related to the total distance of the best fuzzy value. The variable R_i represents the maximum distance of this best fuzzy value.

Step 12. Calculate the value of Q_i based on the last rank as in Eq. (31).

$$Q_i = \frac{v\left(S_i - S^*\right)}{\left(S^- - S^*\right)} + \frac{(1-v)\left(R_i - R^*\right)}{\left(R^- - R^*\right)} \tag{31}$$

$S^* = \underset{i}{\min} S_i; S^- = \underset{i}{\max} S_i;$
$R^* = \underset{i}{\min} R_i; R^- = \underset{i}{\max} R_i$ and v denotes the strategy's weight under maximum group utility. Additionally, $(1 - v)$ demonstrates the individual regret weight.

Step 13. Rank the values of S, R, and Q. Additionally, two conditions should be met. Equation (32) is done for the first condition.

$$Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) \geq \frac{1}{(j-1)} \tag{32}$$

Option A $^{(1)}$ is the top choice and A $^{(2)}$ option is the second-best choice. The stability of the solution can be determined by the second condition. Depending on the v-value, the solution may be chosen based on the strategy that yields the highest group utility when "v>0.5", by consensus when "v ≈ 0.5", or with veto when "v<0.5".

If condition 2 is not fulfilled, the chosen solution must comprise alternatives A $^{(1)}$ and A $^{(2)}$. If condition 1 is unsatisfied, the outcome should be a combination of alternatives A $^{(1)}$, A $^{(2)}$ …, and A$^{(M)}$. Figure 1 provides a summary of the suggested hybrid IVIF methodology flowchart.

Application

The authors have identified seven key barriers according to existing studies, official documents, reports, and experts' consultations. These seven barriers (criteria) along with potential solutions are elucidated in **Sect. 3**. Figure 2 indicates the hierarchical framework of the criteria and alternatives, and input was obtained from four experts using Table A1 related to linguistic terms. The information about the qualifications and background of the participants is shown in Table A2 (see Appendix).

The Kenya-Uganda railway project was initiated in the early 1990 s to promote regional integration within the EAC. The completion of this railway project not only connected Kenya and Uganda but also established the first railway as a template for regional economic integration within the continent. The geographical boundaries of the nations within the East African Community are shown in Fig. 3.

Weighting the criteria

Step 1: The initial step involves each expert evaluating the importance of the criteria identified using Table A1, which

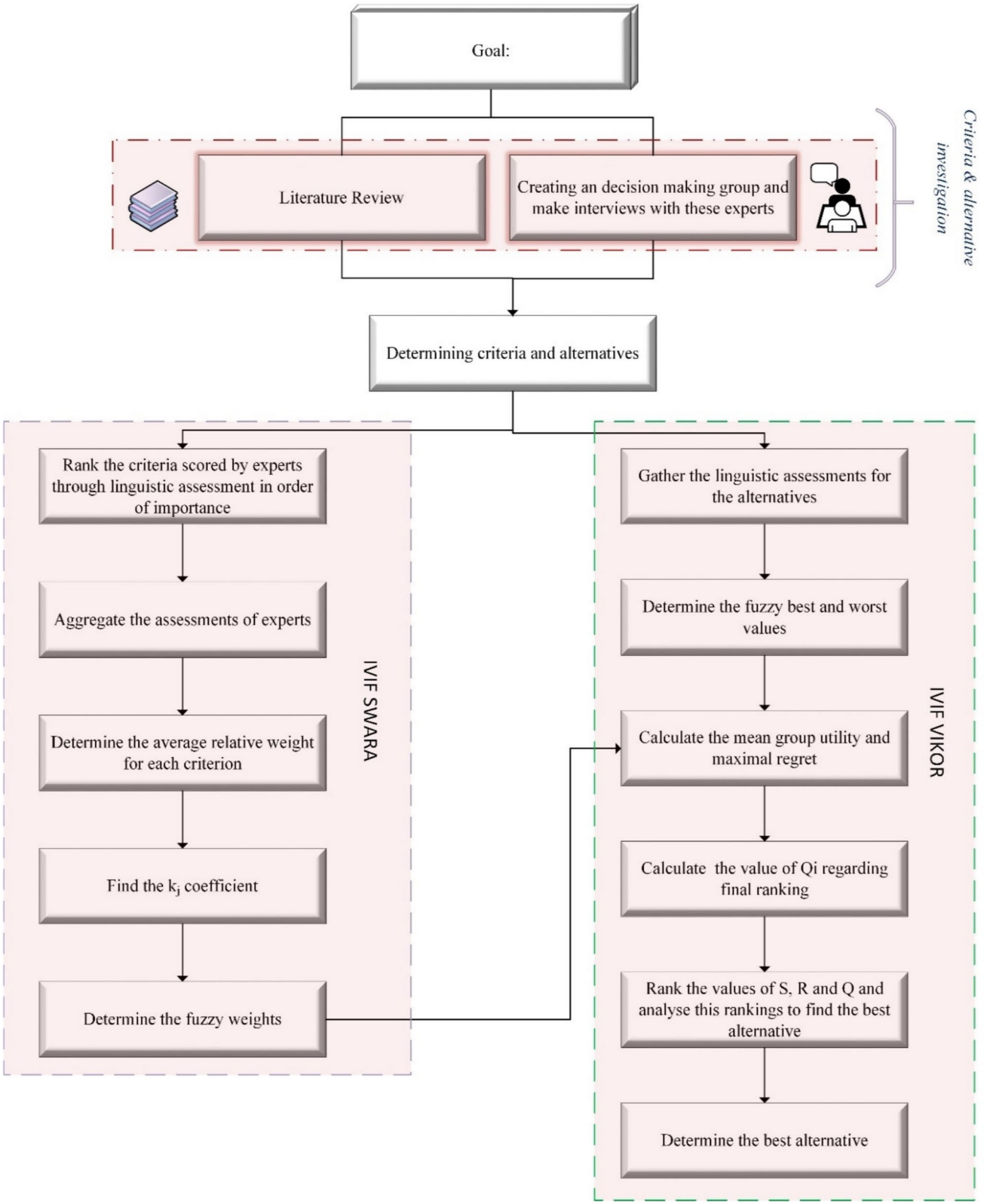


Fig. 1 Flowchart of the proposed hybrid IVIF methodology

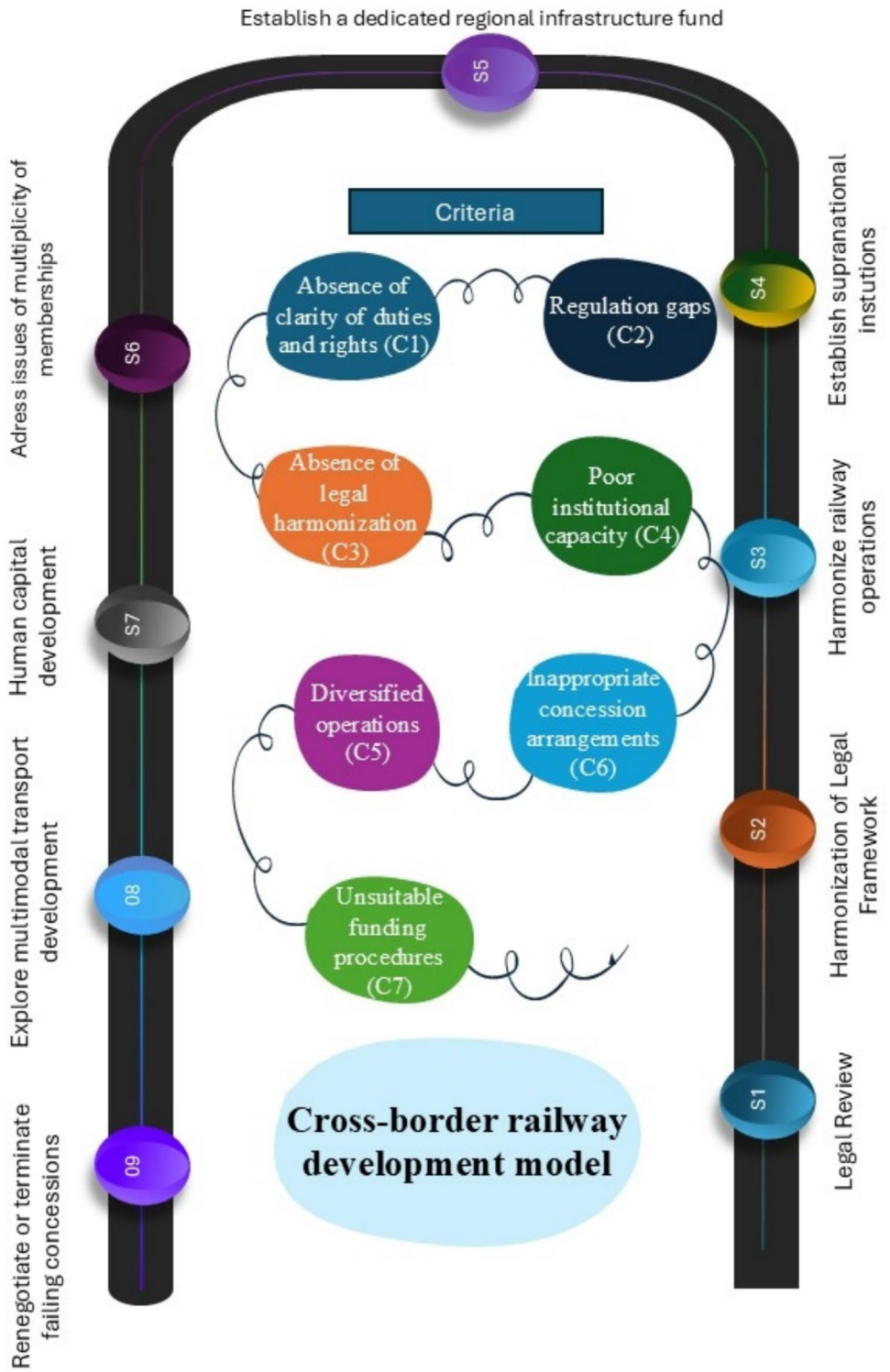


Fig. 2 Hierarchical framework of criteria and alternatives

are then converted into IVIF numbers. Table 4 displays each expert's criteria assessment.

Step 2: By considering the weights of experts, Eq. 22 is utilized to aggregate expert opinions of the criteria (Table 5). It is assumed that the expert weights are equal at this stage.

Steps 3–8: A scoring system is applied to each criterion using Eq. 13, and the criteria are subsequently arranged in decreasing importance of scores. Subsequently, the IVIF-SWARA method is applied, beginning with step 3 and continuing through step 8. The IVIF-SWARA calculation steps are displayed in Table 6.

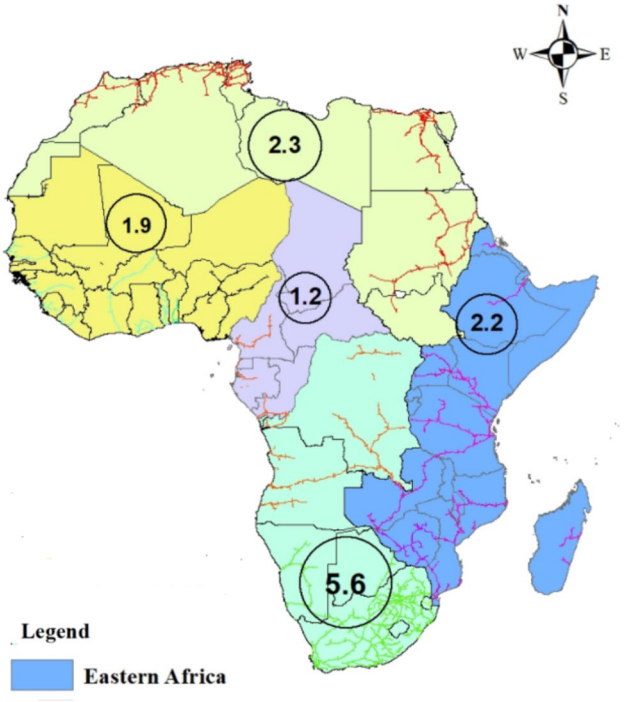


Fig. 3 Railway map of the East African community

Table 4 Assessment of criteria

Criteria	E-1	E-2	E-3	E-4
Absence of clarity of duties and rights (C1)	MH	L	L	VH
Regulation gaps (C2)	H	MH	VH	H
Absence of legal harmonization (C3)	VH	M	H	VL
Poor institutional capacity (C4)	ML	VH	AH	ML
Diversified operations (C5)	L	M	M	ML
Inappropriate concession arrangements (C6)	H	H	ML	MH
Unsuitable funding procedures (C7)	VH	H	VH	VH

Note: E -expert

Table 5 Aggregated evaluations of criteria

Criteria	μ_L	μ_U	v_L	v_U
Absence of clarity of duties and rights (C1)	0.331	0.476	0.401	0.524
Regulation gaps (C2)	0.549	0.649	0.201	0.351
Absence of legal harmonization (C3)	0.397	0.511	0.393	0.489
Poor institutional capacity (C4)	0.395	0.538	0.339	0.462
Diversified operations (C5)	0.334	0.433	0.513	0.567
Inappropriate concession arrangements (C6)	0.441	0.564	0.300	0.436
Unsuitable funding procedures (C7)	0.587	0.687	0.163	0.313

Step 8: The importance of each criterion is illustrated in Fig. 4, which is generated using the final weights obtained by normalizing the recalculated weights using **Eq.** 26.

The results, as illustrated in Fig. 4, show that the experts identified unsuitable funding mechanisms as the most significant barrier. This is followed by gaps in regulation, inappropriate concession agreements, poor institutional capacity, absence of legal harmonization, absence of clarity of duties and rights, and diversified operations.

Table 6 Results of IVIF-SWARA

Steps	4	5	6	7
Criteria	Score	s_j	k_j	q_j
Unsuitable funding procedures (C7)	0.399		1	1
Regulation gaps (C2)	0.323	0.076	1.076	0.929
Inappropriate concession arrangements (C6)	0.135	0.188	1.188	0.782
Poor institutional capacity (C4)	0.067	0.068	1.068	0.732
Absence of legal harmonization (C3)	0.013	0.053	1.053	0.695
Absence of clarity of duties and rights (C1)	−0.059	0.072	1.072	0.648
Diversified operations (C5)	−0.16	0.098	1.098	0.590

Evaluating the strategies

Step 9: Nine different strategies are evaluated using the importance weights established by IVIF-SWARA. This creates the alternative evaluation matrix, as shown in Table A3 (see Appendix). Expert opinions are converted to IVIF numbers based on Table A1. Then, expert opinions about criteria are aggregated by Eq. 22 (see Table 7).

Step 10: Table 8 lists the fuzzy best and fuzzy worst solutions that have been established for each criterion using score values outlined in Definitions 4 and 6.

Step 11: In Fig. 5, the mean group utility S_i and maximal regret R_i values are calculated for each strategy using Euclidean distance.

Step 12: In Fig. 6, the scores Q_i for each strategy are calculated, with 0.5 as the threshold value via the combinations of S_i and R_i values.

Step 13: Lastly, strategies are ordered based on their S_i, R_i and Q_i values. Table 9 shows the rankings of strategies.

C1:"Acceptableadvantage":S4isdeterminedasthesecond-most appropriate strategy. So, the $Q(a'') - Q(a\prime) \geq D(Q)$ becomes $0.394 - 0 \geq 1/(9-1) = 0.125$. So C1 is satisfied.

C2: "Acceptable stability in decision.

Via the IVIF VIKOR method, the appropriate alternative for this problem is found to be a legal review (S1) with a value of 0.000, whereas exploring multimodal transport development (S8) with a value of 0.893 was seen to be the least appropriate alternative. The remaining alternatives are ranked as S4 > S2 > S7 > S3 > S9 > S5 > S6.

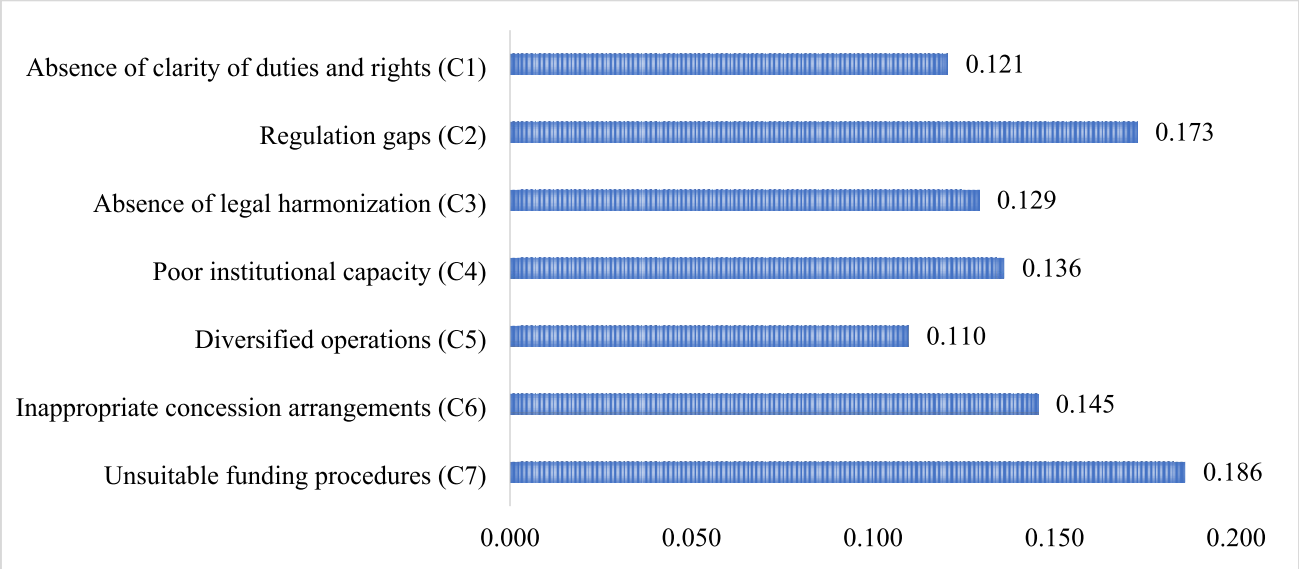


Fig. 4 Criteria weights

Sensitivity Analysis

To illustrate the robustness of our proposed method in varying conditions, a sensitivity analysis is performed in this section by modifying the threshold value (v). The value is incrementally increased by 0.25 and ranges from 0 to 1. Figure 7 illustrates the final classification of alternatives according to different threshold settings. This is necessary as the mean group utility and maximal regret values for each alternative can change. The results in Fig. 5 reveal that strategy 1 (S1) is consistently the best option in all scenarios, indicating that strategy 1 is a robust choice in any situation. As the threshold value increases, strategy 4 maintains its position as the second-best option, but when the threshold value is lowered, it drops to third place. This may be because strategy 4 has a low value for R_i (the maximal regret), which becomes more significant as the threshold value increases. Additionally, strategy 2 consistently performs well across all threshold values. As the threshold value increases, strategy 9 also improves in ranking.

Effective decision-making is essential for achieving strong business performance, and numerous decision analysis methods have been developed to support this process [87, 88]; however, in practice, decisions are often made by a group of experts with varying preferences and objectives [89] which makes it crucial to test the stability of the results. To ensure the robustness and stability of the ranking results, a sensitivity analysis on expert weights is conducted in this section. This analysis involves generating ten different sets of expert weights randomly. Each set is used to solve the criteria's weighting problem independently, allowing us to observe how changes in criteria weights affect the importance of criteria. The randomly generated sets of expert weights are presented in Table 10.

Next, the IVIF-SWARA method is applied to derive the criteria weights from these sets, which are visualized in Fig. 8. This sensitivity analysis provides valuable insights into the reliability of the proposed methodology. By examining how the rankings fluctuate under different weighting scenarios, we can evaluate the consistency and robustness of the results.

Figure 8 demonstrates that the importance of criteria is sensitive to the changing expert weights. The sensitivity analysis demonstrates how changes in expert weights influence the relative importance of criteria. Notably, the criterion "Inefficient funding mechanisms (C7)" consistently remains the most significant across all weight sets, with values ranging between 0.175 and 0.187, suggesting its critical importance regardless of changes in expert input. In contrast, criteria like "Lack of clarity of rights and duties (C1)" and "Disparate operations (C5)" show more variation but maintain relatively lower importance, fluctuating between 0.099 and 0.142 for C1 and 0.108 and 0.119 for C5. The "Weak institutional capacity (C4)" shows noticeable shifts, particularly in Set-2 and Set-8, where its importance rises significantly, indicating that expert perspectives greatly influence its perceived relevance. Overall, the variation in expert weights highlights the robustness of C7 while showing some sensitivity in the ranking of other criteria.

Table 7 Aggregated strategy evaluation matrix

	C1				C2				C3				C4			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
S1	0.574	0.675	0.175	0.325	0.512	0.612	0.238	0.388	0.549	0.649	0.201	0.351	0.416	0.497	0.444	0.503
S2	0.342	0.470	0.431	0.530	0.397	0.536	0.327	0.464	0.446	0.578	0.286	0.422	0.426	0.531	0.375	0.469
S3	0.370	0.509	0.368	0.491	0.449	0.523	0.421	0.477	0.407	0.488	0.452	0.512	0.281	0.409	0.513	0.591
S4	0.351	0.479	0.421	0.521	0.379	0.515	0.349	0.485	0.536	0.581	0.358	0.419	0.462	0.586	0.278	0.414
S5	0.350	0.470	0.444	0.530	0.351	0.493	0.384	0.507	0.446	0.578	0.286	0.422	0.431	0.528	0.378	0.472
S6	0.407	0.488	0.452	0.512	0.407	0.511	0.394	0.489	0.420	0.495	0.447	0.505	0.288	0.425	0.486	0.575
S7	0.379	0.492	0.411	0.508	0.370	0.509	0.368	0.491	0.370	0.509	0.368	0.491	0.326	0.474	0.402	0.526
S8	0.234	0.396	0.491	0.604	0.440	0.514	0.429	0.486	0.334	0.453	0.461	0.547	0.288	0.425	0.486	0.575
S9	0.431	0.505	0.438	0.495	0.523	0.544	0.429	0.456	0.334	0.440	0.494	0.560	0.342	0.462	0.452	0.538
	C5				C6				C7							
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U				
S1	0.379	0.492	0.411	0.508	0.548	0.619	0.279	0.381	0.326	0.474	0.402	0.526				
S2	0.319	0.444	0.468	0.556	0.561	0.661	0.189	0.339	0.416	0.521	0.385	0.479				
S3	0.549	0.620	0.278	0.380	0.301	0.462	0.413	0.538	0.461	0.586	0.279	0.414				
S4	0.388	0.502	0.402	0.498	0.549	0.620	0.278	0.380	0.350	0.501	0.360	0.499				
S5	0.334	0.440	0.494	0.560	0.358	0.502	0.375	0.498	0.456	0.589	0.275	0.411				
S6	0.294	0.403	0.539	0.597	0.334	0.433	0.513	0.567	0.370	0.486	0.429	0.514				
S7	0.512	0.585	0.311	0.415	0.236	0.394	0.494	0.606	0.440	0.538	0.368	0.462				
S8	0.537	0.609	0.289	0.391	0.262	0.412	0.477	0.588	0.561	0.632	0.267	0.368				
S9	0.472	0.597	0.267	0.403	0.585	0.685	0.164	0.315	0.536	0.636	0.214	0.364				

Findings and Discussion

In this section, the study's main findings are disclosed, accompanied by their corresponding theoretical, managerial, and policy-based implications.

Findings

After examining the literature review, reports, official documents, and expert opinions, it has become apparent that numerous institutional and legal barriers have hindered the development of EAC's cross-border railway transportation. From this analysis, seven potential barriers have been identified that may contribute to the unsustainable development of cross-border railway transportation. The determination of criteria weights is done via the IVIF-SWARA methodology. According to the results, the most critical barrier identified by the experts was unsuitable funding mechanisms, with a weight of 0.186, while the diversified operations criteria received the least attention, with a weight of 0.110.

The experts' focus on unsuitable funding mechanisms aligns with the observations made in Article 11 of the agreement of the Northern Corridor Transit and Transport. This article highlights that despite various attempts to secure local funding, the outcomes have fallen short of expectations. Additionally, political disputes have hindered the proper allocation of funds among member nations. Moreover, the establishment of a partnership fund designed to pool resources from relevant stakeholders has not met its intended goals. Consequently, the EAC faces considerable challenges in obtaining the necessary funding to upgrade the infrastructure along the Northern Corridor. To address these challenges effectively, the EAC needs to enhance its financial management within member territories. This approach will result in increased savings and enable the pooling of resources, which can then be directed into a dedicated regional infrastructure fund. Furthermore, EAC partners need to collaborate more extensively with the private sector and leverage their diaspora communities for project financing. Utilizing bankable PPPs and issuing diaspora bonds can serve as an effective means to raise funds. In addition, cost reduction in setting up new institutions can be achieved through regional resource-sharing and the establishment of joint institutions or consolidated one-stop service centers. Furthermore, the EAC should strengthen its engagement with development partners by showcasing concrete results from previous funding efforts. This approach will instill confidence within the donor community by demonstrating the value and effectiveness of their investments.

The study highlights regulatory gaps as the second most significant barrier. To address this issue, it recommends that member nations should create regulations specifically designed to handle cross-border matters not currently covered by their national laws. This involves expanding the scope of their national legislation to encompass issues that transcend their borders. The study also suggests that governments should establish partnerships with the private sector to address concerns such as the movement of people across shared borders and the environmental impacts that affect cross-border areas. These issues should be incorporated into existing railway laws. Furthermore, the study identifies unfavorable concession agreements as the third most critical barrier. In some instances, it has been observed that railway performance did not improve after concession agreements were signed, as seen in cases like Uganda and Kenya. To tackle this challenge, the study proposes conducting a comprehensive feasibility study to assess the concessionaire's ability to fulfill their commitments under the agreements and establish more favorable concession arrangements. By taking this step, nations can assess whether the company in charge possesses the necessary capabilities, including technical expertise, to carry out its responsibilities. Although having a wide range of operations is not a significant barrier to this type of railway development, consistency across all railway systems in the region is crucial. This means that collaborating nations should standardize the width of railway tracks through the standard gauge railway agreement.

The findings of the IVIF-SWARA-VIKOR framework suggest that legal review (**S1**) was deemed the most appropriate strategy by the expert committee as it will clarify the rights and responsibilities of nations, establish clear proactive measures, and close any existing gaps. It is recommended that EAC policymakers prioritize its implementation within a specific timeline of 12 to 18 months. This approach will also address cross-border environmental issues and address the relocation of people living in unclaimed territory. Additionally, the strategy could facilitate the incorporation of laws for public–private partnership in national legislation, creating a clear framework for regulating private sector participation in construction projects. The second most important strategy is the creation of supranational institutions. This approach calls for the speedy implementation of the East African Community Railways Authority (EARA) in the region and its completed operationalization should be targeted within 18 to 24 months. Policymakers should guarantee that the EARA is granted the required power to impose regional guidelines and regulations, especially in fields that are not included in the jurisdiction of national railway regulatory bodies. In addition, actionable roadmaps should be introduced and publicized within the first six months of its implementation, showing decision-making processes, determined responsibilities, and timelines for disclosing monitoring compliance and progress to partner states. Together, these steps offer an adequate time-bound scheme to improve

Table 8 Fuzzy best and fuzzy worst solutions

	C1				C2				C3				C4			
	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U	μ_L	μ_U	v_L	v_U
fjmax	0.574	0.675	0.175	0.325	0.512	0.612	0.238	0.388	0.549	0.649	0.201	0.351	0.462	0.586	0.278	0.414
fjmin	0.234	0.396	0.491	0.604	0.351	0.493	0.384	0.507	0.334	0.440	0.494	0.560	0.281	0.409	0.513	0.591
	C5				C6				C7							
fjmax	0.549	0.620	0.278	0.380	0.585	0.685	0.164	0.315	0.585	0.685	0.164	0.315				
fjmin	0.294	0.403	0.539	0.597	0.236	0.394	0.494	0.606	0.326	0.474	0.402	0.526				

institutional coordination, legal clarity, and regional integration of EAC cross-border railway systems.

Theoretical Contributions

This study presents a new integrated mathematical model that aims to identify the institutional and legal barriers to sustainable cross-border railway transportation. The proposed model extends the SWARA method by incorporating the IVIF environment and utilizes the IVIF-VIKOR approach to rank potential strategies. By merging the strengths of SWARA and VIKOR and enhancing the model with IVIFS, the proposed method is capable of addressing complex uncertainties and solving difficult decision-making issues in diverse areas. Moreover, our methodology demonstrates robustness and effectiveness in addressing complex problems. The study also provides the following theoretical contributions.

- With the integration of IVIF number sets, the proposed model has been fortified to effectively capture and process intricate uncertainties. As a result, the interval-valued intuitionistic fuzzy number (IVIFN) model can be implemented by decision-makers and practitioners to effectively address complicated decision-making challenges that are prevalent across diverse industries, not just limited to cross-border railway transportation.
- The IVIF-SWARA model is a mathematical framework that extends the SWARA method based on IVIFNS and facilitates the identification of decision-making criteria. This model allows for the use of a mathematical tool to determine the influential parameters of the decision-making process, thereby minimizing the impact of subjective and intuition-based evaluations by experts.
- The study proposes IVIF-SWARA-VIKOR as a dependable decision-making model to prioritize solutions for cross-border railway transportation issues. The model's resilience was confirmed through a thorough sensitivity analysis in the preceding section, attesting to its consistency and stability in the face of significant modifications. Consequently, the model provides decision-makers with dependable and precise results.

Managerial Implications

The following managerial implications can be derived from the findings of this study.

- East African Community member states and policymakers can assess the current state of cross-border railway transportation systems by considering the results and conclusions presented in this study. The study provides

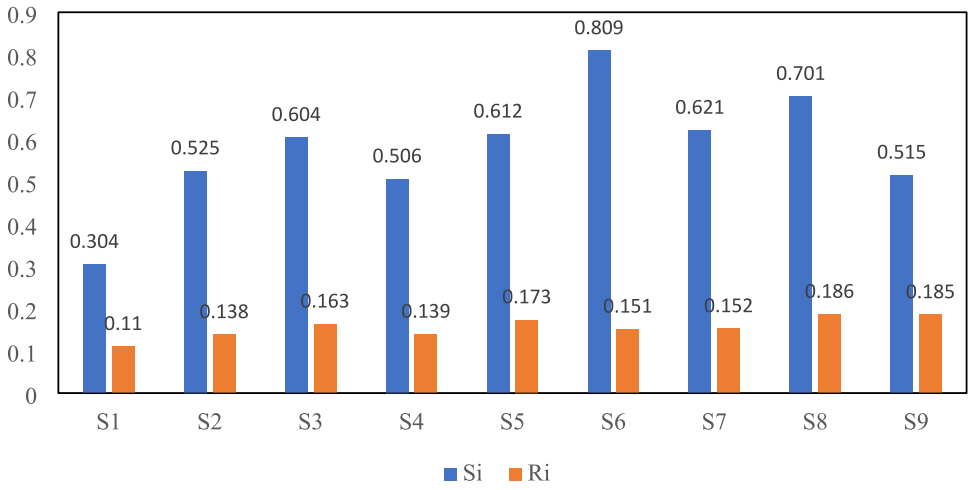


Fig. 5 Mean group utilities and maximal regrets for strategies

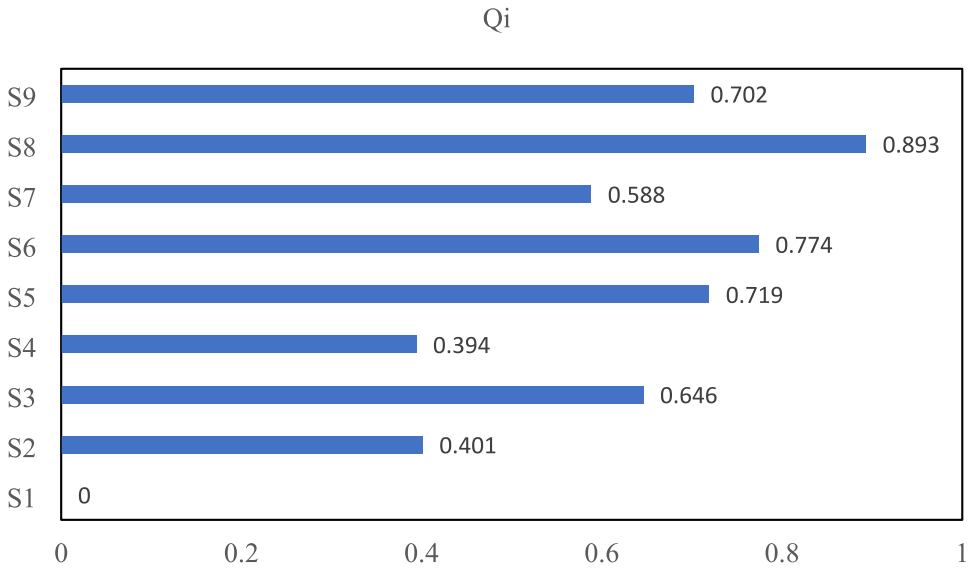


Fig. 6 Score of Q_i for the strategies

Table 9 Ranking of strategies based on S_i, R_i, and Q_i

	S_i	R_i	Q_i
S1	1	1	1
S2	4	2	3
S3	5	6	5
S4	2	3	2
S5	6	7	7
S6	9	4	8
S7	7	5	4
S8	8	9	9
S9	3	8	6

S1 ranked first based on Q_i scores. Then two conditions (C1 and C2) are checked to evaluate S1 as the most appropriate strategy

practical implications regarding the relative importance and impact of strategies that can be implemented to promote sustainable cross-border railway transportation development. It can also help identify which strategies are suitable for financial aid.

- Beneficial perspectives are presented for policymakers who are in charge of reviewing the existing institutional and legal framework for sustainable cross-border railway transportation. By using these perspectives, decision-makers can make progress toward sustainable development. Practitioners can also benefit from the paper's implications, which provide practical guidance for implementing effective strategies for cross-border railway transportation.

Policy Implications

The paper endeavors to address significant gaps in the literature by first evaluating available strategies for the development of cross-border railways and presenting the most appropriate strategies. It aims to provide a useful guide for policymakers to develop optimal approaches for enhancing cross-border railway transportation systems.

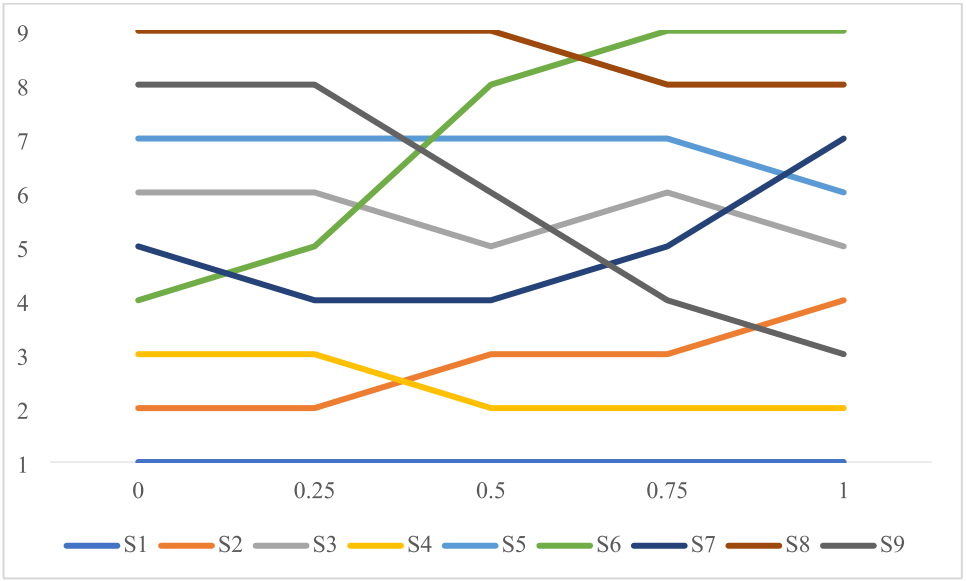


Fig. 7 The ranking of strategies for different threshold values

Table 10 Weight sets for sensitivity analysis

	Set-1	Set-2	Set-3	Set-4	Set-5	Set-6	Set-7	Set-8	Set-9	Set-10	Current
E-1	0.126	0.088	0.084	0.125	0.193	0.195	0.311	0.446	0.027	0.399	0.250
E-2	0.279	0.479	0.419	0.214	0.434	0.393	0.460	0.216	0.123	0.157	0.250
E-3	0.381	0.375	0.085	0.216	0.351	0.091	0.052	0.333	0.294	0.242	0.250
E-4	0.214	0.058	0.412	0.445	0.022	0.321	0.177	0.006	0.556	0.201	0.250

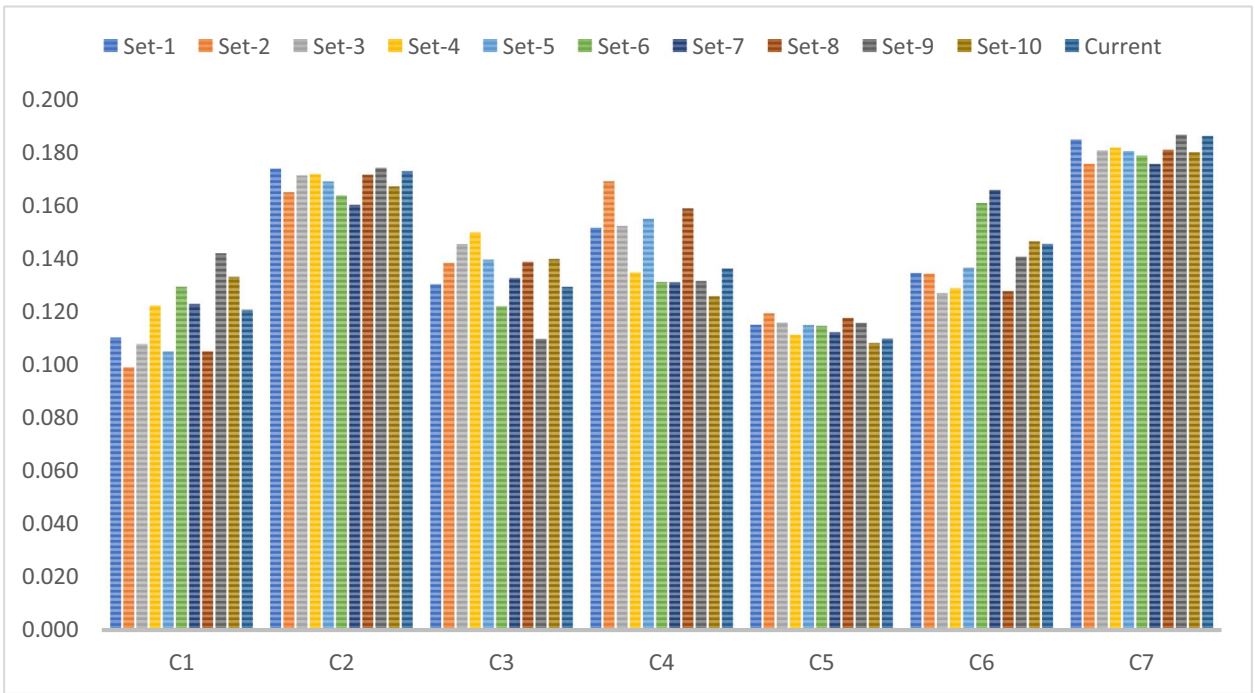


Fig. 8 Criteria weights for different expert weights

The second issue addressed in the paper is the absence of a commonly accepted set of criteria for evaluating strategies to implement sustainable cross-border railway transportation systems. This problem is exacerbated by the lack of literature on the evaluation of development alternatives for this particular type of transportation in this region of Africa. To address this issue, the study combines two classical approaches: identifying criteria used in previous studies

through literature review, reports, official documents, and expert opinions about influential factors. By providing a comprehensive set of criteria, the study aims to assist East African Community member states and policymakers in selecting appropriate strategies for sustainable cross-border railway transportation systems. The third key point in the paper is that the proposed approach offers a way to reduce the impact of subjective opinions from experts and allows for the identification of influential barriers through a mathematical model. This approach prioritizes empirical evidence over personal biases, helping decision-makers make informed decisions that are based on objective data.

Conclusion

This study focused on developing cross-border railway transportation. It achieved a significant milestone by prioritizing the various alternatives for enhancing cross-border railways, a first of its kind. The study introduced nine potential alternatives for cross-border railway transportation, effectively addressing regional transportation needs. These alternatives, coupled with seven key criteria, provided a practical decision-making framework for member states and policymakers in the East African Community dealing with complex cross-border railway development decisions.

Unlike previous studies which were just based on literature review and qualitative methods, an interval-valued intuitionistic fuzzy group decision model was introduced herein to examine the topic under consideration. The significant benefits offered by this model include the thorough consolidation of cognitive input from multiple experts, enhanced accuracy in depicting the actual uncertainties associated with cross-border railway transportation development decision-making, and the efficient determination of objective criteria weights in cases where they are not predetermined.

While the most critical barriers to be considered for the development of cross-border railway transportation are inefficient funding mechanisms, regulatory gaps, and unfavorable concessioning arrangements, the strategies considered to overcome them are conducting a legal review and establishing supranational institutions. Although significant contributions are made through this study, some limitations have been noticed. First, the study didn't perform a comparative analysis with the existing approaches for addressing this issue, leaving room for further studies. Second, the study faced challenges in accessing crucial policy and legal documents due to the absence of websites for many relevant governmental organizations, as well as a lack of English translations for legal texts from all nations. Future research could focus on assessing these essential documents. Third, the study didn't consider non-legal factors that could influence cross-border railway transportation development. Additionally, it didn't address the specific challenges faced by nations without existing railway infrastructure. Future research should conduct a more in-depth analysis of these factors and consider non-legal aspects. Lastly, the data collection relied on a small group of experts. To enhance future research, a more extensive range of experts should be involved, and clear criteria for their selection should be established. The proposed approach could also be adopted to address other complex decision-making issues, such as renewable energy source selection, sustainability assessment, transportation decarbonization, and circular economy implementation, offering valuable opportunities for future research and application. In future studies, the number of experts could be increased to gain a broader perspective, and different methods for aggregating expert opinions, such as those tested by Duleba and Szádoczki [90] and Duleba, Alkharabsheh [91], could be used to enhance the robustness and consistency of the decision-making process. Future works could use the approach developed by Gregory, Atkins [92] to bring together experts and introduce a level of rigor to allow comparison of cases and differentiation of stakeholder identification and engagement models.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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