



Framework for Assessing Development Quality of the Digital Rural Economy Under Uncertainty

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ABSTRACT

The evaluation of development quality in the digital rural agricultural economy, against the background of rural revitalization, is a multiple-attribute decision-making (MADM) problem. This study first presents the fundamental operational rules of interval-valued intuitionistic fuzzy sets (IVIFSs), including the Hamacher sum and Hamacher product operations. On this basis, an induced interval-valued intuitionistic fuzzy Hamacher interactive hybrid weighted averaging (I-IVIFHIHWA) operator is proposed, which integrates the advantages of the interval-valued intuitionistic fuzzy Hamacher interactive hybrid weighted averaging operator and the induced ordered weighted averaging operator. Several desirable properties of the I-IVIFHIHWA operator are also investigated. Subsequently, the proposed operator is applied to solve MADM problems within the IVIFS framework. Finally, a practical case concerning the development quality assessment of the digital rural agricultural economy under rural revitalization is presented to verify the validity of the operator.

KEYWORDS

Multiple-Attribute Decision-Making (MADM), Interval-Valued Intuitionistic Fuzzy Sets (IVIFSs), I-IVIFHIHWA Operator, Development Quality Evaluation

INTRODUCTION

Compared with cities, the digital development of rural areas started relatively late and has been constrained by underdeveloped infrastructure. Economic and cultural disparities have led to rural residents' insufficient overall understanding of digital villages, resulting in inadequate and ineffective use of resources, with some even lying idle (Cha et al., 2025; Ding et al., 2025). Although cities possess abundant resources, institutional differences between urban and rural areas prevent many high-quality resources and development plans from being directly transferred to rural regions. Furthermore, the significant urban-rural gap has left many rural areas lacking corresponding infrastructure (D. M. Zhang et al., 2024; Zheng, 2024; Zhu et al., 2024). These issues have further widened the digital development divide between urban and rural areas, thereby restricting the progress of digital village construction.

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In the process of building digital villages, it is essential to further promote the modernization of agriculture and rural areas, establish a modern agricultural production and operation system, and enhance agricultural production efficiency. However, current rural industries remain overly simplistic and predominantly rely on traditional agriculture with a low level of development. Traditional agriculture is highly susceptible to natural environmental factors and lacks the capacity to promptly predict and prevent certain disasters, making it difficult to improve production efficiency and economic benefits. Additionally, most rural areas are characterized by small-scale production and low product quality, as well as the unscientific use of fertilizers and pesticides, resulting in products that fail to meet social demands (Tao et al., 2024; Wang et al., 2024; Wen et al., 2024; Xu, 2024). The inadequate application of digital technologies in production and operation, together with poor integration between rural industries and digital technologies, has hindered the process of rural digitalization.

The in-depth integration of digital empowerment with agriculture and rural areas has emerged as a new driving force for economic growth. It facilitates the development of new formats and models, advances industrial and economic digitalization, and unleashes the amplifying, superimposing, and multiplying effects of digital empowerment on China's agricultural economic development. This integration promotes transformations in the efficiency and driving forces of China's agricultural economic development, narrows the urban-rural digital divide, and provides valuable development experience for building a digital China (Ahmad et al., 2024; Hu et al., 2024; Liu et al., 2024; Miao et al., 2024; Zhai et al., 2023).

Multiple-attribute decision-making (MADM) is a core approach in decision science for addressing complex choices involving conflicting, heterogeneous criteria (Fang & Huang, 2026; Lien et al., 2026; Zhang & Wei, 2023; Zhang et al., 2022b; M. Zhou et al., 2025; Y. J. Zhou et al., 2025). It systematically evaluates alternative options by integrating performance data across multiple dimensions, often navigating uncertainty or imprecision in real-world scenarios, such as resource allocation, policy assessment, or quality evaluation (Chen et al., 2023; Ning et al., 2022; Zhang et al., 2022a; Zhao et al., 2022). MADM's strength lies in structuring vague or multifaceted problems, leveraging mathematical models and weighting mechanisms to derive rational, defensible conclusions (Chen et al., 2023; Liao et al., 2023; Ning et al., 2022; Zhang et al., 2023; Zhang & Wei, 2023). Widely applied in engineering, management, and policy-making, it bridges theoretical rigor with practical utility, helping decision-makers balance trade-offs and select optimal solutions amid competing demands (Miao, 2025; Mohammed et al., 2025; Rashid et al., 2025; Sun et al., 2025).

Confronted with the inherent limitations of traditional precise mathematical theories—particularly their inability to adequately capture and model ambiguous or imprecise information in real-world scenarios—Zadeh (1965) revolutionized the field by introducing the theory of fuzzy sets. This pioneering work laid the groundwork for handling uncertainty, but subsequent advancements sought to refine its expressive power: Atanassov (1986) expanded upon fuzzy sets by proposing intuitionistic fuzzy sets, which integrate both membership and non-membership degrees to more accurately depict vague concepts. Building on this progress, Atanassov and Gargov (1989) further enhanced the framework with interval-valued intuitionistic fuzzy sets (IVIFSs), allowing membership and non-membership values to be defined as intervals rather than fixed numbers, thereby improving adaptability to complex decision-making environments.

Notably, despite the widespread application of these fuzzy set extensions in MADM, a critical research gap persists: To date, no studies have leveraged the interactive Hamacher method to develop an MADM model specifically tailored for evaluating the development quality of the digital rural agricultural economy within the context of rural revitalization. This gap is significant, as the digital transformation of rural agriculture involves multifaceted, uncertain attributes that demand robust uncertainty-handling tools.

To address this limitation, the present study extends the interactive Hamacher method (Garg et al., 2017) and introduces the induced interval-valued intuitionistic fuzzy Hamacher interactive hybrid weighted averaging (I-IVIFHIHWA) operator. The operator is developed by combining the

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