Journal of Innovation & Knowledge 8 (2023) 100430

Journal of Innovation & Knowledge

https://www.journals.elsevier.com/journal-of-innovation-and-knowledge

Challenges of the collaborative innovation system in public higher education in the era of industry 4.0 using an integrated framework

Xiaohua Li[1], Weibing Chen[2,*], Melfi Alrasheedi[3]

[1] College of Marxism, Jilin Institute of Chemical Technology, Jilin 132000, China
[2] School of Chinese Language and Literature, Guizhou University of Finance and Economics, Guiyang, Guizhou 550025, China
[3] Department of Quantitative Methods, School of Business, King Faisal University, Saudi Arabia

A R T I C L E I N F O

Article History:
Received 14 October 2022
Accepted 21 August 2023
Available online 7 September 2023

Keywords:
Collaborative innovation system
industry 4.0
public higher education
innovation
decision making

JEL code:
O3
O31
O36
L8
I23
C44

A B S T R A C T

Collaborative innovation systems comprise certain functions created by integrating a number of interconnected items in a certain order. These systems essentially create a connection between different elements for the achievement of a certain goal. To properly develop or transform a system, the relationships among the elements of the system must be well understood. Numerous structural models have been designed to be applied to collaborative innovation systems in higher education. Thus, the current paper deals with this gap by comprehensively analyzing the challenges that may arise for collaborative innovation systems in public higher education (PHE) in the era of industry 4.0, specifically in the context of developing countries. This study developed an integrated framework to identify and evaluate the main challenges of the collaborative innovation system in public higher education. This framework is applied to determine the subjective and objective weights of the main challenges of the collaborative innovation system in PHE in the era of industry 4.0. In addition, the framework is used to assess the preferences of PHE organizations over different main challenges of the collaborative innovation system in the era of industry 4.0. Finally, an empirical case study is taken to evaluate the main challenges of the collaborative innovation system in PHE in the era of industry 4.0. The results of this study found that; the holistic acceptance of the innovation with a weight value of 0.0614 has come out to be the most important challenge of the collaborative innovation system in PHE; in addition, the lack of technical infrastructure with a weight value of 0.0594 is the second most important challenge of the collaborative innovation system in the PHE, and educational policy has third with significance value 0.0588.

Introduction

To pursue innovation, many stakeholders need to collaborate (Papa et al. 2020), which include private companies, public organizations (e.g., higher education), and nonprofit organizations (also known as the third sector); (Miller 2016; Walsh et al. 2016; Demircioglu and Audretsch 2019; Adomako and Tran 2022; Li et al. 2022). Such cross-sectoral collaboration has become increasingly vital in recent decades in both norm and practice because it is needed to address magnificent challenges in modern life (Waardenburg et al. 2020; Blanken et al. 2022). Moreover, a great deal of existing evidence confirms that higher degrees of innovation are achievable through cross-sectoral collaborations (Torfing and Triantafillou 2016). As a result, a major innovation strategy for innovation is cross-sectoral collaboration (Hartley et al. 2013; Adel et al. 2021; Wang et al. 2022), and companies show great enthusiasm for promoting more collaborative activities with more and more partners.

A number of scholars have attempted to show some contingencies that could be well addressed only through collaboration, and this way, they have attempted to unveil the gaps that exist in this regard (Wong et al. 2021; Hetemi et al. 2022). For example, Galbraith (1974) investigated how private companies could select a certain governance form by considering the factors related to the innovation problem. Hartley et al. (2013) made a comparison among the innovation strategies implemented in companies of the public sector. They also showed the conditions causing collaborative innovation to be superior to "in-house" innovation. In another study, O'Toole Jr (1997) highlighted the significance of determining and assessing the interagency collaboration cost since collaboration can burden governments with substantial costs. In the same way, Fallis (2006) examined various approaches taken by different scholars in different

* Corresponding author.
E-mail address: chenweibing985@163.com (W. Chen).

https://doi.org/10.1016/j.jik.2023.100430

fields for the analysis of collaboration and also attempted to understand the reason for such differences. The findings of that study determined the academic research characteristics that could result in successful collaboration.

Public organizations tend to adopt innovation and collaboration as two key strategies for improving common crises management (Elston et al. 2018; Nohrstedt et al. 2018; Lopes and Farias 2020; Wong et al. 2021) and optimizing existing resources (Diamond and Vangen 2017; Lewis et al. 2017) and responding to both social and technological developments (Seo et al. 2018). On the other hand, integrating both into one concept as 'collaborative innovation' could be more advantageous than other innovation strategies. This is because collaboration has at least two capacities: benefitting all steps along the innovation path and making the stage ready for sharing benefits, risks, and costs (Torfing 2019). Numerous scholars have argued that the management, leadership, and governance models used by public organizations management arise many complications and challenges in the course of adopting innovative practices (Andersen and Jakobsen 2018; Boon and Verhoest 2018). In addition, a number of scholars in this field have concentrated on collaborative innovation in the public sector from the perspective of the organizations' internal dynamics (Bernier et al. 2015; Mu and Wang 2022). They have highlighted the drawbacks enforced by conventional bureaucratic practices and also attempted to suggest some solutions to such problems (Wegrich 2019). The research conducted on this form of innovation has covered the concept inherent to the innovation process itself, as well as the interconnections amongst public companies and between the public sector and society (Bekkers and Tummers 2018).

A number of studies have also been conducted on the influence of educational institutions and knowledge on innovation systems and processes (Etzkowitz and Leydesdorff, 2000; Morawska-Jancelewicz, 2022). Overall, to achieve a deep insight into collaborative innovation and its influence, it is necessary to investigate all sectors, and the way collaboration develops amongst them is crucial. The 'collaborative education' concept was pioneered by an American scholar called Grow, who believed that collaborative innovation could be developed by a group of people or organizations with the same goals. They normally employ exchange tools for the purpose of exchanging their ideas in a way to finally achieve common goals. To develop the collaborative education concept, Chinese academics have attempted to redefine this concept based on the basic national conditions of their own country (Klara et al., 2013). They believed that such innovation is primarily based on multiple organizations and directed by the common goals and paths for the obtainment of a mutually-complementary complementary and innovation model at both ideological and technical levels. To construct faculty in higher colleges, collaborative innovation principally takes scientific research institutions, vocational colleges, enterprises, and society as the main body, where faculty construction is taken into account as the common goal. The innovation model is constructed, and the faculty is optimized by sharing the available technologies and resources. As a result, the most important characteristics of collaborative innovation in the context of higher education are interaction, diversity, and integrity.

Industry 4.0 is in its infancy stage and is immature in most sectors; however, it is gaining increasing attention from scholars, practitioners, and policymakers across various sectors (Kanski and Pizon 2023). Industry 4.0 is widely recognized as a synthesis of numerous technologies (Forum 2018). Since the 1980s, robots have been applied to education, especially in teaching different subjects of science, mathematics, engineering, and technology (Tymon 2013). Nevertheless, the implementation of digital technologies that underpin Industry 4.0 cannot be limited to the utilization of computers and e-materials; rather, this needs to be well adapted to the learner-oriented approaches of teaching so that it could effectively improve their learning experiences. With such an exponential rate at which Industry 4.0 is currently dispersing across all sectors, it will affect tremendously not only the economy but also people's social and private lives with the ways they commune with each other. For example, some technology innovations and smart devices, which are particularly applied to social media, could considerably decrease individuals' face-to-face interactions (Saini and Abraham 2019) and negatively influence the attainment of related soft skills, e.g., emotional intelligence, interpersonal skills, and communication, particularly amongst the younger population.

The research on the private sector (Terjesen and Patel 2015; Audretsch and Belitski 2020; Evan and Holý 2021; Jiemin and Chen 2022) is primarily concentrated on industrial, commercial, and scientific innovations, wherein the key objective is the creation of value through increased profits or market share. On the other hand, the research on the public and third sectors is focused on social and public innovation with the aim of creating social and public value (Torfing and Triantafillou 2016). The current study addresses such limitations by taking a sector-neutral perspective on innovation to analyze cross-sectoral collaborations. Note that the majority of studies carried out in this domain have attempted to determine the conditions favoring collaboration, and the literature still lacks systematic analyses on the challenges that may arise in the collaborative innovation systems in public higher education (PHE) in the era of Industry 4.0.

In order to identify, evaluate, and analyze the main challenges for collaborative innovation systems in the era of industry 4.0, we selected for empirical study for public higher education in China. This study adopts rigorous and approved management methods to collect empirical data. First, we have conducted a survey approach using current literature on innovation systems as well as an interview with experts. Second, we have done a comprehensive literature survey to identify the main challenges for collaborative innovation systems in the era of industry 4.0 for higher education. In this regard, we have identified 37 challenges to evaluating collaborative innovation systems in the era of industry 4.0. Thus, in this study, we have developed a framework for the assessment of the main challenges of the collaborative innovation system in PHE in the era of industry 4.0. The main contributions of this study are presented as

- ☐ Based on a comprehensive survey and online questionnaire, we classify the key challenges of the collaborative innovation system in PHE in the era of industry 4.0.
- ☐ We evaluate and analyze the related challenges of the collaborative innovation system in PHE in the era of industry 4.0 using an integrated decision-support approach.
- ☐ We develop a new framework to obtain the weight value of the main challenges of the collaborative innovation system in PHE.
- ☐ The developed framework is used for the ranking of PHE organizations to assess the main challenges of the collaborative innovation system in PHE.

The remaining paper is prepared as follows. A literature review on the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 is given in Section 2. In Section 3, the preliminaries and the developed IF-Entropy-SWARA-MARCOS method are discussed. Section 4 gives experimental findings and comparative and sensitivity analysis results. Section 5 concludes the study.

Background of study for collaborative innovation

Innovation refers to developing and implementing novel ideas that habitual upset practices and the common wisdom dominating the solution context (Hartley et al. 2013). Thus, innovation is something beyond the constant enhancement of current practices and ideational mindsets (Hartley 2013). It essentially causes the transformation of the way things are normally imagined and performed. In general, the quest for innovation is supported by the idea that innovative solutions perform better than the old ones and result in desired endings, though innovation, in many cases, fails to realize its promises, and even it can lead to unpredicted adverse outcomes. For that reason, innovation cannot be introduced as an undoubted 'normative good' (Osborne and Brown 2011). Despite the fact over one century, scholars have introduced innovation as the most important factor. Two factors have been assumed to cause overwhelming barriers to innovation in the higher education sector; those are the "*lack of competition and economic incentives*" and the "*predominance of hierarchical control and red tape*" (Mazzucato 2011). The prevalent idea that the higher education sector possesses higher degrees of dynamicity and innovation compared to its reputation and that professional and political goals could be realized more effectively through the stimulation of innovation has caused practitioners and scholars to pay a growing attention to innovation in higher education. Innovation is expanding towards the top agenda of the higher education sector since it provides an intellectual, economical alternative to visionless, across the-board cuts in times of calamitous economic restraints.

Collaboration is described as "the process through which two or more actors engage in a constructive management of differences in order to define common problems and develop joint solutions based on provisional agreements that may coexist with disagreement and dissent" (Hartley 2013). It is different from coordination, which is the "orderly arrangement of the group effort to provide unity of action in the pursuit of a common purpose" (Mooney 1954), and from cooperation, which is the "joint pursuit of an agreed-on goal(s) in a manner corresponding to a shared understanding about contributions and payoffs" (Gulati et al. 2012). Collaboration can be seen as merging cooperation with coordination (Gulati et al. 2012). In general, an organization gets involved in collaboration with other organizations in order to attain more resources and, at the same time, achieve its own objectives and interests (Tseng et al. 2020; Dias and Selan 2022). Such collaboration with common interests causes the involved organizations to become more innovative since, through this procedure, they will be able to learn from each other (Martínez-Costa et al. 2019; Demircioglu and Audretsch 2020; Tseng et al. 2020). As a result, collaboration has a close relation with innovation, especially in cases where the organizations hold common interests, goals, and values (van der Voet and Steijn 2021).

The term 'collaborative innovation' was first introduced by researchers who integrated the findings of some recent studies into collaborative governance (Emerson et al. 2011); (Hartley et al. 2013). Furthermore, collaborative innovation may occur across sectors in various forms, contexts, and partnerships. For example, it may occur in the Triple Helix model (university-industry-government), postulating the dynamism through continuous reorganization of the innovation collaboration because of the technological and cultural evolution (Audretsch and Belitski 2022), or in the Quadruple Helix model adding culture-based and media-based public relations to this dynamism (Miller et al. 2018). From a traditional perspective, collaborative innovation has progressed within the private sector as the "creation of innovations across firm (and perhaps industry) boundaries through the sharing of ideas, knowledge, expertise, and opportunities" (Ketchen Jr et al. 2007). Then, it has been effectively extended to other sectors. To realize collaborative innovation, innovation and production of new knowledge must be encouraged along with collaboration and communication between organizations with high degrees of dynamicity and effectiveness. In other words, it is necessary to explore novel methods to develop expertise and innovation in the current knowledge processes by providing the opportunity for more and better cooperation among the private, public, and education sectors (particularly higher education) (Lamprini and Brochler 2018). This response to this necessity should be integrated and comprehensive, and it must involve all stakeholders, from the private and public sectors to academia and civil society.

Private and public actors mainly unfold collaborative innovation. However, it tends to engage a diverse group of private and public actors when there is a need to solve a problem creatively. Through the process of exchanging varied ideas, experiences, and opinions, conventional practices and their cognitive and normative foundations may be disturbed. This triggers transformative learning processes and, at the same time, builds joint ownership over novel and conventional solutions. Such a formula could not be easily beaten in comparison with competitive and hierarchical innovation strategies that cannot take advantage of the creative potential that arises from continuous negotiation with exterior actors (Powell and Grodal 2005).

Moreover, collaborative innovation could be well benefitted from hierarchical leadership authorizing members of various companies to work together; collaborative innovation can give them a 'license to innovate' (Crosby and Bryson 2010). Findings of many qualitative case studies have confirmed that multi-actor collaboration can positively influence public innovation (Torfing and Ansell 2014). Roberts and King (1996) demonstrated the way multi-actor collaboration strengthens innovation in public schools. According to Newman et al. (2001), local governments that hold feeble interagency and stakeholder networks typically offer extremely-confined innovation patterns. Dente et al. (2005) compared the cutting-edge urban planning of Turin, Italy, with the less inventive development in Milan, considering the advanced density and diversity of collaborative networks in the former. Steelman (2010) explained how a diversified group, including both political and social actors, was able to foster an innovative plan to protect land in an extremely-politicized setting. In another study, Hale (2011) analyzed the way horizontal and vertical collaborations between state offices, professional associations, and local administrations allow for establishing and diffusing drug courts offering a novel alternative to incarceration.

The articles on organizational innovation were subjected to some meta-analyses whose results showed that if the involved actors, the dispersion of power, and the nature of external and internal communication are well diversified, it can positively influence the private and public firms' capacity for innovation (Damanpour 1991). In an attempt to collect more irrefutable facts regarding the influence of collaboration on public innovation and its capacity for generating desired outcomes, a study produced a criteria-based evaluation tool capable of measuring the degree of innovation, collaboration, and preventive crime impacts in a total of 24 local projects carried out in Copenhagen, Denmark (Torfing et al. 2017). The results were exposed to multiple regression analysis, which showed that if various private and public actors collaborate with each other, it spreads innovation, which could ultimately cause the enhancement of the crime-preventive impacts of local projects. Collaboration is in fact the only innovation strategy wherein the existence of organizational and institutional boundaries does not determine the parties that can be engaged in generating innovative solutions; rather, the important factor in this sense isto hold several relevant innovation assets such as creativity, experience, implementation capacity, financial means, and courage (Bommert 2010). One of the problems is that the public sector has been grouped bureaucratically, each of which has concentrated on definite policy programs and public services they are expected to deliver as well as the budget frames and the number of employees at their disposal (Downs 1967).

As asserted by the World Economy Forum (Forum 2020), the technology revolution induced by Industry 4.0 has blurred the borders among the digital, physical, and biological scopes. With the complete maturity of innovation, especially in the education sector, it can improve individuals' skills through data analytics, artificial intelligence, and algorithms and helps decrease struggles on complicated, time-consuming assignments through modeling and simulation. The former three industrial revolutions mainly affected society and its economy; on the other hand, Industry 4.0 shows more relevancy to people's daily lives, which includes the way people learn and work

(Brown 2015). Furthermore, the former industrial revolutions resulted in the mass production of education services by preparing the stage ready for innovative curricular developments and online teaching by establishing countless academic institutions across the globe (Chang and Wills 2013).

In the 21st century, the knowledge economy developed in societies, which caused higher education to face many demands for the improvement of collaborations to boost this sector's capacities for the establishment and distribution of knowledge and also to maximize impact upon practice (Katz and Martin 1997). Accordingly, higher education institutions (HEIs) needed to establish networks with stakeholders and other HEIs as well as inside their own institutions (Jongbloed et al. 2008). The establishment of such collaboration and networking practices in this sector contributed to both the knowledge & research theme and the institutional management theme of research in higher education (Tight 2014). The literature consists of evidence indicating the benefits of collaboration in higher education (Lewis et al. 2012); however, it still lacks research into how higher education management can enable and improve collaboration. According to (Kezar 2005), higher education managers require to shift from supporting individual work to smoothing collaboration. She also asserted that the literature comprises "virtually no research on how to enable higher education institutions to conduct collaborative work" (p. 831). In more recent years, (Cooke and Hilton 2015) carried out a consensus study into research collaboration and reported the shortage of literature on how to improve research collaborations in higher education. Their study had to rely greatly upon the inferences extracted from the literature on group dynamics in other circumstances. To address an important gap in the higher education literature, the current study attempts to find out the way higher education managers can improve collaborative work, predominantly research collaboration, in an institution. Collaboration among scholars inside an institution improves the institution's research capacity at an interpersonal level (Huang 2014). This capacity, for instance, in the context of innovation and collaboration amongst enterprises, has been shown to enhance an enterprise's capability to prosper in external collaborations (Bougrain and Haudeville 2002). According to Tight (2014), the import of theories from different disciplines to apply to higher education research is a significant approach that can improve higher education as a rising field of research.

Therefore, in this study, to identify the main challenges including *C_1: Negative attitudes, C_2: Adopt the innovation mindset, C_3: Lack of addressable communities, C_4: Adopt the pedagogical mindset, C_5: Lack of technical infrastructure, C_6: Lack of e-learning tools, C_7: Bureaucracy, C_8: Competence of the teachers, C_9: Motivation in using ICT, C_{10}: Lack of skills, C_{11}: Cultural differences, C_{12}: Resistance to change, C_{13}: Lack of leading and support strategies, C_{14}: Educational policy, C_{15}: Holistic acceptance of the innovation, C_{16}: Lack of technical support, C_{17}: Lack of learning resources, C_{18}: Complex technologies, C_{19}: Lack of time to use the technology in classrooms* and *C_{20}: Language barriers* to the collaborative innovation system in public higher education in the era of industry 4.0, a survey approach is conducted using the literature review and interview with experts.

Proposed Intuitionistic Fuzzy-based MADA method

Preliminaries

Here, we present some concepts about the IFSs.

Definition 1. (Atanassov (1986)). An IFS S on $T = \{t_1,\ t_2,\ \ldots,\ t_n\}$ is defined as

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

where $\mu_S : Z \to [0,\ 1]$ and $\nu_S : Z \to [0,\ 1]$ show the *MF* and *NF* of t_i to S in T, with the condition $0 \le \mu_S(t_i) + \nu_S(t_i) \le 1,\ \forall\ \ t_i \in T$. An "indeterminacy function (IF)" of an object $t_i \in T$ to S is defined as $\pi_S(t_i) = 1 - \mu_S(t_i) - \nu_S(t_i)$ and $0 \le \pi_S(t_i) \le 1,\ \ \forall\ t_i \in T$. Also, Xu (2007) considered the "intuitionistic fuzzy number (IFN)" $\zeta = (\mu_\zeta,\ \nu_\zeta)$ with the constraint $\mu_\zeta, \nu_\zeta \in [0, 1]$ and $0 \le \mu_\zeta + \nu_\zeta \le 1$.

Definition 2. (Xu, 2015). Consider $\zeta_j = (\mu_j,\ \nu_j), j = 1(1)n$, be the IFNs. Then

$$\mathbb{S}\left(\zeta_j\right) = \frac{1}{2}\left(\left(\mu_j - \nu_j\right) + 1\right),\ H\left(\zeta_j\right) = \left(\mu_j + \nu_j\right), \tag{2}$$

are called the score and accuracy values, respectively.

Assume that $\zeta_1 = (\mu_1,\ \nu_1)$ and $\zeta_2 = (\mu_2,\ \nu_2)$ are two IFNs. Then, the ordering scheme is given by

If $\mathbb{S}(\zeta_1) > \mathbb{S}(\zeta_2)$, then ζ_1\succ$\zeta_2$,
If $\mathbb{S}(\zeta_1) = \mathbb{S}(\zeta_2)$, then
if $H(\zeta_1) > H(\zeta_2)$, then ζ_1\succ$\zeta_2$,
if $H(\zeta_1) = H(\zeta_2)$, then $\zeta_1 = \zeta_2$.

Definition 3. (Xu (2007)). Let $\zeta_j = (\mu_j,\ \nu_j), j = 1(1)n$ be the IFNs. Then the "intuitionistic fuzzy weighted averaging (IFWA)" and "intuitionistic fuzzy weighted geometric (IFWG)" operators are defined as

$$IFWA_w(\zeta_1, \zeta_2, \ldots, \zeta_n) = \mathop{\oplus}_{j=1}^{n} w_j\zeta_j = \left[1 - \prod_{j=1}^{n}\left(1 - \mu_j\right)^{w_j},\ \prod_{j=1}^{n}\nu_j^{w_j}\right], \tag{3}$$

$$IFWG_w(\zeta_1, \zeta_2, \ldots, \zeta_n) = \mathop{\otimes}_{j=1}^{n} w_j\zeta_j = \left[\prod_{j=1}^{n}\mu_j^{w_j},\ 1 - \prod_{j=1}^{n}(1 - \nu_j)^{w_j}\right], \tag{4}$$

where $w_j = (w_1, w_2, \ldots, w_n)^T$ is a weight vector of $\zeta_j,\ \ j = 1, 2, \ldots, n$, with $\sum_{j=1}^{n} w_j = 1$ and $w_j \in [0,\ 1]$.

Introduced IF-Entropy-SWARA-MARCOS approach

This section proposes an extended MADA methodology called the IF-Entropy-SWARA-MARCOS. The MARCOS framework considers the advantages of diverse "reference points (RPs)" and "utility degrees (UDs)" in a suitable manner. The "combined utility function (CUF)" of the MARCOS approach widely considers the utility values and the reference points, and thus, the final ranking result has high reliability. The process of the IF-Entropy-SWARA-MARCOS approach is discussed as follows (Flowchart 1):

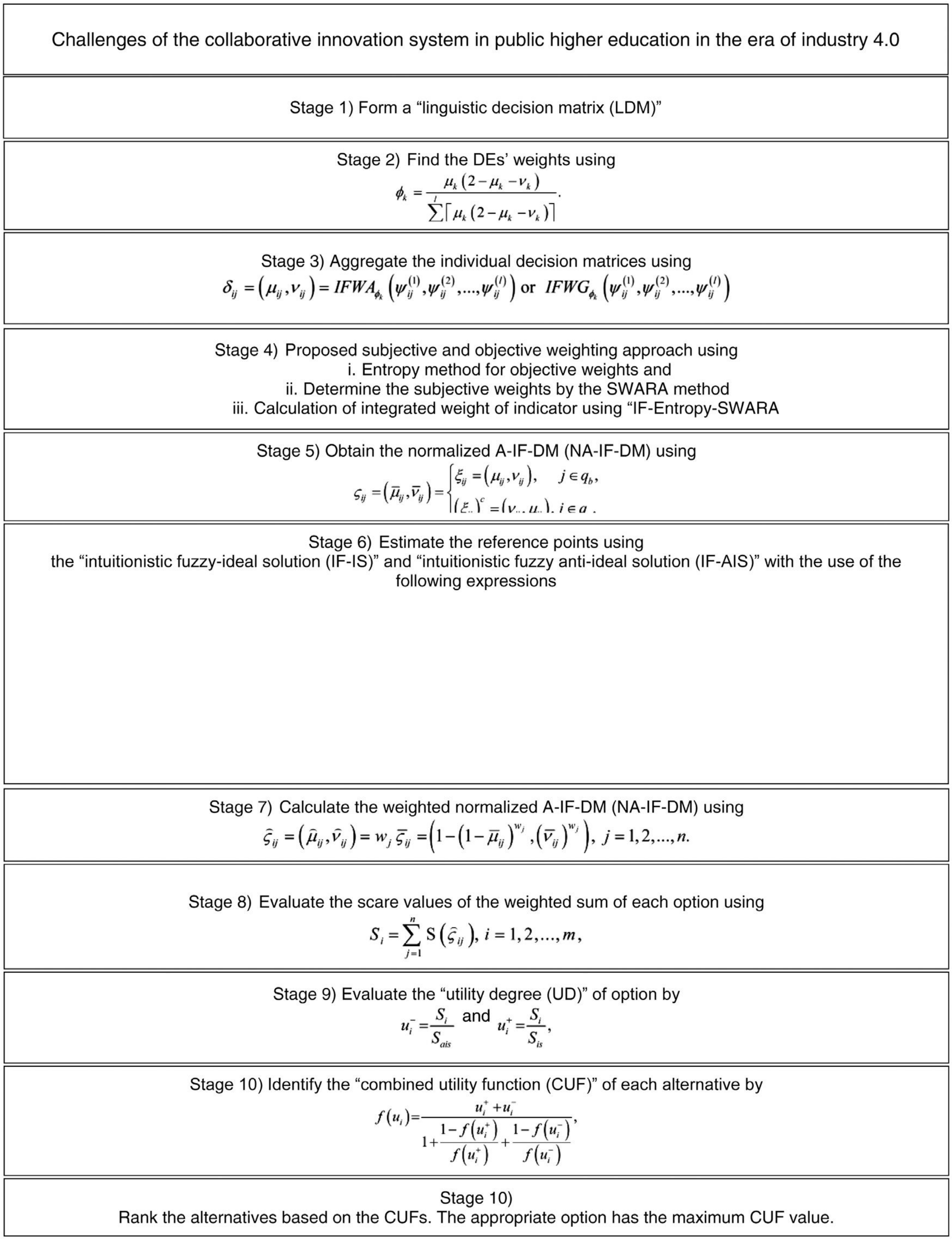
Step 1: Form a "linguistic decision matrix (LDM)".

In the MCDM procedure, consider a set of m options $P = \{p_1, p_2, \ldots, p_m\}$ over a criterion set $Q = \{q_1,\ q_2, \ldots, q_n\}$. Form a committee of experts $D = \{d_1, d_2, \ldots, d_l\}$ to find the best choice(s). Let $T = (\psi_{ij}^{(k)})_{m\times n}$ be the "linguistic decision matrix (LDM)" expressed by "decision experts (DEs)", where $\psi_{ij}^{(k)}$ denotes the linguistic assessment value of p_i by means of the criterion q_j offered by k^{th} DE. Based on the linguistic rating table, the LDM is converted into IF-DM.

Step 2: Find the DEs' weights.

To find the weight of the DE, firstly, the assessment rating of DEs is taken as "linguistic variables (LVs)" and then articulated by IFNs. If $d_k = (\mu_k,\ \nu_k)$ be the assessment rating of k^{th} DE, then the weight-determining formula is given as

$$\phi_k = \frac{\mu_k(2 - \mu_k - \nu_k)}{\sum_{k=1}^{l}[\mu_k(2 - \mu_k - \nu_k)]}. \tag{5}$$



Flowchart 1. Challenges of the collaborative innovation system in public higher education in the era of Industry 4.0

Clearly, $\phi_k \geq 0$ and $\sum_{k=1}^{l} \phi_k = 1$.

Step 3: Aggregate the individual decision matrices.

To aggregate the individual decision matrices into a combined form, the IFWA (or IFWG) operator is used and formed the aggregated matrix $Z = (\delta_{ij})_{m\times} n$,where

$$\delta_{ij} = (\mu_{ij}, \nu_{ij}) = IFWA_{\phi_k}\left(\psi_{ij}^{(1)}, \psi_{ij}^{(2)}, ..., \psi_{ij}^{(l)}\right) \text{ or } IFWG_{\phi_k}\left(\psi_{ij}^{(1)}, \psi_{ij}^{(2)}, ..., \psi_{ij}^{(l)}\right) \quad (6)$$

Step 4: Proposed subjective and objective weighting approach.

Suppose $w = (w_1, w_2, ..., w_n)^T$ is the weight vector of criterion set with $\sum_{j=1}^{n} w_j = 1$ and $w_j \in [0, 1]$. Now, we find the criteria weight by combining the objective and subjective weights as follows:

Case I. Entropy method for objective weights.

To find the criteria weights, the entropy model is extended under the PFS environment as

$$w_j^o = \frac{\sum_{i=1}^{m} (1 - \overline{H}(\delta_{ij}))}{\sum_{j=1}^{n} \left(\sum_{i=1}^{m} (1 - \overline{H}(\delta_{ij})) \right)} \tag{7}$$

where,

$$\overline{H}(\delta_{ij}) = H(\delta_{ij}) / \max_{i=1,...,m} H(\delta_{ij}),\ j = 1, 2, ..., n, \tag{8}$$

$$H(\delta_{ij}) = 1 - \frac{1}{n} \sum_{i=1}^{n} \left[\left(\mu_{ij} - \nu_{ij} \right) I_{[\mu_{ij} \geq \nu_{ij}]} + \left(\nu_{ij} - \mu_{ij} \right) I_{[\mu_{ij} < \nu_{ij}]} \right], \tag{9}$$

signifies the entropy measure (taken from Mishra and Rani, 2019).

Case II. Determine the subjective weights by the SWARA method.

Step 4a: Determine the crisp degrees. Score degrees $\mathbb{S}(\delta_{kj})$ of IFNs are computed by Eq. (2).

Step 4b: Prioritize the criteria. The criteria are prioritized based on the DE's preferences from the most significant to the least significant attribute.

Step 4c: Evaluate the comparative significance of the average value. The significance degree is estimated from the criterion ordered in the second position, and the comparative significance is derived by making a comparison between the criteria s_j and s_{j-1}.

Step 4d: Evaluate the comparative coefficient κ_j as follows:

$$\kappa_j = \begin{cases} 1, & j = 1 \\ \sigma_j + 1, & j > 1. \end{cases} \tag{10}$$

Step 4e: Compute the weights. The recalculated weight ρ_j is given by

$$\rho_j = \begin{cases} 1, & j = 1 \\ \frac{\rho_{j-1}}{\kappa_j}, & j > 1. \end{cases} \tag{11}$$

Step 4f: The normalized weight is computed as

$$w_j^s = \frac{\rho_j}{\sum_{j=1}^{q} \rho_j}. \tag{12}$$

Case III. Calculation of integrated weight of indicator using "IF-Entropy-SWARA".

To find the integrated weight indicator, DEs need to utilize the both subjective and objective weights of indicators. The expression for the integrated weight is given by

$$w_j = \gamma w_j^o + (1 - \gamma) w_j^s,\ j = 1, 2, ..., n, \tag{13}$$

where $\gamma \in [0, 1]$ is a precision coefficient.

Step 5: Obtain the normalized A-IF-DM (NA-IF-DM).

The normalization is utilized to assess the values of the A-IF-DM $Z = (\delta)_m \times n$ and create the NA-IF-DM $\mathbb{N} = (\varsigma_{ij})_m \times n$. Let q_b and q_n signifies the benefit and cost-type criteria, then the expression for normalization is given by

$$\varsigma_{ij} = \left(\overline{\mu}_{ij}, \overline{\nu}_{ij} \right) = \begin{cases} \xi_{ij} = \left(\mu_{ij}, \nu_{ij} \right), & j \in q_b, \\ (\xi_{ij})^c = \left(\nu_{ij}, \mu_{ij} \right), & j \in q_n. \end{cases} \tag{14}$$

Step 6: Estimate the reference points.

We compute the "intuitionistic fuzzy-ideal solution (IF-IS)" and "intuitionistic fuzzy anti-ideal solution (IF-AIS)" with the use of the following expressions:

$$\alpha_j^+ = \begin{cases} (\max_i \mu_{ij}, \min_i \nu_{ij}), & \text{for } \textit{benefit criterion } q_b \\ (\min_i \mu_{ij}, \max_i \nu_{ij}), & \text{for } \textit{cost criterion } q_n \quad \textit{for } j = 1, 2, ..., n, \end{cases} \tag{15}$$

$$\alpha_j^- = \begin{cases} (\min_i \mu_{ij}, \max_i \nu_{ij}), & \text{for } \textit{benefit criterion } q_b \\ (\max_i \mu_{ij}, \min_i \nu_{ij}), & \text{for } \textit{cost criterion } q_n \quad \textit{for } j = 1, 2, ..., n. \end{cases} \tag{16}$$

Step 7: Calculate the weighted normalized A-IF-DM (NA-IF-DM)

Here, the weighted NA-IF-DM $\mathbb{N}_w = (\varsigma_{\widehat{ij}})_m \times n$is calculated, wherein

$$\varsigma_{\widehat{ij}} = \left(\mu_{\widehat{ij}}, \nu_{\widehat{ij}} \right) = w_j \overline{\varsigma}_{ij} = \left(1 - \left(1 - \overline{\mu}_{ij} \right)^{w_j} (\overline{\nu}_{ij})^{w_j} \right),\ j = 1, 2, ..., n. \tag{17}$$

Step 8: Evaluate the scare values of the weighted sum of each option

$$S_i = \sum_{j=1}^{n} \mathbb{S}\left(\varsigma_{\widehat{ij}} \right),\ i = 1, 2, ..., m, \tag{18}$$

where $\mathbb{S}(\varsigma_{\widehat{ij}})$represents the score values of each element of the weighted NA-IF-DM.

Step 9: Evaluate the "utility degree (UD)" of option

$$u_i^- = \frac{S_i}{S_{ais}} \text{ and } u_i^+ = \frac{S_i}{S_{is}}, \tag{19}$$

where S_{is} and S_{ais} signify the sum of score values of weighted values of α_{jw}^+ and α_{jw}^-, respectively.

Step 10: Identify the "combined utility function (CUF)" of each alternative.

The CUF is the compromise solution of alternatives associated with the IF-IS and IF-AIS. Thus, the CUF of alternatives is defined by

$$f(u_i) = \frac{u_i^+ + u_i^-}{1 + \frac{1 - f(u_i^+)}{f(u_i^+)} + \frac{1 - f(u_i^-)}{f(u_i^-)}}, \text{ where } f(u_i^+) = \frac{u_i^-}{u_i^- + u_i^+} \text{ and } f(u_i^-) = \frac{u_i^+}{u_i^- + u_i^+},\ i = 1, 2, ..., m. \tag{20}$$

Step 11: Rank the alternatives based on the CUFs. The appropriate option has the maximum CUF value.

Results and discussion

Case study

To identify, evaluate, and analyze the main challenges for collaborative innovation systems in the era of industry 4.0, we selected public higher education in China for empirical study. This study adopts rigorous and approved management methods to collect empirical data. First, a survey was carried out using the existing literature on innovation systems and holding some interviews with a number of selected experts. Then, the literature was comprehensively reviewed for the purpose of identifying the most important challenges that may arise for collaborative innovation systems in the Industry 4.0 era, particularly in the higher education context. The review resulted in the identification of 37 challenges. Third, a questionnaire was provided considering the identified challenges to be distributed among invited participants, who had expertise in the areas of Industry 4.0, innovation, and higher education. In the following round, 16 related experts from the higher education sector were invited to assess the questionnaires via online platforms such as WeChat and email. Each questionnaire was associated with an invitation letter explaining the objectives and values of the current study. All of the invited experts indicated great interest and readiness to provide their ideas in regard to the selected challenges. In the meantime, the experts asked us to provide them with feedback after reaching a conclusion in order to identify their shortcomings in collaborative innovation. Eight interview groups were created; each group employed two professionals to help us to gather the data needed for the next round of data collection. For the experts who agreed to cooperate, the advice offered by Jiang and Li (2009) was used to revise the evaluation challenges and experts (for instance, the executive directors). The questionnaire asked the participants to provide their advice on the challenges arising for higher education when analyzing the collaborative innovation system in the Industry 4.0 era. Moreover, the experts were invited to directly determine the challenges that may arise within the higher education sector when using collaborative innovation systems in order to make up for the weaknesses of the existing theoretical research scale in reflecting reality. The experts' feedback was considered to evaluate the questionnaires' content and accuracy level. The data were collected in a 3-month period (from December, April to June 2021). According to the results of this round of data collection, we have identified 20 main challenges for evaluating and analyzing the collaborative innovation system in the era of industry 4.0 for higher education.

In the next stage, to evaluate and analyze these 20 challenges using the integrated framework, we conducted the second round of data collection with four decision-makers in five PHE sectors in China. These four decision-makers have several years of experience in the PHE sector. This study is proposed an integrated framework to identify and evaluate the main challenges of the collaborative innovation systems in PHE. This framework is applied to calculate the subjective and objective weights of the main challenges of the collaborative innovation systems in PHE in the era of industry 4.0. In addition, the framework is used to assess the preferences of PHE organizations over different main challenges of the collaborative innovation systems in PHE in the era of industry 4.0. The implementation of the IF-Entropy-SWARA-MARCOS methodology is discussed as

Steps 1-3: Table 1 presents the linguistic ratings and their corresponding IFNs for the assessment of DEs, alternatives, and criteria. Based on Table 1 and Eq. (5), the weights of four DEs are computed in Table 2. On the basis of DEs' opinions, the linguistic assessment ratings of PHE organizations have presented each challenge of the collaborative innovation system in public higher education in the era of Industry 4.0. As a result, the LDM is constructed in Table 3.

From Eq. (6) and Table 3, the A-IF-DM is constructed to identify the main challenges of the collaborative innovation system in public higher education in the era of industry 4.0 and in Table 4.

Table 1
Linguistic rating scale

LVs	IFNs
Extremely good (EG)	(0.95, 0.05)
Very very good (VVG)	(0.85, 0.10)
Very good (VG)	(0.80, 0.15)
Good (G)	(0.70, 0.20)
Slightly good (MG)	(0.60, 0.30)
Moderate (M)	(0.50, 0.40)
Slightly bad (MB)	(0.40, 0.50)
Bad (B)	(0.30,0.60)
Very bad (VB)	(0.20, 0.70)
Very very bad (VVB)	(0.10, 0.80)
Extremely bad (EB)	(0.05, 0.95)

Table 2
The DEs' weights for challenges of the collaborative innovation system in PHE in the era of industry 4.0

DEs	d_1	d_2	d_3	d_4
LVs	G (0.70, 0.20)	VG (0.80, 0.15)	VVG (0.85, 0.10)	EG (0.95, 0.05)
Score degree	0.770	0.840	0.8925	0.950
Weight	0.2230	0.2433	0.2585	0.2752

Step 4: With the use of Eqs (7)-(9), the IF-entropy-based procedure is applied to determine the objective weights for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0, shown in Table 5.

$w_j^o =$ (0.0238, 0.0351, 0.0624, 0.0410, 0.0759, 0.0558, 0.0255, 0.0532, 0.0683, 0.0559, 0.0445, 0.0505, 0.0403, 0.0670, 0.0710, 0.0490, 0.0290, 0.0622, 0.0426, 0.0468).

From Eq. (10)-Eq. (12), the IF-SWARA procedure is utilized to derive the subjective weights for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 that shown in Table 6.

w_j^s= (0.0531, 0.0522, 0.0499, 0.0504, 0.0429, 0.0538, 0.0496, 0.0501, 0.0487, 0.0526, 0.0450, 0.0476, 0.0507, 0.0507, 0.0517, 0.0515, 0.0520, 0.0478, 0.0495, 0.0504).

Based on objective and subjective weights, the final weights of criteria are computed as ($\tau = 0.5$)

w_j= (0.0385, 0.0437, 0.0562, 0.0457, 0.0594, 0.0548, 0.0376, 0.0517, 0.0585, 0.0543, 0.0448, 0.0490, 0.0455, 0.0588, 0.0614, 0.0503, 0.0405, 0.0550, 0.0461, 0.0486).

Here, Fig. 1 shows the weight values of the different main challenges of the collaborative innovation system in PHE in the era of industry 4.0 with respect to the goal. The holistic acceptance of the innovation (q_{15}) with a weight value of 0.0614 has come out to be the most important challenge of the collaborative innovation system in PHE. Lack of technical infrastructure (q_5) with a weight value of 0.0594 is the second most important challenge of the collaborative innovation system in the PHE. Educational policy (q_{14}) has third with a significance value of 0.0588, motivation in using ICT (q_9) has fourth with a weight value of 0.0585, lack of addressable communities (q_3) with a significance value of 0.0562 has the fifth most important challenge, and others are considered crucial the main challenges of the collaborative innovation system in PHE in the era of industry 4.0.

Step 5: Since all criteria are beneficial-type criteria, thus, there is no need for Eq. (14) in order to transform A-IF-DM into NA-IF-DM.

Step 6: From Eq. (15)-Eq. (16) and Table 4, the IF-IS and the IF-AIS for the main challenges of the collaborative innovation system in public higher education in the era of industry 4.0 are obtained as follows:

α_j^+ **= {**(0.564, 0.331, 0.105), (0.620, 0.290, 0.090), (0.680, 0.232, 0.088), (0.643, 0.269, 0.088), (0.734, 0.193, 0.074), (0.661, 0.251, 0.088), (0.567, 0.328, 0.105), (0.706, 0.222, 0.073), (0.681, 0.230, 0.088), (0.670, 0.243, 0.086), (0.634, 0.263, 0.103), (0.664, 0.249,

Table 3
The LDM of each option by DEs to challenges of the collaborative innovation system in PHE in the era of industry 4.0

	p_1	p_2	p_3	p_4	p_5
q_1	(MG,MB,G,M)	(M,M,MB,MG)	(M,VB,MB,G)	(VB,MB,MG,B)	(G,M,VB,VB)
q_2	(MB,G,B,MG)	(MG,B,MB,M)	(VVG,MG,MB,M)	(MG,B,G,B)	(G,MG,B,MB)
q_3	(M,B,M,G)	(G,MB,VG,G)	(G,MG,B,MB)	(VG,G,M,MB)	(VG,G,M,MG)
q_4	(M,MG,G,M)	(VG,M,G,M)	(MB,MB,MG,G)	(MB,MG,M,MB)	(G,MB,VB,M)
q_5	(MG,MG,G,M)	(MB,G,G,MG)	(MG,MB,M,G)	(MB,M,VG,G)	(VVG,G,VG,M)
q_6	(VG,MG,M,MG)	(M,VB,MB,M)	(VG,G,M,MG)	(G,M,MG,MB)	(G,MG,MB,MG)
q_7	(M,MG,B,M)	(B,MB,B,M)	(MB,MG,M,M)	(MG,M,MB,G)	(G,VB,MB,M)
q_8	(MG,VG,VG,M)	(M,VVG,VG,M)	(MB,M,MG,MB)	(M,MG,MB,MG)	(G,B,VB,MG)
q_9	(MG,MG,G,M)	(M,VG,G,MG)	(M,MB,G,MB)	(MB,VG,MG,M)	(VVG,G,MG,M)
q_{10}	(M,VG,G,MG)	(B,MG,G,M)	(M,MG,MB,G)	(MG,MB,MG,G)	(VG,M,VB,M)
q_{11}	(MB,MB, B,M)	(MG,MB,B,MB)	(MG,VG,M,MG)	(G,M,MG,G)	(MG,MG,M,M)
q_{12}	(M,B,MB,M)	(MB,MG,MB,M)	(G,VG,M,MG)	(VG,M,MG,M)	(G,M,MG,G)
q_{13}	(MG,M,G,MG)	(M,MG,G,MG)	(M,MG,MB,M)	(MG,MB,M,MG)	(G,M,VB,MB)
q_{14}	(MG,M,MG,M)	(M,MG,MG,M)	(MB,VG,MG,M)	(VG,MG,M,G)	(VVG,G,MB,G)
q_{15}	(VG,MG,M,M)	(MB,VVG,G,MG)	(M,MB,VVG,G)	(MB,VG,MG,MG)	(G,M,M,MB)
q_{16}	(M,B,B,MB)	(M,MB,VB,M)	(MG,MG,VG,M)	(M,VG,G,MG)	(M,MB,B,B)
q_{17}	(B,MB,M,MG)	(B,B,MB,M)	(MG,MB,M,G)	(MB,M,MG,G)	(G,M,VB,VB)
q_{18}	(G,VG,G,MG)	(MG,VG,G,M)	(M,VB,MB,M)	(VB,MB,MB,M)	(VVG,G,MB,M)
q_{19}	(VG,MG,B,MB)	(MG,B,MB,G)	(G,G,B,MB)	(MG,B,G,G)	(MG,B,VB,MB)
q_{20}	(MG,MG,VB,G)	(G,VB,MB,MG)	(VG,G,MB,MB)	(VG,MB,G,MG)	(G,B,VB,B)

0.086), (0.610, 0.288, 0.102), (0.693, 0.217, 0.090), (0.680, 0.232, 0.088), (0.670, 0.243, 0.086), (0.573, 0.323, 0.105), (0.706, 0.208, 0.086), (0.607, 0.286, 0.107), (0.649, 0.262, 0.089)**}**

α_j^+ **= {**(0.399, 0.497, 0.104), (0.459, 0.439, 0.103), (0.515, 0.377, 0.107), (0.473, 0.418, 0.109), (0.568, 0.327, 0.105), (0.412, 0.486, 0.102), (0.385, 0.513, 0.101), (0.483, 0.415, 0.102), (0.518, 0.375, 0.106), (0.540, 0.371, 0.089), (0.406, 0.493, 0.101), (0.431, 0.468, 0.101), (0.470, 0.421, 0.109), (0.551, 0.348, 0.101), (0.531, 0.364, 0.105), (0.375, 0.524, 0.101), (0.387, 0.512, 0.101), (0.392, 0.507, 0.102), (0.387, 0.509, 0.104), (0.400, 0.489, 0.111)**}.**

Step 7: According to Eq. (17) and Table 4, the weighted NA-IF-DM for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 is created and given in Table 7.

Step 8: Using Eq. (18) and Table 7, the score values of each alternative, IF-IS, and IF-AIS, for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 are determined and given in Table 8.

Steps 9-11: From Eq. (19) and Eq. (20), we estimate the utility degrees, CUFs, and ranking order of PHE alternatives which are given in Table 9. Hence, the prioritization of options is p_4\succ$p_3$\succ$p_1$\succ$p_2$\succ$p_5$, and the higher education option-IV (p_4) is the best choice with maximum CUF for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0.

Sensitivity investigation

This study also involves a sensitivity investigation with respect to different values of parameter γ. The deviation of γ helps to assess the approach's sensitivity level, changing from objective weighting to subjective weighting procedures.

Table 10 and Fig. 2 present the results of the sensitivity investigation. The evaluation results provide the preferences of PHE organizations for the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 as p_4\succ$p_3$\succ$p_1$\succ$p_2$\succ$p_5$ when $\gamma = 0.0$ using the IF-SWARA weighting procedure, p_4\succ$p_3$\succ$p_1$\succ$p_5$\succ$p_2$ when $\gamma = 0.5$ using the integrated IF-Entropy-SWARA weighting procedure and p_4\succ$p_1$\succ$p_3$\succ$p_2$\succ$p_5$ when $\gamma = 1.0$ using the IF-Entropy-based weighting procedure, which implies PHE-IV (p_4) is at the top of the ranking for each value of γ. As a result, the developed method was observed to have enough stability with respect to diverse values of the parameter. Table 10 shows that the IF-Entropy-SWARA-MARCOS method successfully produced preference

Table 4
The A-IF-DM for challenges of the collaborative innovation system in PHE in the era of industry 4.0

	p_1	p_2	p_3	p_4	p_5
q_1	(0.564, 0.331, 0.105)	(0.507, 0.391, 0.101)	(0.489, 0.401, 0.109)	(0.399, 0.497, 0.104)	(0.427, 0.462, 0.111)
q_2	(0.528, 0.364, 0.107)	(0.459, 0.439, 0.103)	(0.620, 0.290, 0.090)	(0.575, 0.387, 0.039)	(0.515, 0.377, 0.107)
q_3	(0.529, 0.365, 0.107)	(0.680, 0.232, 0.088)	(0.515, 0.377, 0.107)	(0.622, 0.289, 0.090)	(0.661, 0.251, 0.088)
q_4	(0.585, 0.312, 0.103)	(0.643, 0.269, 0.088)	(0.554, 0.340, 0.106)	(0.481, 0.417, 0.102)	(0.473, 0.418, 0.109)
q_5	(0.605, 0.292, 0.102)	(0.621, 0.274, 0.105)	(0.568, 0.327, 0.105)	(0.643, 0.270, 0.087)	(0.734, 0.193, 0.074)
q_6	(0.637, 0.277, 0.086)	(0.412, 0.486, 0.102)	(0.661, 0.251, 0.088)	(0.557, 0.338, 0.105)	(0.583, 0.313, 0.104)
q_7	(0.483, 0.414, 0.102)	(0.385, 0.513, 0.101)	(0.507, 0.392, 0.101)	(0.567, 0.328, 0.105)	(0.476, 0.416, 0.108)
q_8	(0.700, 0.229, 0.071)	(0.706, 0.222, 0.073)	(0.483, 0.415, 0.102)	(0.533, 0.365, 0.102)	(0.486, 0.404, 0.110)
q_9	(0.605, 0.292, 0.102)	(0.670, 0.243, 0.086)	(0.518, 0.375, 0.106)	(0.607, 0.307, 0.086)	(0.681, 0.230, 0.088)
q_{10}	(0.670, 0.243, 0.086)	(0.553, 0.341, 0.106)	(0.569, 0.326, 0.105)	(0.592, 0.304, 0.104)	(0.540, 0.371, 0.089)
q_{11}	(0.406, 0.493, 0.101)	(0.430, 0.468, 0.103)	(0.642, 0.273, 0.085)	(0.634, 0.263, 0.103)	(0.549, 0.350, 0.101)
q_{12}	(0.431, 0.468, 0.101)	(0.483, 0.415, 0.102)	(0.664, 0.249, 0.086)	(0.615, 0.298, 0.086)	(0.634, 0.263, 0.103)
q_{13}	(0.608, 0.290, 0.102)	(0.610, 0.288, 0.102)	(0.504, 0.395, 0.101)	(0.532, 0.366, 0.102)	(0.470, 0.421, 0.109)
q_{14}	(0.551, 0.348, 0.101)	(0.553, 0.346, 0.101)	(0.607, 0.307, 0.086)	(0.665, 0.248, 0.088)	(0.693, 0.217, 0.090)
q_{15}	(0.614, 0.300, 0.086)	(0.680, 0.232, 0.088)	(0.667, 0.244, 0.089)	(0.630, 0.284, 0.086)	(0.531, 0.364, 0.105)
q_{16}	(0.378, 0.521, 0.101)	(0.410, 0.488, 0.102)	(0.644, 0.271, 0.084)	(0.670, 0.243, 0.086)	(0.375, 0.524, 0.101)
q_{17}	(0.470, 0.427, 0.103)	(0.387, 0.512, 0.101)	(0.568, 0.327, 0.105)	(0.573, 0.323, 0.105)	(0.427, 0.462, 0.111)
q_{18}	(0.706, 0.208, 0.086)	(0.666, 0.247, 0.087)	(0.412, 0.486, 0.102)	(0.392, 0.507, 0.102)	(0.646, 0.263, 0.091)
q_{19}	(0.557, 0.354, 0.089)	(0.530, 0.362, 0.108)	(0.548, 0.342, 0.110)	(0.607, 0.286, 0.107)	(0.387, 0.509, 0.104)
q_{20}	(0.558, 0.334, 0.108)	(0.507, 0.384, 0.109)	(0.603, 0.306, 0.091)	(0.649, 0.262, 0.089)	(0.400, 0.489, 0.111)

Table 5
Significance degree of challenges of the collaborative innovation system in PHE in the era of industry 4.0

Challenges	d_1	d_2	d_3	d_4	A-IF-DM	Crisp values
q_1	G	G	M	B	(0.568, 0.324, 0.109)	0.622
q_2	M	MG	M	MG	(0.555, 0.345, 0.101)	0.605
q_3	M	MB	B	G	(0.505, 0.388, 0.108)	0.559
q_4	G	B	M	M	(0.516, 0.378, 0.106)	0.569
q_5	B	MB	B	MB	(0.354, 0.546, 0.100)	0.404
q_6	M	G	MG	M	(0.583, 0.314, 0.103)	0.635
q_7	MB	M	G	B	(0.499, 0.393, 0.108)	0.553
q_8	MG	M	B	MG	(0.512, 0.385, 0.103)	0.564
q_9	MB	M	MG	MB	(0.483, 0.415, 0.102)	0.534
q_{10}	G	MG	MB	MG	(0.560, 0.335, 0.104)	0.612
q_{11}	M	MB	M	G	(0.400, 0.495, 0.104)	0.453
q_{12}	MB	M	MG	B	(0.461, 0.436, 0.103)	0.512
q_{13}	G	MB	B	MG	(0.522, 0.371, 0.107)	0.575
q_{14}	G	B	MB	MG	(0.523, 0.370, 0.107)	0.576
q_{15}	MG	G	B	M	(0.542, 0.352, 0.106)	0.595
q_{16}	MB	G	M	M	(0.540, 0.355, 0.105)	0.592
q_{17}	MG	M	MG	M	(0.551, 0.348, 0.101)	0.601
q_{18}	B	M	MG	MB	(0.465, 0.432, 0.103)	0.516
q_{19}	M	MB	G	B	(0.498, 0.395, 0.108)	0.551
q_{20}	MB	G	M	B	(0.516, 0.378, 0.108)	0.569

results of high stability and flexibility in different utility parameters. This characteristic plays an important role in MCDM procedures.

Comparative study

This study also compared the results obtained by IF-Entropy-SWARA-MARCOS and other approaches. To evaluate the efficiency level and show the unique qualities of the proposed method, we have chosen some methods, such as the IF-WASPAS (Rani and Mishra, 2020) and IF-TOPSIS (Mishra, 2016), which have good efficiency in terms of solving MCDM problems.

IF-WASPAS

This method involves the following steps:

Steps 1-5: Same as the aforementioned model.

Step 6: Find the measures of the "weighted sum model (WSM)" and "weighted product model (WPM)" using Eq. (21) and Eq. (22), respectively.

$$\mathbb{C}_i^{(1)} = \overset{n}{\underset{j=1}{\oplus}} w_j\, \varsigma_{ij}. \tag{21}$$

$$\mathbb{C}_i^{(2)} = \overset{n}{\underset{j=1}{\otimes}} \varsigma_{ij}^{w_j}. \tag{22}$$

Step 7: Compute the measure of "weighted aggregated sum product assessment (WASPAS)" using

$$\mathbb{C}_i = \lambda\, \mathbb{C}_i^{(1)} + (1-\lambda)\, \mathbb{C}_i^{(2)},\ \ \lambda \in [0,\ 1]. \tag{23}$$

Step 8: Rank the options according to the values of WASPAS measure.

With the use of Eqs (21)-(23), the steps of IF-WASPAS model are computed and presented in Table 11. Based on IF-WASPAS model, the priority order of the options is p_4\succ p_3\succ p_1\succ p_2\succ$p_5$.

IF-TOPSIS

The IF-TOPSIS model involves the following procedural steps:

Steps 1-5: Follow the previous method.

Step 6: Compute the degree of distances from IF-IS and IFA-IS.

With the use of Mishra (2016), we calculate the degree-weighted distance $S(p_i, \alpha_j^+)$ between the options $p_i (i = 1(1)m)$ and the IF-IS α_j^+.

$$S\left(p_i,\ \alpha_j^+\right) = \frac{1}{2}\sum_{i=1}^{n} w_j \left[\left|\mu_{\varsigma_{ij}} - \mu_{\alpha_j^+}\right| + \left|\nu_{\varsigma_{ij}} - \nu_{\alpha_j^+}\right| + \left|\pi_{\varsigma_{ij}} - \pi_{\alpha_j^+}\right|\right], \tag{24}$$

and the degree of distances $S(p_i, \alpha_j^-)$ among the options $p_i (i = 1(1)m)$ and the IFA-IS α_j^- is given as follows:

$$S\left(p_i,\ \alpha_j^-\right) = \frac{1}{2}\sum_{i=1}^{n} w_j \left[\left|\mu_{\varsigma_{ij}} - \mu_{\alpha_j^-}\right| + \left|\nu_{\varsigma_{ij}} - \nu_{\alpha_j^-}\right| + \left|\pi_{\varsigma_{ij}} - \pi_{\alpha_j^-}\right|\right]. \tag{25}$$

Step 7: Determine the relative closeness coefficient (CC).

The relative CC of each option with respect to the IF ideal solutions is given as

$$\mathbb{C}(h_i) = \frac{S\left(p_i,\ \alpha_j^-\right)}{S\left(p_i,\ \alpha_j^+\right) + S\left(p_i,\ \alpha_j^-\right)},\quad i = 1, 2, \ldots, m. \tag{26}$$

Step 8: Choose the maximum value $\mathbb{C}(p_k)$ among the values $\mathbb{C}(p_i)$, $i = 1, 2, \ldots, m$. Hence, p_k is the optimal choice.

From Eq. (24)-Eq. (26), the overall results of the IF-TOPSIS method are given in Table 12.

Table 6
The weight of different challenges of the collaborative innovation system in PHE in the era of industry 4.0 using the IF-SWARA method

Challenges	Crisp degrees	Comparative importance of attributes	Coefficient	Recalculated weight	Final weight (w_j^s)
q_6	0.635	-	1.000	1.0000	0.0538
q_1	0.622	0.013	0.013	0.9872	0.0531
q_{10}	0.612	0.010	1.010	0.9774	0.0526
q_2	0.605	0.007	1.007	0.9706	0.0522
q_{17}	0.601	0.004	1.004	0.9667	0.0520
q_{15}	0.595	0.006	1.006	0.9609	0.0517
q_{16}	0.592	0.003	1.003	0.9580	0.0515
q_{14}	0.576	0.016	1.016	0.9429	0.0507
q_{13}	0.575	0.001	1.001	0.9420	0.0507
q_4	0.569	0.006	1.006	0.9364	0.0504
q_{20}	0.569	0.000	1.000	0.9364	0.0504
q_8	0.564	0.005	1.005	0.9317	0.0501
q_3	0.559	0.005	1.005	0.9271	0.0499
q_7	0.553	0.006	1.006	0.9216	0.0496
q_{19}	0.551	0.002	1.002	0.9198	0.0495
q_9	0.534	0.017	1.017	0.9044	0.0487
q_{18}	0.516	0.018	1.018	0.8884	0.0478
q_{12}	0.512	0.004	1.004	0.8849	0.0476
q_{11}	0.453	0.059	1.059	0.8356	0.0450
q_5	0.404	0.049	1.049	0.7966	0.0429

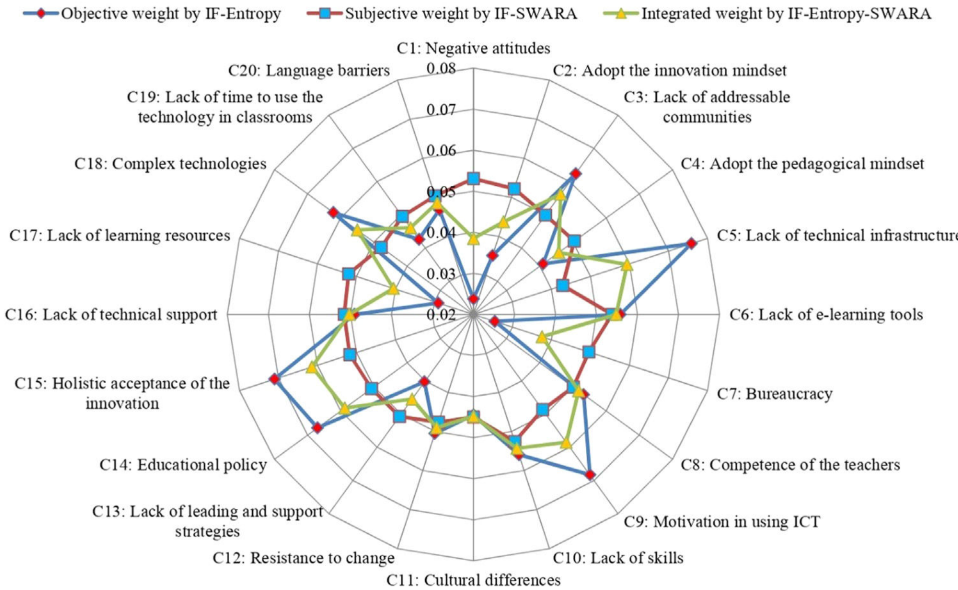


Fig. 1. Weights of challenges of the collaborative innovation system in PHE in the era of industry 4.0

From Table 12, p_4 is the best PHE alternative and prioritization of PHE organizations for assessing the main challenges of the collaborative innovation system in PHE in the era of industry 4.0 is p_4\succ$p_3$ \succ$p_1$\succ p_5\succ$p_2$.

Next, the prioritization of options obtained by the IF-Entropy-SWARA-MARCOS framework is similar to the IF-WASPAS (Mishra et al., 2020) and IF-TOPSIS (Mishra, 2016). Tables 9 and 11-12 show the prioritizations of five PHE organizations of the main challenges of the collaborative innovation system in PHE in the era of industry 4.0. From Table 9 and Tables 11-12, option PHE-IV (p_4) has secured the first rank in PHE in the era of industry 4.0. Also, the CUFs/UDs of PHE organizations of the main challenges of the collaborative innovation system are depicted in Fig. 3. In comparison with these methods, the main merits of the proposed methodology are presented as

- In the proposed IF-Entropy-SWARA-MARCOS framework, we use the aggregated compromise algorithm with different aggregation strategies to acquire a compromise solution. The MARCOS tool comprises as (i) considering "intuitionistic fuzzy ideal solution (IF-IS)" and "intuitionistic fuzzy anti-ideal solution (IF-AIS)" as reference points, (ii) establishing the relationship with options and IF-IS/IF-AISs, (iii) describing the "utility degree (UD)" of each option in association to IF-IS and IF-AISs. Hence, the proposed methodology is a superior structure, precisely estimating the reference values for selecting the best option.
- In the IF-WASPAS and IF-TOPSIS models, the only objective weight of criteria is computed. While in the proposed framework, the IF-Entropy-based tool has been used to compute the objective weight, and IF-SWARA has been employed to achieve the subjective weight of the criteria. In order to utilize the benefits of objective and subjective weighting procedures, we presented an integrated weighting model to determine the criteria weights. Thus, the proposed model has higher practicality, reliability, and efficiency in order to deal with MCDM problems.

Table 7
The weighted NA-IF-DM of each option

	p_1	p_2	p_3	p_4	p_5	α^+_{jw}	α^-_{jw}
q_1	(0.031, 0.958, 0.010)	(0.027, 0.965, 0.009)	(0.026, 0.965, 0.009)	(0.019, 0.973, 0.007)	(0.021, 0.971, 0.008)	(0.031, 0.958, 0.010)	(0.019, 0.973, 0.007)
q_2	(0.032, 0.957, 0.011)	(0.026, 0.965, 0.009)	(0.041, 0.947, 0.011)	(0.037, 0.959, 0.004)	(0.031, 0.958, 0.011)	(0.041, 0.947, 0.011)	(0.026, 0.965, 0.009)
q_3	(0.041, 0.945, 0.014)	(0.062, 0.921, 0.017)	(0.040, 0.947, 0.013)	(0.053, 0.933, 0.014)	(0.059, 0.925, 0.016)	(0.062, 0.921, 0.017)	(0.040, 0.947, 0.013)
q_4	(0.039, 0.948, 0.012)	(0.046, 0.942, 0.012)	(0.036, 0.952, 0.012)	(0.030, 0.961, 0.010)	(0.029, 0.961, 0.010)	(0.046, 0.942, 0.012)	(0.029, 0.961, 0.010)
q_5	(0.054, 0.930, 0.017)	(0.056, 0.926, 0.018)	(0.049, 0.936, 0.016)	(0.059, 0.925, 0.016)	(0.076, 0.907, 0.018)	(0.076, 0.907, 0.017)	(0.049, 0.936, 0.016)
q_6	(0.054, 0.932, 0.014)	(0.029, 0.961, 0.010)	(0.058, 0.927, 0.015)	(0.044, 0.942, 0.014)	(0.047, 0.938, 0.015)	(0.058, 0.927, 0.015)	(0.029, 0.961, 0.010)
q_7	(0.024, 0.967, 0.008)	(0.018, 0.975, 0.007)	(0.026, 0.965, 0.008)	(0.031, 0.959, 0.010)	(0.024, 0.968, 0.008)	(0.031, 0.959, 0.010)	(0.018, 0.975, 0.007)
q_8	(0.060, 0.927, 0.013)	(0.061, 0.925, 0.014)	(0.034, 0.956, 0.011)	(0.039, 0.949, 0.012)	(0.034, 0.954, 0.012)	(0.061, 0.925, 0.014)	(0.034, 0.956, 0.011)
q_9	(0.053, 0.931, 0.016)	(0.063, 0.921, 0.017)	(0.042, 0.944, 0.014)	(0.053, 0.933, 0.014)	(0.065, 0.918, 0.018)	(0.065, 0.918, 0.018)	(0.042, 0.944, 0.014)
q_{10}	(0.058, 0.926, 0.015)	(0.043, 0.943, 0.014)	(0.045, 0.941, 0.014)	(0.047, 0.937, 0.015)	(0.041, 0.948, 0.011)	(0.058, 0.926, 0.016)	(0.041, 0.948, 0.011)
q_{11}	(0.023, 0.969, 0.008)	(0.025, 0.967, 0.009)	(0.045, 0.944, 0.012)	(0.044, 0.942, 0.014)	(0.035, 0.954, 0.011)	(0.044, 0.942, 0.014)	(0.023, 0.969, 0.008)
q_{12}	(0.027, 0.963, 0.009)	(0.032, 0.958, 0.010)	(0.052, 0.934, 0.014)	(0.046, 0.942, 0.012)	(0.048, 0.937, 0.015)	(0.052, 0.934, 0.014)	(0.027, 0.963, 0.009)
q_{13}	(0.042, 0.945, 0.013)	(0.042, 0.945, 0.013)	(0.031, 0.959, 0.010)	(0.034, 0.955, 0.011)	(0.028, 0.961, 0.010)	(0.042, 0.945, 0.013)	(0.028, 0.961, 0.010)
q_{14}	(0.046, 0.940, 0.014)	(0.046, 0.940, 0.014)	(0.053, 0.933, 0.014)	(0.062, 0.921, 0.017)	(0.067, 0.914, 0.019)	(0.067, 0.914, 0.019)	(0.046, 0.940, 0.014)
q_{15}	(0.057, 0.929, 0.015)	(0.067, 0.914, 0.018)	(0.065, 0.917, 0.018)	(0.059, 0.926, 0.015)	(0.045, 0.940, 0.015)	(0.068, 0.914, 0.018)	(0.045, 0.940, 0.015)
q_{16}	(0.024, 0.968, 0.009)	(0.026, 0.965, 0.009)	(0.051, 0.937, 0.013)	(0.054, 0.931, 0.014)	(0.023, 0.968, 0.009)	(0.054, 0.931, 0.014)	(0.023, 0.968, 0.009)
q_{17}	(0.025, 0.966, 0.008)	(0.020, 0.973, 0.007)	(0.033, 0.956, 0.011)	(0.034, 0.955, 0.011)	(0.022, 0.969, 0.009)	(0.034, 0.955, 0.011)	(0.020, 0.973, 0.007)
q_{18}	(0.065, 0.917, 0.018)	(0.059, 0.926, 0.015)	(0.029, 0.961, 0.010)	(0.027, 0.963, 0.010)	(0.056, 0.929, 0.015)	(0.065, 0.917, 0.018)	(0.027, 0.963, 0.010)
q_{19}	(0.037, 0.953, 0.010)	(0.034, 0.954, 0.012)	(0.036, 0.952, 0.012)	(0.042, 0.944, 0.014)	(0.022, 0.969, 0.008)	(0.042, 0.944, 0.014)	(0.022, 0.969, 0.008)
q_{20}	(0.039, 0.948, 0.013)	(0.034, 0.955, 0.012)	(0.044, 0.944, 0.012)	(0.050, 0.937, 0.013)	(0.025, 0.966, 0.010)	(0.050, 0.937, 0.013)	(0.025, 0.966, 0.010)

Table 8
Score values weighted NA-IF-DM of each option

	p_1	p_2	p_3	p_4	p_5	α_{jw}^{+}	α_{jw}^{-}
q_1	0.037	0.031	0.030	0.023	0.025	0.037	0.023
q_2	0.038	0.031	0.047	0.039	0.036	0.047	0.031
q_3	0.048	0.070	0.047	0.060	0.067	0.070	0.047
q_4	0.046	0.052	0.042	0.034	0.034	0.052	0.034
q_5	0.062	0.065	0.056	0.067	0.084	0.084	0.056
q_6	0.061	0.034	0.065	0.051	0.054	0.065	0.034
q_7	0.029	0.021	0.030	0.036	0.028	0.036	0.021
q_8	0.067	0.068	0.039	0.045	0.040	0.068	0.039
q_9	0.061	0.071	0.049	0.060	0.074	0.074	0.049
q_{10}	0.066	0.050	0.052	0.055	0.047	0.066	0.047
q_{11}	0.027	0.029	0.051	0.051	0.040	0.051	0.027
q_{12}	0.032	0.037	0.059	0.052	0.056	0.059	0.032
q_{13}	0.048	0.048	0.036	0.039	0.034	0.049	0.034
q_{14}	0.053	0.053	0.060	0.071	0.076	0.077	0.053
q_{15}	0.064	0.077	0.074	0.067	0.053	0.077	0.053
q_{16}	0.028	0.031	0.057	0.061	0.028	0.061	0.028
q_{17}	0.030	0.023	0.039	0.039	0.027	0.039	0.023
q_{18}	0.074	0.066	0.034	0.032	0.063	0.074	0.032
q_{19}	0.042	0.040	0.042	0.049	0.026	0.049	0.026
q_{20}	0.045	0.040	0.050	0.056	0.029	0.056	0.029
S_i	0.957	0.938	0.959	0.987	0.922	1.191	0.717

Table 9
The utility degrees and CUF of each option for prioritizing BESS

PHE organizations	u_i^{+}	u_i^{-}	$f(u_i)$	Ranks
p_1	0.803	1.333	0.6549	3
p_2	0.788	1.307	0.6422	4
p_3	0.806	1.337	0.6568	2
p_4	0.829	1.375	0.6756	1
p_5	0.774	1.285	0.6309	5

Conclusion and policy implications

Generally, companies are not capable of creating and commercializing innovation. This problem could be solved by sharing or acquiring relevant resources through collaboration. The effectiveness of collaborative relationships is dependent upon the type and quality of the partners involved and also the degree to which they are proximate to each other. This is especially true in the developing innovation systems of countries when they are to move from middle- to high-income levels. Since the knowledge economy commenced in the current century, the higher education sector has faced many demands for the improvement of collaborations with boosting its capacity for creating and disseminating knowledge and also for maximizing the impact on practice. Because of such demands, higher education institutes (HEIs) must create a network with all their stakeholders, other HEIs, and other parties inside their institutions. Creating collaboration and networks in this sector can contribute to both the institutional management theme and the knowledge and research theme of research in higher education. The current higher education-related literature is rich in research into the benefits of collaboration, but it lacks research on how higher education managers can effectively promote collaboration in this sector. Numerous structural models have been developed in recent decades regarding the theme of the collaborative innovation system in higher education. Accordingly, the present paper addresses this gap by comprehensively analyzing the challenges of the collaborative innovation system in the PHE sector in the Industry 4.0 era in the emergent innovation systems recently implemented in developing countries. In order to analyze, rank and evaluate the main challenges of the collaborative innovation system in PHE in the era of industry 4.0, this study introduced an integrated decision-making method using IFSs. For this purpose, an innovative decision support system is introduced to evaluate the main challenges of the collaborative innovation system in PHE in the era of industry 4.0. To rank the main challenges of the collaborative innovation system in PHE in the era of industry 4.0, the IF-Entropy-SWARA method is utilized, and to compute the preference order of different PHE organizations of the main challenges of the collaborative innovation system in PHE in the era of industry 4.0, the IF-MARCOS method is used. The results of this study found that; the holistic acceptance of the innovation with a weight value of 0.0614 has come out to be the most important challenge of the collaborative innovation system in PHE; in addition, the lack of technical infrastructure with a weight value of 0.0594 is the second most important challenge of the collaborative innovation system in the PHE, and educational policy has third with significance value 0.0588. To validation of the results of this study, a comparison using the IF-TOPSIS, IF-WSM, IF-WPM, and IF-WASPAS methods is conducted.

Table 10
Ranking results of the IF-Entropy-SWARA-MARCOS method with different values of γ

γ	p_1	p_2	p_3	p_4	p_5	Ranking order
γ = 0.0 (Subjective weight by IF-SWARA method)	0.6579	0.6368	0.6657	0.6793	0.6205	p_4\succ$p_3$\succ$p_1$\succ$p_2$\succ$p_5$
γ = 0.5 (Integrated method by IF-Entropy-SWARA)	0.6549	0.6422	0.6568	0.6756	0.6309	p_4\succ$p_3$\succ$p_1$\succ$p_5$\succ$p_2$
γ = 1.0 (Objective weight by IF-entropy-based method)	0.6520	0.6474	0.6484	0.6720	0.6409	p_4\succ$p_1$\succ$p_3$\succ$p_2$\succ$p_5$

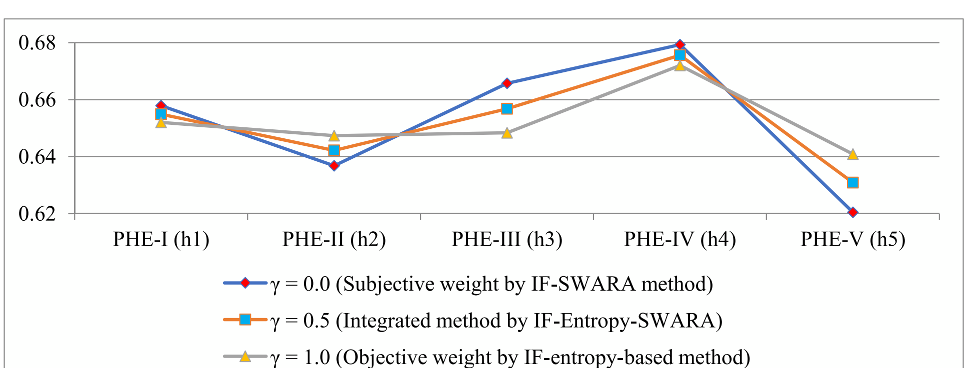


Fig. 2. Sensitivity of the CUFs over the strategic parameter γ

Table 11
The *UD* of option for the challenges of the collaborative innovation system in PHE in the era of industry 4.0

options	WSM		WPM		$UD(\mathbb{C}_i)$	Ranking
	$\mathbb{C}_i^{(1)}$	$\mathbb{S}(\mathbb{C}_i^{(1)})$	$\mathbb{C}_i^{(2)}$	$\mathbb{S}(\mathbb{C}_i^{(2)})$		
h_1	(0.574, 0.328, 0.098)	0.623	(0.557, 0.344, 0.099)	0.607	0.6147	3
h_2	(0.566, 0.335, 0.099)	0.616	(0.543, 0.357, 0.100)	0.593	0.6043	4
h_3	(0.574, 0.328, 0.098)	0.623	(0.564, 0.337, 0.099)	0.614	0.6186	2
h_4	(0.587, 0.319, 0.094)	0.634	(0.575, 0.330, 0.095)	0.623	0.6285	1
h_5	(0.559, 0.340, 0.101)	0.609	(0.534, 0.364, 0.103)	0.585	0.5970	5

Table 12
Ranking orders of IF- TOPSIS method

Options	$S(p_i, \alpha_j^+)$	$S(p_i, \alpha_j^-)$	$\mathbb{C}(p_i)$	Ranking
p_1	0.093	0.105	0.5293	3
p_2	0.104	0.095	0.4773	5
p_3	0.090	0.110	0.5515	2
p_4	0.078	0.122	0.6093	1
p_5	0.112	0.091	0.4469	4

Policy implications

Implementing a collaborative innovation system could have several policy implications for governments, institutions, and other stakeholders. Implementing a collaborative innovation system would require a cultural shift towards collaboration and knowledge sharing. This could be challenging, especially in organizations that are used to working in silos or where competition is emphasized. The implementation process would need to be accompanied by change management efforts to encourage buy-in and adoption. Moreover, the collaborative innovation system would create an environment where ideas are shared freely and stakeholders are encouraged to think outside the box. This would promote creativity and innovation, enabling stakeholders to develop new solutions to complex problems. The collaborative innovation system would create opportunities for stakeholders to collaborate and share their expertise. This would increase engagement and motivation, as stakeholders feel valued and invested in the process. Policymakers could initiate innovation challenges to engage higher education institutions and other stakeholders in developing solutions to complex challenges facing the sector. Challenges could be structured around specific themes, such as improving student outcomes, reducing costs, or increasing access to education. In addition, by supporting collaboration and knowledge sharing, policies could be developed to encourage collaboration and knowledge sharing among stakeholders. This could involve incentivizing organizations to collaborate, establishing networks or platforms that facilitate knowledge sharing, and providing funding for collaborative projects. Furthermore, by encouraging innovation and creativity, policies could be developed to encourage innovation and creativity, such as funding innovation challenges, establishing innovation hubs or incubators, and providing tax incentives for innovative projects. Additionally, by enhancing capacity and skills development, policies could be developed to enhance capacity and skills development among stakeholders, such as funding training programs, establishing mentorship or coaching programs, and creating opportunities for knowledge exchange. Overall, implementing a collaborative innovation system could have significant implications for governments, institutions, and other stakeholders involved. The system could drive organizational growth and competitiveness by promoting a culture of collaboration and innovation, enabling evidence-based decision-making, and enhancing stakeholder engagement and motivation. However, successful implementation would require careful planning, communication, and change management efforts to overcome cultural barriers and ensure buy-in and adoption.

Study limitations

This study has different limitations. The findings of a study conducted in public higher education in China context may not be easily generalizable to other contexts or countries. The collaborative innovation system in public higher education can vary significantly across regions, institutions, and countries due to differences in resources, infrastructure, policies, and cultural factors. Future research should aim to include a diverse range of institutions and contexts to enhance the external validity of the findings. The next limitation is related to the sampling data; the sample used in the study may not fully represent the diversity of public higher education institutions or the stakeholders involved in collaborative innovation. This can limit the generalizability of the findings and may introduce biases in the results. Future studies could consider using mixed methods approaches and leveraging multiple data sources to enhance the validity and reliability of the findings. The availability of relevant and reliable data for studying collaborative innovation systems in public higher education can be a challenge. Data may be limited or difficult to access, especially when studying emerging phenomena in the Era of Industry 4.0. Researchers may need to rely on self-reported data or qualitative approaches, which can have limitations in terms of

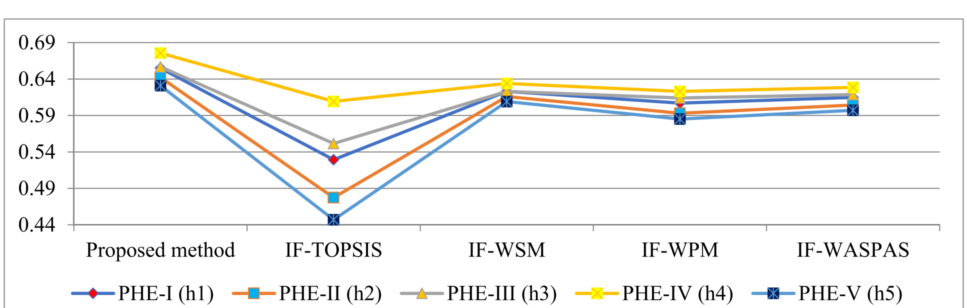


Fig. 3. Variation of CUFs/UDs of options with the different methods

accuracy and objectivity. Another limitation was related to data collection, for conducting a comprehensive study on collaborative innovation systems in public higher education requires significant time and resources. Researchers may face limitations in terms of time available for data collection, analysis, and the long-term observation of the outcomes of collaborative innovation initiatives. In addition, collaborative innovation systems involve multiple stakeholders, such as universities, industry partners, government agencies, and students. Future research should include a wide range of stakeholders and employ participatory research methods to understand their experiences and viewpoints comprehensively. Moreover, understanding and analyzing the complex dynamics, interactions, and interdependencies among these stakeholders can be challenging. It may require interdisciplinary approaches and collaboration between researchers from different fields. Industry 4.0 is a rapidly evolving phenomenon, and the landscape of collaborative innovation in higher education is continuously changing. Research findings may become outdated quickly as new technologies, practices, and policies emerge. Longitudinal studies or ongoing field monitoring may be necessary to capture the dynamic nature of the collaborative innovation system. Therefore, by addressing these limitations and pursuing future recommendations, researchers can contribute to a more comprehensive understanding of collaborative innovation systems in public higher education in the Era of Industry 4.0 and support the development of effective policies and practices in this domain.

Acknowledgement

This work was supported by the Teaching Reform Rroject of Undergraduate Higher Education in Jilin Province managed by the Department of Education of Jilin Province in 2020. The project involves the reform and practical research of Ideological and political courses in Applied Undergraduate Colleges under the background of new liberal arts. (Project Certificate No.: 2020285M98P009B)

References

Adel, Heba Mohamed, Zeinhom, Ghada Aly, & Younis, Raghda Abulsaoud Ahmed (2021). From university social-responsibility to social-innovation strategy for quality accreditation and sustainable competitive advantage during COVID-19 pandemic. *Journal of Humanities and Applied Social Sciences, 4*(5), 410–437.

Adomako, Samuel, & Tran, Mai Dong (2022). Environmental collaboration, responsible innovation, and firm performance: The moderating role of stakeholder pressure. *Business Strategy and the Environment, 31*(4), 1695–1704.

Andersen, Simon Calmar, & Jakobsen, Mads Leth (2018). Political Pressure, Conformity Pressure, and Performance Information as Drivers of Public Sector Innovation Adoption. *International Public Management Journal, 21*(2), 213–242.

Atanassov, Krassimir T (1986). Intuitionistic fuzzy sets. *Fuzzy sets and Systems, 20*(1), 87–96.

Audretsch, David B., & Belitski, Maksim (2020). The Limits to Collaboration Across Four of the Most Innovative UK Industries. *British Journal of Management, 31*(4), 830–855.

Audretsch, David B., & Belitski, Maksim (2022). A strategic alignment framework for the entrepreneurial university. *Industry and Innovation, 29*(2), 285–309.

Bekkers, Victor, & Tummers, Lars (2018). Innovation in the public sector: Towards an open and collaborative approach. *International Review of Administrative Sciences, 84*(2), 209–213.

Bernier, Luc, Hafsi, Taïeb, & Deschamps, Carl (2015). Environmental Determinants of Public Sector Innovation: A study of innovation awards in Canada. *Public Management Review, 17*(6), 834–856.

Blanken, Mariëlle, Mathijssen, Jolanda, van Nieuwenhuizen, Chijs, Raab, Jörg, & van Oers, Hans (2022). Cross-sectoral collaboration: comparing complex child service delivery systems. *Journal of Health Organization and Management, 36*(9), 79–94.

Bommert, Ben (2010). Collaborative innovation in the public sector. *International public management review, 11*(1), 15–33.

Boon, Jan, & Verhoest, Koen (2018). On the Dynamics of Reform Resistance: Why and How Bureaucratic Organizations Resist Shared Service Center Reforms. *International Public Management Journal, 21*(4), 533–557.

Bougrain, Frédéric, & Haudeville, Bernard (2002). Innovation, collaboration and SMEs internal research capacities. *Research Policy, 31*(5), 735–747.

Brown, Jill P. (2015). Complexities of digital technology use and the teaching and learning of function. *Computers & Education, 87*, 112–122.

Chang, Victor, & Wills, Gary (2013). *A university of Greenwich case study of cloud computing: education as a service. E-Logistics and E-Supply Chain Management: applications for evolving business*. (pp. 232−253). IGI Global.

Cooke, N. J., & Hilton, M. L. (2015). *Enhancing the effectiveness of team science*. Washington, DC: e National Academies Press.

Crosby, Barbara C., & Bryson, John M. (2010). Integrative leadership and the creation and maintenance of cross-sector collaborations. *The Leadership Quarterly, 21*(2), 211–230.

Damanpour, Fariborz (1991). Organizational Innovation: A Meta-Analysis of Effects of Determinants and Moderators. *The Academy of Management Journal, 34*(3), 555–590.

Demircioglu, Mehmet Akif, & Audretsch, David B (2019). Public sector innovation: the effect of universities. *The Journal of Technology Transfer, 44*(2), 596–614.

Demircioglu, Mehmet Akif, & Audretsch, David B (2020). Conditions for complex innovations: evidence from public organizations. *The Journal of Technology Transfer, 45*(3), 820–843.

Dente, Bruno, Bobbio, Luigi, & Spada, Alessandra. (2005). Government or Governance of Urban Innovation? *disP - The Planning Review, 41*(162), 41–52.

Diamond, Janet, & Vangen, Siv (2017). Coping with austerity: innovation via collaboration or retreat to the known? *Public Money & Management, 37*(1), 47–54.

Dias, Alexandre, & Selan, Beatriz (2022). How does university-industry collaboration relate to research resources and technical-scientific activities? An analysis at the laboratory level. *The Journal of Technology Transfer*.

Downs Anthony. Inside bureaucracy. 1967.

Elston, Thomas, MacCarthaigh, Muiris, & Verhoest, Koen (2018). Collaborative cost-cutting: productive efficiency as an interdependency between public organizations. *Public Management Review, 20*(12), 1815–1835.

Emerson, Kirk, Nabatchi, Tina, & Balogh, Stephen (2011). An Integrative Framework for Collaborative Governance. *Journal of Public Administration Research and Theory, 22*(1), 1–29.

Etzkowitz, Henry, & Leydesdorff, Loet (2000). The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university−industry−government relations. *Research Policy, 29*(2), 109–123.

Evan, Tomáš, & Holý, Vladimír (2021). Economic conditions for innovation: Private vs. public sector. *Socio-Economic Planning Sciences, 76*, 100966.

Fallis, Don (2006). The Epistemic Costs and Benefits of Collaboration. *The Southern Journal of Philosophy, 44*(S1), 197–208.

Forum WE. The future of jobs report 2018

Forum World Economic. The future of jobs report 2020

Galbraith, Jay R (1974). Organization Design: An Information Processing View. *INFORMS Journal on Applied Analytics, 4*(3), 28–36.

Gulati, Ranjay, Wohlgezogen, Franz, & Zhelyazkov, Pavel (2012). The Two Facets of Collaboration: Cooperation and Coordination in Strategic Alliances. *The Academy of Management Annals, 6*(1), 531–583.

Hale, Kathleen (2011). *How information matters: Networks and public policy innovation*. Georgetown University Press.

Hartley, Jean (2013). *Public and private features of innovation. Handbook of innovation in public services*. Edward Elgar Publishing.

Hartley, Jean, Sørensen, Eva, & Torfing, Jacob (2013). Collaborative Innovation: A Viable Alternative to Market Competition and Organizational Entrepreneurship. *Public Administration Review, 73*(6), 821–830.

Hetemi, Ermal, Ordieres, Joaquin, & Nuur, Cali (2022). Inter-organisational collaboration and knowledge-work: a contingency framework and evidence from a mega-project in Spain. *Knowledge Management Research & Practice, 20*(4), 641–653.

Huang, Jun Song (2014). Building Research Collaboration Networks—An Interpersonal Perspective for Research Capacity Building. *Journal of Research Administration, 45*(2), 89–112.

jiemin, Huang, & chen, Wen (2022). The impact of private sector energy investment, innovation and energy consumption on China's carbon emissions. *Renewable Energy, 195*, 1291–1299.

Jongbloed, Ben, Enders, Jürgen, & Salerno, Carlo (2008). Higher education and its communities: Interconnections, interdependencies and a research agenda. *Higher Education, 56*(3), 303–324.

Kanski, Lukasz, & Pizon, Jakub (2023). The impact of selected components of industry 4.0 on project management. *Journal of Innovation & Knowledge, 8*,(1) 100336.

Katz, J. Sylvan, & Martin, Ben R (1997). What is research collaboration? *Research Policy, 26*(1), 1–18.

Ketchen, David J., Jr., Ireland, R. Duane, & Snow, Charles C (2007). Strategic entrepreneurship, collaborative innovation, and wealth creation. *Strategic Entrepreneurship Journal, 1*(3-4), 371–385.

Kezar, Adrianna (2005). Redesigning for Collaboration within Higher Education Institutions: An Exploration into the Developmental Process. *Research in Higher Education, 46*(7), 831–860.

Klara, Kristina, Hou, Ning, Lawman, Allison, & Wang, Li-Qiong (2013). Developing and Implementing a Collaborative Teaching Innovation in Introductory Chemistry from the Perspective of an Undergraduate Student. *Journal of Chemical Education, 90*(4), 401–404.

Lamprini, Kolovou, & Brochler, Raimund (2018). How Collaborative Innovation and Technology in Educational Ecosystem Can Meet the Challenges Raised by the 4 th Industrial Revolution. *World Technopolis Review, 7*(1), 2–14.

Lewis, Jenny M., Ricard, Lykke Margot, & Klijn, Erik Hans (2017). How innovation drivers, networking and leadership shape public sector innovation capacity. *International Review of Administrative Sciences, 84*(2), 288–307.

Lewis, Jenny M., Ross, Sandy, & Holden, Thomas (2012). The how and why of academic collaboration: disciplinary differences and policy implications. *Higher Education, 64*(5), 693–708.

Li, Ying, Wang, Yating, Wang, Lei, & Xie, Jingci (2022). Investigating the effects of stakeholder collaboration strategies on risk prevention performance in a digital innovation ecosystem. *Industrial Management & Data Systems, 122*(9), 2045–2071.
Lopes, André Vaz, & Farias, Josivania Silva (2020). How can governance support collaborative innovation in the public sector? A systematic review of the literature. *International Review of Administrative Sciences, 88*(1), 114–130.
Martínez-Costa, Micaela, Jiménez-Jiménez, Daniel, & Dine, Rabeh Hammady Ahmed (2019). The effect of organisational learning on interorganisational collaborations in innovation: an empirical study in SMEs. *Knowledge Management Research & Practice, 17*(2), 137–150.
Mazzucato, Mariana (2011). The entrepreneurial state. *Soundings, 49*(49), 131–142.
Miller Jennifer, M. (2016). International inter-sectoral collaboration in university research centres: innovation systems in the United States and beyond in comparative perspective. *Asia Pacific Journal of Public Administration, 38*(4), 239–250.
Miller, Kristel, McAdam, Rodney, & McAdam, Maura (2018). A systematic literature review of university technology transfer from a quadruple helix perspective: toward a research agenda. *R&D Management, 48*(1), 7–24.
Mooney, James D (1954). *The principles of organization*. (p. 1954). Horper and Publisher.
Morawska-Jancelewicz, Joanna (2022). The Role of Universities in Social Innovation Within Quadruple/Quintuple Helix Model: Practical Implications from Polish Experience. *Journal of the Knowledge Economy, 13*(3), 2230–2271.
Mu, Rui, & Wang, Huanming (2022). A systematic literature review of open innovation in the public sector: comparing barriers and governance strategies of digital and non-digital open innovation. *Public Management Review, 24*(4), 489–511.
Newman, Janet, Raine, John, & Skelcher, Chris (2001). Developments: Transforming Local Government: Innovation and Modernization. *Public Money & Management, 21*(2), 61–68.
Nohrstedt, Daniel, Bynander, Fredrik, Parker, Charles, & 't Hart, Paul (2018). Managing Crises Collaboratively: Prospects and Problems—A Systematic Literature Review. *Perspectives on Public Management and Governance, 1*(4), 257–271.
O'Toole, Laurence J., Jr. (1997). Treating Networks Seriously: Practical and Research-based. *Agendas in Public Administration, 57*(1).
Osborne, Stephen P., & Brown, Louise (2011). Innovation, public policy and public services delivery in the UK. The word that would be king? *Public Administration, 89*(4), 1335–1350.
Papa, Armando, Dezi, Luca, Gregori, Gian Luca, Mueller, Jens, & Miglietta, Nicola (2020). Improving innovation performance through knowledge acquisition: the moderating role of employee retention and human resource management practices. *Journal of Knowledge Management, 24*(3), 589–605.
Powell Walter W, Grodal Stine. Networks of innovators. The Oxford handbook of innovation, 2005.
Roberts, Nancy C, & King, Paula J (1996). *Transforming public policy: Dynamics of policy entrepreneurship and innovation*. Jossey-Bass.
Saini, Charu, & Abraham, Jessy (2019). Implementing Facebook-based instructional approach in pre-service teacher education: An empirical investigation. *Computers & Education, 128*, 243–255.
Seo, Inhee, Kim, Yonghee, & Choi, Jeongil (2018). Assessment of efficiency in public service − focused on Government 3.0 case in Korea. *Total Quality Management & Business Excellence, 29*(9-10), 1161–1184.
Steelman, Toddi A (2010). *Implementing innovation: fostering enduring change in environmental and natural resource governance*. Georgetown University Press.
Terjesen, Siri, & Patel, Pankaj C (2015). In Search of Process Innovations: The Role of Search Depth, Search Breadth, and the Industry Environment. *Journal of Management, 43*(5), 1421–1446.
Tight, Malcolm (2014). Discipline and theory in higher education research. *Research Papers in Education, 29*(1), 93–110.
Torfing, Jacob (2019). Collaborative innovation in the public sector: the argument. *Public Management Review, 21*(1), 1–11.
Torfing, Jacob, & Ansell, Christopher (2014). *Collaboration and design: new tools for public innovation. Public innovation through collaboration and design*. (pp. 1−18). Routledge.
Torfing Jacob, Krogh Andreas Hagedorn, Ejrnæs Anders. Samarbejdsdrevet innovation i kriminalpræventive indsatser: Slutrapport om sammenhængene mellem samarbejde, innovation og kriminalpræventiv effekt og måling heraf. 2017.
Torfing, Jacob, & Triantafillou, Peter (2016). *Enhancing public innovation by transforming public governance*. Cambridge University Press.
Tseng, Fan-Chuan, Huang, Mu-Hsuan, & Chen, Dar-Zen (2020). Factors of university −industry collaboration affecting university innovation performance. *The Journal of Technology Transfer, 45*(2), 560–577.
Tymon, Alex (2013). The student perspective on employability. *Studies in Higher Education, 38*(6), 841–856.
van der Voet, Joris, & Steijn, Bram (2021). Team innovation through collaboration: how visionary leadership spurs innovation via team cohesion. *Public Management Review, 23*(9), 1275–1294.
Waardenburg, Maurits, Groenleer, Martijn, de Jong Jorrit, & Keijser, Bas (2020). Paradoxes of collaborative governance: investigating the real-life dynamics of multi-agency collaborations using a quasi-experimental action-research approach. *Public Management Review, 22*(3), 386–407.
Walsh, John P., Lee, You-Na, & Nagaoka, Sadao (2016). Openness and innovation in the US: Collaboration form, idea generation and implementation. *Research Policy, 45*(8), 1660–1671.
Wang, Manman, Chen, Menghan, & Yang, Feng (2022). The optimal subsidy scheme and technology innovation strategy considering consumers' green premium. *Asia Pacific Journal of Marketing and Logistics, 34*(8), 1573–1595.
Wegrich, Kai (2019). The blind spots of collaborative innovation. *Public Management Review, 21*(1), 12–20.
Wong, Chee Yew, Boon-itt, Sakun, & Wong, Christina W. Y. (2021). The contingency effects of internal and external collaboration on the performance effects of green practices. *Resources, Conservation and Recycling, 167*, 105383.
Xu, Z. (2007). Methods for aggregating interval-valued intuitionistic fuzzy information and their application to decision making. *Control and decision, 22*(2), 215.