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Strategies for Enhancing Industry 4.0 Adoption in East Africa: An Integrated Spherical Fuzzy SWARA-WASPAS Approach

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Abstract: Developed countries have successfully implemented various Industry 4.0 (I4.0) initiatives, showcasing their ability to reap the benefits of this new industrial revolution. Active pursuit of excellence in Industry 4.0 is evident in these nations. However, in Africa, many countries still lack a clear understanding of Industry 4.0, with some remaining trapped in Industry 1.0 and others facing challenges in transitioning to Industry 2.0. Moreover, a significant number of these African countries continue to grapple with limited access to reliable electricity. To address the issue, this study examines seven strategies identified as criteria for enhancing the adoption of Industry 4.0 within the East African Community (EAC). These strategies are derived from observations of Industry 4.0 initiatives implemented in developed countries. Subsequently, the criteria are used to evaluate and rank the level of Industry 4.0 adoption in two specific East African countries. To tackle the challenges of complex group decision-making, the study integrates the Weighted Aggregated Sum Product Assessment (WASPAS) technique with the Step-Wise Weight Assessment Ratio Analysis (SWARA) within a spherical fuzzy (SF) framework. The SF-SWARA approach is applied to determine the weight and importance of the criteria, while SF-WASPAS is employed to rank the countries based on the criteria weighted by SF-SWARA. According to the findings, it was revealed that education and training, research, development, and innovation, as well as public-private partnerships and policy innovation, are the three most influential strategies for significantly improving the adoption of Industry 4.0 within the East African community. Furthermore, the results indicate that Rwanda stands out as the leading country in terms of implementing these strategies to enhance the adoption of Industry 4.0 technology. To verify the reliability and suitability of the proposed methodology, a sensitivity analysis was conducted, which affirmed the stability and practicality of the suggested approach.

Keywords: Industry 4.0 (I4.0) adoption; WASPAS; SWARA; Spherical fuzzy sets

1 Introduction

The urgency and competitiveness of achieving Industry 4.0 (I4.0) have been widely recognized, necessitating proactive participation from Africa in this industrial revolution [1]. Unlike previous industrial transformations that excluded Africa, I4.0 is rapidly evolving and pervasive, making it essential for every African country to prepare thoroughly and early for its adoption [2]. The rapid pace of I4.0 evolution presents a multitude of opportunities, yet it can exacerbate existing inequalities if nations are unprepared for the changes it brings [3]. Governments, private sectors, and public-private partnerships have initiated national strategic initiatives to facilitate the implementation and widespread adoption of I4.0 in various countries. However, a lack of understanding remains regarding the number and nature of these initiatives.

2 Literature Review

Studies have focused on the adoption of I4.0 technology [4–6], with methodologies such as DEMATEL-based ANP [5], modified SWARA and WASPAS techniques [6], and fuzzy DEMATEL-TOPSIS approach [7] being employed to investigate various aspects of I4.0 implementation. Other methodologies have also been proposed, including DANP and PROMETHEE II [8], hybrid AHP-VIKOR [9], q-ROF-MEREC-RS approach [10], q-ROF-CRITIC model [11], neutrosophic MCDM methodology [12], MEREC-fuzzy MARCOS model [13], and a new decision-making framework by Rani et al. [14].

In the African context, studies have examined the development and application of I4.0 technology, in various countries such as South Africa, Kenya, Nigeria [15–20], and a broader literature review covering various regions [21]. However, few researchers have proposed strategies to strengthen the adoption of I4.0 technology in Africa [17, 22, 23]. Furthermore, only one study by Bongomin et al. [21] has addressed the strategies for enhancing I4.0 adoption in the East Africa Community, but it did not prioritize these strategies nor conduct a comparative analysis between the countries within this specific region.

Considering the limitations of previous research, it becomes evident that the adoption of I4.0 technology necessitates the evaluation of a diverse set of paradoxical parameters. Conventional decision-making approaches centered around a single criterion are insufficient for addressing the inherent complexities of these challenges [24–30]. Consequently, multi-criteria decision-making (MCDM) approaches have gained traction, demonstrating promise in providing policymakers and managers with flexible and adaptable tools [31–39]. These approaches use predetermined parameters to classify and select one or more elements from a set of alternatives [40–46], and the chosen parameters are subsequently assessed based on their effectiveness in fulfilling their respective functions and determining the suitability of alternative options [47–52].

In this study, an integrated approach combining SWARA and WASPAS methods under a spherical fuzzy set (SFS) framework is presented. This methodology aims to address the limitations of previous research by facilitating the identification and prioritization of strategies for enhancing the adoption of I4.0 within the East Africa Community. Additionally, it enables a comparative analysis of the effectiveness of these strategies between two countries within this specific region of Africa.

3 Methodology

This study adopts the integrated methodology initially developed by Hashemkhani Zolfani et al. [53] and further applies it to various research contexts [54–58].

3.1 Preliminaries

Spherical fuzzy sets (SFS) enable the representation of imprecision and uncertainty through linguistic expressions. Ayyildiz and Taskin [59] have defined three functions that can be extended to cover a wider area, providing experts with increased flexibility in expressing their opinions. These functions are defined within a range of 0 to 1. Kutlu Gündoğdu and Kahraman [60] stipulate that a spherical fuzzy number (SFN) must fulfill the following condition.

Definition 1: A SFN is presented as $\tilde{S}$:

$$\widetilde{\mathrm{S}} \cong \left\{\mathrm{x}, \tilde{\mathrm{S}}\left(\mu_{\tilde{\mathrm{s}}}(\mathrm{x}), \mathrm{v}_{\tilde{\mathrm{s}}}(\mathrm{x}), \pi_{\tilde{\mathrm{s}}}(\mathrm{x})\right); \mathrm{x} \in \mathrm{X}\right\} \tag{1}$$

$\mu_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0,1], \mathrm{v}_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0,1]$ and $\pi_{\tilde{\mathrm{s}}}(\mathrm{x}) : \mathrm{X} \mapsto [0,1]$ characterize the membership, non-membership, and hesitancy function of the component $\mathrm{x} \in \mathrm{X}$ to $\tilde{S}$, respectively and X is a fixed set. And their sum of squares cannot be greater than 1.

$$0 \leq \mu_{\tilde{s}}(\mathrm{x})^2 + \mathrm{v}_{\tilde{s}}(\mathrm{x})^2 + \pi_{\tilde{s}}(\mathrm{x})^2 \leq 1; \mathrm{x} \in \mathrm{U} \tag{2}$$

Definition 2: Two SFNs $\widetilde{\alpha} = \mathrm{S}\left(\mu_\alpha, \mathrm{v}_\alpha, \pi_\alpha\right)$ and $\tilde{\beta} = S\left(\mu_\beta, v_\beta, \pi_\beta\right)$ are summed [61]:

$$\widetilde{\alpha} \oplus \tilde{\beta} = \tilde{S}\left(\sqrt{\mu_{\widetilde{\alpha}}^2 + \mu_{\widetilde{\beta}}^2 - \mu_{\widetilde{\alpha}}^2 \mu_{\widetilde{\beta}}^2}, v_{\widetilde{\alpha}} v_{\widetilde{\beta}}, \sqrt{\left(1 - \mu_{\widetilde{\alpha}}^2\right) \pi_{\widetilde{\beta}}^2 + \left(1 - \mu_{\widetilde{\beta}}^2\right) \pi_{\widetilde{\alpha}}^2 - \pi_{\widetilde{\alpha}}^2 \pi_{\widetilde{\beta}}^2}\right) \tag{3}$$

Definition 3: Two SFNs $\widetilde{\alpha} = S\left(\mu_\alpha, v_\alpha, \pi_\alpha\right)$ and $\tilde{\beta} = \mathrm{S}\left(\mu_\beta, v_\beta, \pi_\beta\right)$ are multiplied:

$$\widetilde{\alpha} \otimes \tilde{\beta} = \widetilde{S}\left(\mu_{\widetilde{\alpha}} \mu_{\widetilde{\beta}}, \sqrt{v_{\widetilde{\alpha}}^2 + v_{\widetilde{\beta}}^2 - v_{\widetilde{\alpha}}^2 v_{\widetilde{\beta}}^2}, \sqrt{\left(1 - v_{\widetilde{\alpha}}^2\right) \pi_{\widetilde{\beta}}^2 + \left(1 - v_{\widetilde{\beta}}^2\right) \pi_{\widetilde{\alpha}}^2 - \pi_{\widetilde{\alpha}}^2 \pi_{\widetilde{\beta}}^2}\right) \tag{4}$$

Definition 4: A SFN $\widetilde{\alpha} = S\left(\mu_\alpha, v_\alpha, \pi_\alpha\right)$ is multiplied by a positive scalar:

$$\lambda\widetilde{\alpha} = \widetilde{S}\left(\sqrt{1-\left(1-\mu_{\widetilde{\alpha}}^2\right)^\lambda}, v_{\widetilde{\alpha}}^\lambda, \sqrt{\left(1-\mu_{\widetilde{\alpha}}^2\right)^\lambda - \left(1-\mu_{\widetilde{\alpha}}^2-\pi_{\widetilde{\alpha}}^2\right)^\lambda}\right) \tag{5}$$

Definition 5: The positive power of SFN $\widetilde{\alpha} = \mathrm{S}\left(\mu_\alpha, \mathrm{v}_\alpha, \pi_\alpha\right)$:

$$\widetilde{\alpha}^\lambda = \tilde{S}\left(\mu_{\widetilde{\alpha}}^\lambda\sqrt{1-\left(1-v_{\widetilde{\alpha}}^2\right)^\lambda}, \sqrt{\left(1-v_{\widetilde{\alpha}}^2\right)^\lambda - \left(1-v_{\widetilde{\alpha}}^2-\pi_{\widetilde{\alpha}}^2\right)^\lambda}\right) \tag{6}$$

Definition 6: The score function for an $\widetilde{\alpha} = S\left(\mu_\alpha, v_\alpha, \pi_\alpha\right)$ [59]:

$$\text{Score }(\tilde{\alpha}) = \left(2\mu_{\tilde{\alpha}} - \pi_{\tilde{\alpha}}\right)^2 - \left(v_{\tilde{\alpha}} - \pi_{\tilde{\alpha}}\right)^2 \tag{7}$$

Definition 7: Spherical Weighted Arithmetic Mean (SWAM) is given below where $w = \left(w_1, w_2 \ldots\ldots, w_n\right); w_i \in [0,1]; \sum_{i=1}^n w_i = 1$ [62]:

$$\begin{aligned} &SWAM_w\left(\widetilde{\alpha}_1, \ldots\ldots, \widetilde{\alpha}_n\right) = w_1\widetilde{\alpha}_1 + w_2\widetilde{\alpha}_2 + \cdots\ldots + w_n\widetilde{\alpha}_n \\ &= \left\{\begin{matrix} \left[1-\prod_{i=1}^n\left(1-\mu_{\widetilde{\alpha}_i}^2\right)^{w_i}\right]^{1/2}, \prod_{i=1}^n v_{\widetilde{\alpha}_i}^{w_i}, \\ \left[\prod_{i=1}^n\left(1-\mu_{\widetilde{\alpha}_i}^2\right)^{w_i} - \prod_{i=1}^n\left(1-\mu_{\widetilde{\alpha}_i}^2-\pi_{\widetilde{\alpha}_i}^2\right)^{w_i}\right]^{1/2} \end{matrix}\right\} \end{aligned} \tag{8}$$

3.2 Spherical Fuzzy SWARA

The SWARA approach has demonstrated its utility as a decision-making tool across various domains [63]. It has been effectively employed in diverse areas, such as enhancing decision-making quality through the incorporation of experts' evaluations of their ideas' reliability [64], addressing humanitarian supply chains [56], analyzing performance in hydropower plants [65], managing trade-off problems [66], evaluating the sustainability of railway systems [67], conducting analysis on the operation and implementation of BRT systems [68], examining ERP software [69], classifying the performance of regional transport infrastructures projects [70], assessing intellectual capital aspects in companies [71], studying bioenergy technology production [72], facilitating supplier selection [73], making solar panel selections [74], and determining suitable locations for logistics centers [75]. In this study, the SF-SWARA methodology is employed for criteria weighting. Unlike the conventional SWARA approach that uses crisp numbers to evaluate the criteria, spherical fuzzy numbers (SFNs) are utilized in SF-SWARA. The steps of SF-SWARA are as follows.

Step 1: A decision matrix is assigned to each expert, where the significance of the criteria is evaluated based on linguistic terms provided in Table 1. Let $\tilde{A}_{jk} = \left(\mu_{\mathrm{jk}}, \mathrm{v}_{\mathrm{jk}}, \pi_{\mathrm{jk}}\right)$ be the SFN for an evaluation of criterion j by expert k.

Table 1. Definition and fuzzy rate of linguistic terms [76]

Linguistic terms	**Spherical fuzzy numbers**		
	μ	**v**	**π**
Extremely Low -EL	0.1	0.9	0
Very Low -VL	0.2	0.8	0.1
Low -L	0.3	0.7	0.2
Medium Low -ML	0.4	0.6	0.3
Medium -M	0.5	0.5	0.4
Medium High -MH	0.6	0.4	0.3
High -H	0.7	0.3	0.2
Very High -VH	0.8	0.2	0.1
Extremely High -EH	0.9	0.1	0

Step 2: The SWAM operator, as defined in Definition 7, is used to aggregate expert opinions.

$$\begin{aligned} &SWAM_{\omega_k}\left(\tilde{A}_{jk}, \ldots\ldots, \tilde{A}_{jt}\right) = \omega_1 A\tilde{A}_{j1} + \omega_2\tilde{A}_{j2} + \cdots\cdots + \omega_t\tilde{A}_{jt} \\ &\tilde{z}_j = \left(\mu_j, v_j, \pi_j\right) = \left\{\begin{matrix} \left[1-\prod_{k=1}^t\left(1-\mu_{\tilde{A}_{jk}}^2\right)^{\omega_k}\right]^{1/2}, \prod_{k=1}^t v_{\tilde{A}_{jk}}^{\omega_k}, \\ \left[\prod_{k=1}^t\left(1-\mu_{\tilde{A}_{jk}}^2\right)^{\omega_k} - \prod_{k=1}^t\left(1-\mu_{\tilde{A}_{jk}}^2-\pi_{\tilde{A}_{jk}}^2\right)^{\omega_k}\right]^{1/2} \end{matrix}\right\} \end{aligned} \tag{9}$$

The weight of expert k is denoted by ω_k, where t represents the total number of experts. The aggregated value for criterion j is represented as Z_j.

Step 3: The score value for each criterion is calculated according to Definition 6.

$$\text{Score}\left(\tilde{z}_j\right) = \left(2\mu_j - \pi_j\right)^2 - \left(v_j - \pi_j\right)^2 \tag{10}$$

Step 4: Criteria are sorted in descending order based on their score values, from highest to lowest.

Step 5: Starting from the second criterion, the comparative significance (c_j) is determined by calculating the difference between the score values of the criterion (j) and criterion $(j-1)$.

Step 6: The comparative coefficient (k_j) is established for each criterion.

$$k_j = \begin{cases} 1, & j = 1 \\ c_j + 1, & j > 1 \end{cases} \tag{11}$$

Step 7: The estimated weight for each criterion (q_j) is recalculated.

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{(j-1)}}{k_j}, & j > 1 \end{cases} \tag{12}$$

Step 8: The recalculated weights are normalized to obtain the weight of each criterion, where n represents the total number of criteria.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{13}$$

3.3 Spherical Fuzzy WASPAS

The WASPAS approach has been widely utilized as a valuable decision-making tool across various fields, such as determining the optimal site for solid waste disposal [63], analyzing societal dynamics [77], managing reservoir flood control [78], evaluating green suppliers [78], selecting the ideal mode of transportation [79], choosing physicians [80], deciding petrol station locations [81], determining refugee camp sites [82], selecting parker locker locations [83], choosing emergency supply depot locations [84], assessing the quality of public transportation services [84], selecting air conditioning systems [85], determining bridge construction locations [86], selecting last-mile delivery modes [87], selecting hub location [88], choosing a supplier in steel industry [89], and identifying suitable locations for constructing roundabouts [90]. A comprehensive evaluation of two selected countries is conducted in this study using the integrated SF-WASPAS method based on a set of weighted criteria (strategies). The initial step involves defining the weighted criteria with the SF-SWARA method, followed by the application of the SF-WASPAS method to identify the country that has adopted the technology to a greater extent based on these established criteria. The sequential steps involved in the SF-WASPAS methodology are outlined as follows:

Step 1: A matrix for alternative assessment is established for each expert using linguistic variables (Table 1). Let $\widetilde{\mathrm{X}}_{\mathrm{ijk}} = \left(\mu_{\mathrm{ijk}}, \mathrm{v}_{\mathrm{ijk}}, \pi_{\mathrm{ijk}}\right)$ be the SFN for an evaluation of alternative i concerning criterion j by expert k.

Step 2: Expert opinions are aggregated using the SWAM operator defined in Definition 7.

$$\begin{gathered} \mathrm{sWAM}_{\omega_{\mathrm{k}}}\left(\widetilde{\mathrm{X}}_{\mathrm{ijk}}, \ldots\ldots, \widetilde{\mathrm{X}}_{\mathrm{ijt}}\right) = \omega_1 \widetilde{\mathrm{X}}_{\mathrm{ij1}} + \omega_2 \widetilde{\mathrm{X}}_{\mathrm{ij2}} + \cdots\cdots + \omega_{\mathrm{t}} \widetilde{\mathrm{X}}_{\mathrm{ijt}} \\ \widetilde{\mathrm{R}}_{\mathrm{ij}} = \left(\mu_{\mathrm{ij}}, \mathrm{v}_{\mathrm{ij}}, \pi_{\mathrm{ij}}\right) = \left\{ \begin{array}{c} \left[1 - \prod_{\mathrm{k}=1}^{\mathrm{t}} \left(1 - \mu_{\widetilde{\mathrm{X}}_{\mathrm{ijk}}}^2\right)^{\omega_{\mathrm{k}}}\right]^{1/2}, \prod_{\mathrm{k}=1}^{\mathrm{t}} \mathrm{v}_{\widetilde{\mathrm{X}}_{\mathrm{ijk}}}^{\omega_{\mathrm{k}}}, \\ \left[\prod_{\mathrm{k}=1}^{\mathrm{t}} \left(1 - \mu_{\widetilde{\mathrm{X}}_{\mathrm{ijk}}}^2\right)^{\omega_{\mathrm{k}}} - \prod_{\mathrm{k}=1}^{\mathrm{t}} \left(1 - \mu_{\widetilde{\mathrm{X}}_{\mathrm{ijk}}}^2 - \pi_{\widetilde{\mathrm{X}}_{\mathrm{ijk}}}^2\right)^{\omega_{\mathrm{k}}}\right]^{1/2} \end{array} \right\} \end{gathered} \tag{14}$$

Step 3: A weighted decision matrix is constructed, taking into account the weights of the criteria.

Step 4: Using the criteria weights obtained through SF-SWARA, WSM $\left(\widetilde{\mathrm{Q}}^1\right)$ is computed for each alternative. It is worth noting that n denotes the number of criteria.

$$\widetilde{\mathrm{Q}}_{\mathrm{i}}^1 = \sum_{\mathrm{i}=1}^{\mathrm{n}} \widetilde{\mathrm{R}}_{\mathrm{ijw}} \tag{15}$$

$$\widetilde{\mathrm{R}}_{\mathrm{ijw}} = \widetilde{\mathrm{R}}_{\mathrm{ij}} \mathrm{w}_{\mathrm{j}} = \left(\sqrt{1 - \left(1 - \mu_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w}_{\mathrm{j}}}}, \mathrm{v}_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^{\mathrm{w}_{\mathrm{i}}}, \sqrt{\left(1 - \mu_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w}_{\mathrm{j}}} - \left(1 - \mu_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2 - \pi_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w}_{\mathrm{j}}}}\right) \tag{16}$$

Step 5: WPM $\left(\widetilde{\mathrm{Q}}^2\right)$ is computed, taking into account the criteria weights obtained through SF-SWARA, for each alternative.

$$\widetilde{\mathrm{Q}}_{\mathrm{i}}^2 = \prod_{\mathrm{j}=1}^{\mathrm{n}} \widetilde{\mathrm{R}}_{\mathrm{ij}}^{\mathrm{w_j}} \tag{17}$$

$$\widetilde{\mathrm{R}}_{\mathrm{ij}}^{\mathrm{w_j}} = \left(\mu_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^{\mathrm{w_j}}\sqrt{1-\left(1-\mathrm{v}_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w_j}}}, \sqrt{\left(1-\mathrm{v}_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w_j}}-\left(1-\mathrm{v}_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2-\pi_{\widetilde{\mathrm{R}}_{\mathrm{ij}}}^2\right)^{\mathrm{w_j}}}\right) \tag{18}$$

Step 6: The integration of WSM and WMP is carried out by incorporating the threshold value (λ).

$$\lambda\widetilde{\mathrm{Q}}_{\mathrm{i}}^1 = \left(\sqrt{1-\left(1-\mu_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^1}^2\right)^{\lambda}}, \mathrm{v}_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^1}^{\lambda}, \sqrt{\left(1-\mu_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^1}^2\right)^{\lambda}-\left(1-\mu_{\widetilde{\mathrm{Q}}_{i}^1}^2-\pi_{\widetilde{\mathrm{Q}}_{i}^1}^2\right)^{\lambda}}\right) \tag{19}$$

$$(1-\lambda)\widetilde{\mathrm{Q}}_{\mathrm{i}}^2 = \left(\sqrt{1-\left(1-\mu_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^2}^2\right)^{(1-\lambda)}}, \mathrm{v}_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^2}^{1-\lambda}, \sqrt{\left(1-\mu_{\widetilde{\mathrm{Q}}_{i}^2}^2\right)^{(1-\lambda)}-\left(1-\mu_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^2}^2-\pi_{\widetilde{\mathrm{Q}}_{\mathrm{i}}^2}^2\right)^{(1-\lambda)}}\right) \tag{20}$$

Step 7: The relative weight is determined for each alternative.

$$\widetilde{\mathrm{Q}}_{\mathrm{i}} = \lambda\widetilde{\mathrm{Q}}_{\mathrm{i}}^1 + (1-\lambda)\widetilde{\mathrm{Q}}_{\mathrm{i}}^2 \tag{21}$$

Step 8: The final scores are determined by de-fuzzifying the SFNs using the score function specified in Definition 6 [91].

Step 9: Alternatives are arranged in descending order based on their final scores, with the highest score indicating the best alternative.

4 Application

The study aimed to identify strategies (criteria) for enhancing the adoption of I.40, based on expert opinions and a literature review. These criteria included international collaboration and partnerships (C1), international and regional cooperation (C2), education and training (C3), open innovation initiative (C4), research, development, and innovation (C5), public-private partnership (PPP) and policy innovation (C6), and a focus on small and medium enterprises (C7). In this context, the alternatives under consideration were Kenya (A1) and Rwanda (A2). Rwanda was distinguished as one of three African nations (alongside South Africa and Morocco) that had taken steps toward developing I.40 strategies and technology centers, in addition to having ICT policies [92]. In the digital realm, Kenya had been labeled "Africa's Silicon Savannah" due to its robust, targeted ICT policy aligned with its Vision 2030 plan [93]. To evaluate the factors promoting I4.0 implementation, a team of three experts (referred to as "Es") was established. The Es group was responsible for assessing I4.0 adoption and included specialists in various fields such as the Internet of Things (IoTs), Big Data, Artificial Intelligence (AI), and Blockchain technologies. Specifically, two of the experts had backgrounds in Big Data and AI, while the third was knowledgeable in blockchain technology and IoTs.

4.1 Application of SF-SWARA for Weighting Strategies

A questionnaire was employed to collect data from the expert teams on the importance of each criterion. The weight assigned to each criterion by the expert panel, following the SF-SWARA method, is presented in Table 2 as linguistic indicators.

After collecting the opinions of the experts, the integration process was conducted using SWAM operators, as indicated in Table 3, while considering the experts' weights. The determination of expert weights took into account their reputations, which were evaluated based on factors such as years of work, experience, and expertise in the subject. During the interviews with the experts, their weights were determined accordingly, resulting in E1 having a weight of 0.35, E2 with a weight of 0.30, and E3 carrying a weight of 0.35.

Following Eq. (7), the score value was calculated, and the weight of the criteria was determined using the SF-SWARA method, as presented in Table 4.

The final weights of each challenge were determined by normalizing the recalculated weights (q_j) using Eq. (13). According to the findings depicted in Figure 1, experts acknowledged that education and training was the most appropriate strategy. Following education and training, the second to seventh positions were occupied by research, development, and innovation; public-private partnership and policy innovation; international and regional cooperation; international collaboration and partnerships; open innovation initiative; and small and medium enterprises focus, respectively. The normalized weight assigned to criterion C3, which pertained to education and training, was 0.410. Conversely, criterion C7, which focused on small and medium enterprises, received the least consideration from experts with a normalized weight of 0.004. In Figure 1, education and training were significantly emphasized by the experts. The findings of this study were in line with previous research conducted by Spoettl and Tūtlys [94], which highlighted the importance of vocational education and training in response to the challenges posed by I4.0. The study emphasized the need for vocational systems to cater to new technological demands while aligning with the workforce's needs and expectations.

Table 2. Importance of criteria weights

Criteria	E1	E2	E3
C1	H	H	H
C2	VH	H	MH
C3	EH	EH	EH
C4	VH	MH	MH
C5	EH	VH	EH
C6	H	VH	H
C7	MH	M	M

Table 3. Weights of criteria according to SWAM operator

Criteria	Criterion weight		
	μ	v	π
C1	0.700	0.300	0.640
C2	0.719	0.284	0.623
C3	0.900	0.100	0.409
C4	0.690	0.314	0.642
C5	0.873	0.127	0.443
C6	0.741	0.260	0.614
C7	0.539	0.462	0.753

Table 4. Results of SF-SWARA

Criteria	Score value	s_j	k_j	q_j
C3	1.839		1	1
C5	1.600	0.239	1.239	0.807
C6	0.628	0.972	2.211	0.365
C2	0.549	0.079	2.290	0.159
C1	0.463	0.086	2.376	0.067
C4	0.439	0.024	2.400	0.028
C7	0.022	0.417	2.817	0.010

According to the information presented in Figure 1, research, development, and innovation were identified as the second most significant strategy, following education and training. These findings were consistent with research conducted by Schneider et al. [95], which highlighted that research efforts in the context of I4.0 had expanded beyond the development of innovative technologies to include the creation of methodological tools. Additionally, Dikhanbayeva et al. [96] found that the outcomes of research in this field were valuable for policymakers, scientists, and other stakeholders, as they could be utilized to formulate forecasts, strategic plans, and further investigations about the implementation of I4.0.

The public-private partnership and policy innovation, which ranked third in importance, served as notable strategies for I4.0 adoption within a country [97]. While the ICT policy had its limitations, it was becoming increasingly insufficient in the face of the I4.0 revolution. Consequently, the EAC should consider incorporating an I4.0 strategy alongside the existing ICT policy to maintain competitiveness. This necessitated a re-evaluation of leadership infrastructure by governments. To successfully embrace I4.0, it was crucial to implement structural transformations through the development of national policies similar to the ICT policy established by EAC member countries [21]. In this context, the effective adoption of I4.0 depended on the commitment of governments, businesses, and citizens through public-private partnerships to support societal transformation into a modern and technologically advanced society driven by innovation, advanced skills, responsive policies, and cutting-edge technology.

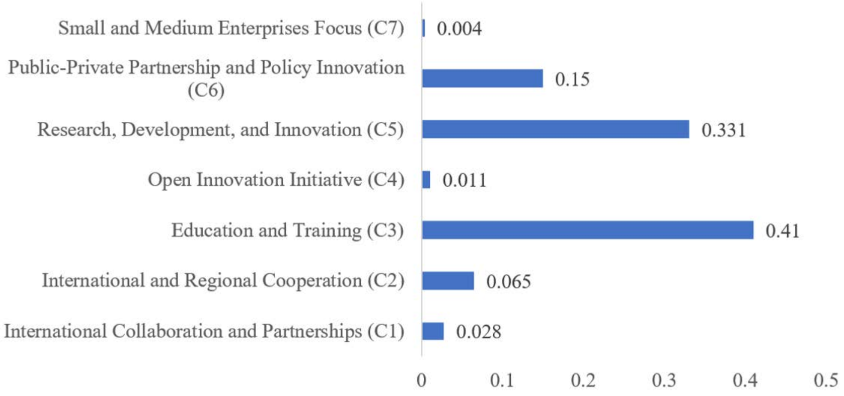

Figure 1. Weights of strategies for the sustainable adoption of Industry 4.0 in the East Africa community

4.2 Application of SF-WASPAS for Ranking Countries

Subsequent to the determination of strategy importance, a panel of experts, with appropriate qualifications, was employed to establish the initial decision grid using linguistic variables. This aimed at evaluating which country had adopted I4.0 technology to a greater extent, based on the identified strategies, via the SF-WASPAS approach (Table 5).

Table 5. Decision grid for the strategy evaluation

	Criteria	E-1	E-2	E-3
A1	C1	H	VH	VH
	C2	MH	MH	M
	C3	VH	H	VH
	C4	L	ML	L
	C5	VL	EL	MI
	C6	H	MH	H
	C7	M	H	MH
A2	C1	H	H	H
	C2	M	H	H
	C3	EH	H	VH
	C4	VL	VL	L
	C5	M	ML	MI
	C6	VH	VH	VH
	C7	M	M	M

Initially, the linguistic variables were converted into spherical fuzzy numbers by utilizing the scale presented in Table 1. Then, the SWAM operator was employed for aggregating expert opinions and determining expert weights. This procedure resulted in the formation of a spherical fuzzy decision matrix, as depicted in Table 6.

Following the acquisition of weights for each strategy, these values were employed to rank the countries. The execution of SF-WASPAS steps led to the calculation of the Weighted Sum Model (WSM) and Weighted Product Model (WPM) for each country, based on strategy weights (Table 7).

A threshold value (λ) of 0.5 was established to integrate the WSM and WPM models. Subsequently, the spherical fuzzy outcomes derived from the SF-WASPAS method were defuzzified. The results, obtained from the integrated SF-SWARA-WASPAS methodology, were presented as final scores, with countries ranked accordingly (Table 8).

As indicated in Table 8, Rwanda (alternative A2) emerged as the country that had predominantly embraced strategies aimed at enhancing the adoption of I4.0 technology, with a final score of 3.703. On the other hand, Kenya was identified as the country exhibiting the lowest level of technology adoption.

Table 6. Spherical fuzzy decision grid

	Criteria	μ	v	π
A1	C1	0.770	0.230	0.136
	C2	0.569	0.432	0.336
	C3	0.775	0.226	0.131
	C4	0.334	0.668	0.237
	C5	0.274	0.749	0.198
	C6	0.674	0.327	0.231
	C7	0.607	0.397	0.307
A2	C1	0.700	0.300	0.200
	C2	0.645	0.359	0.273
	C3	0.825	0.177	0.104
	C4	0.240	0.763	0.145
	C5	0.439	0.563	0.343
	C6	0.800	0.200	0.100
	C7	0.500	0.500	0.400

Table 7. The WSM and WPM models

	WSM			**WPM**		
	μ	v	π	μ	v	π
A1	0.933	1.000	0.081	0.496	0.571	0.197
A2	0.950	0.000	0.041	0.499	0.567	0.182

Table 8. The classification of alternatives

Ranking	**Country**	**Final score**
2	A1	1.560
1	A2	3.703

5 Sensitivity Analysis

To ascertain the accuracy of the proposed method, a sensitivity analysis was conducted. This analysis entailed systematically adjusting the threshold value in increments of 0.25, ranging from 0 to 1. Subsequently, the recalculated final scores for countries were determined using the updated threshold values, as presented in Table 9.

Table 9. The final scores for different threshold values

	Threshold value				
	0	0.25	0.5	0.75	1
A1	1.560	1.527	1.085	0.583	4.40E-05
A2	3.702	3.991	4	4	4

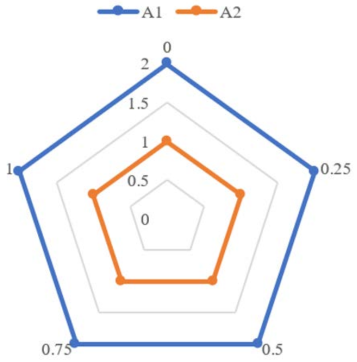

Figure 2. The final rankings of countries

The sensitivity analysis results indicate that altering the threshold value impacts the final scores as expected, due to the influence of WSM and WPM. However, the final ranking of countries remained consistent despite changes in threshold values. The ranking of alternatives is illustrated in Figure 2.

6 Conclusions

This study presents an approach for enhancing Industry 4.0 adoption in a spherical fuzzy environment by integrating the Weighted Aggregated Sum Product Assessment and Step-Wise Weight Assessment Ratio Analysis methods. Through a case study involving two East African Community countries, the practical effectiveness of the proposed model was demonstrated. The findings revealed that the most influential strategies for substantially improving Industry 4.0 adoption within the East African community include education and training, research and development, innovation, public-private partnerships, and policy innovation. Furthermore, the results identified Rwanda as the leading country, in comparison to Kenya, regarding the successful implementation of these strategies to promote Industry 4.0 technology adoption.

The study offers two primary contributions that can be regarded from distinct perspectives. First, it provides a framework aimed at enhancing Industry 4.0 adoption within the East African Community, outlining suitable strategies for logical and systematic implementation, thereby representing a professional contribution. Second, the study introduces a scientific contribution by applying integrated SWARA and WASPAS methods within a spherical fuzzy environment to support Industry 4.0 adoption in this specific African region. This approach is innovative and has not been explored in existing literature.

Despite the study's significant contributions, it is essential to acknowledge its limitations. First, the proposed methodology was not compared to other fuzzy-based multicriteria procedures specifically addressing this issue, presenting an opportunity for future research to conduct comparative analyses. Second, as the data collection focused solely on the East African Community, the applicability of findings to other regional economic communities within the African Union may be limited due to their unique conditions and environments. Consequently, it is crucial to replicate the research framework used in this study across other regional economic communities and perform a comparative analysis of the outcomes. Finally, it is important to note that the data collection process involved a limited number of experts. Future research should aim to include a larger and more diverse pool of experts and establish clear criteria for their selection, ensuring comprehensive and reliable analysis.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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