Mathematical Problems in Engineering

Application of Operations Research Tools for Solving Sustainable Engineering Problems

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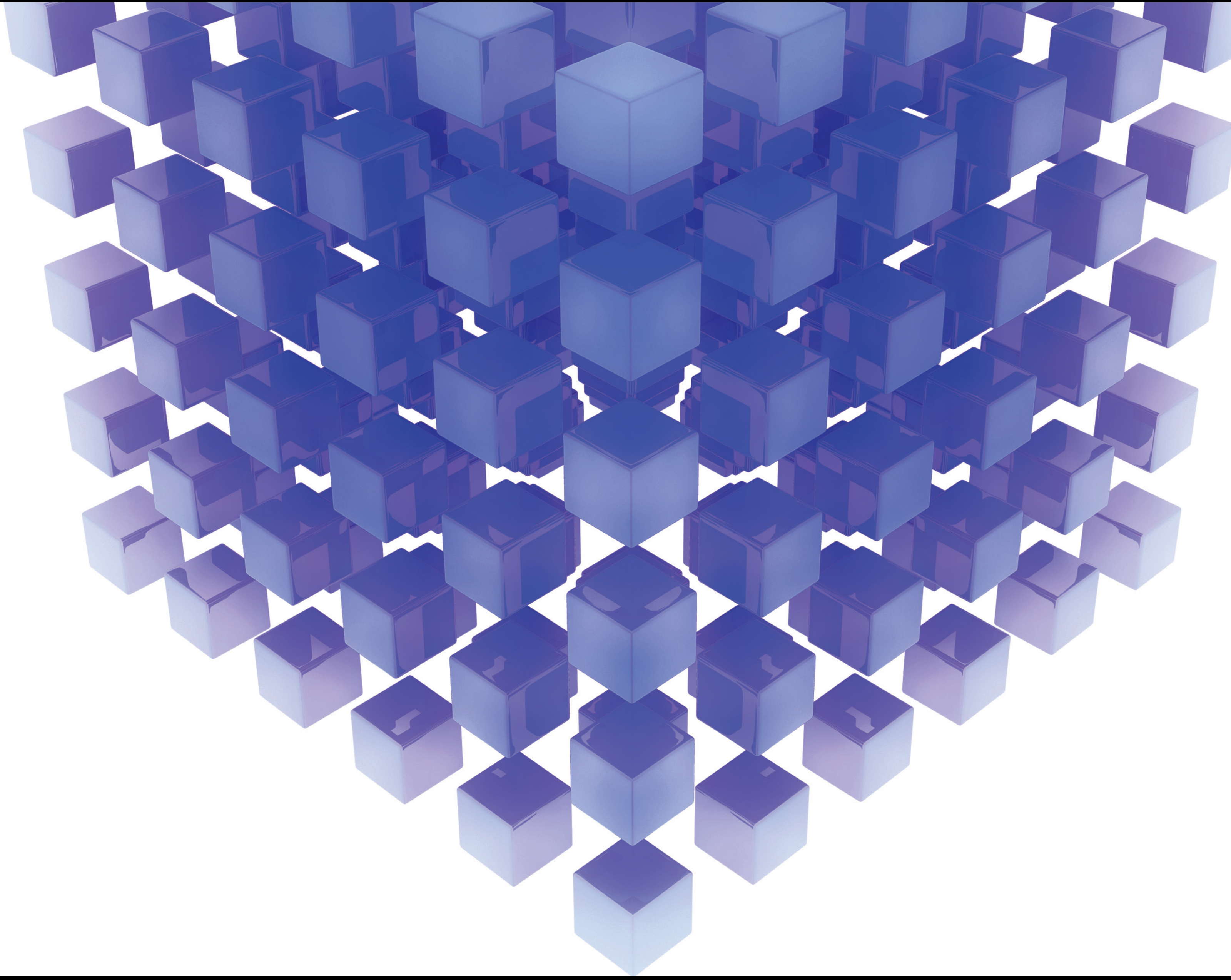
Guest Editors: Snežana Tadić, Prasenjit Chatterjee, and Violeta Roso



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Research Article

Research on Evolutionary Game of Collaborative Innovation in Supply Chain under Digitization Background

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The development of digital technology has been rapidly pushing forward collaborative innovation in supply chain. This paper analyzes the influence mechanism of information sharing, resource integration, and trustworthiness among the enterprises in supply chain to collaborative innovation under the digitization background and builds the model of dynamic evolutionary game in which enterprises in supply chain participate collaborative innovation, and then, through the methods of model solution analysis and numerical simulation the following concrete conclusions are reached: the increase of data sharing profit coefficient, resource integration coefficient, and trustworthiness causes the increase of the probability that an enterprise selects to participate collaborative innovation in supply chain, and the increase of data sharing cost, security risk coefficient, and free rider income causes the decrease of the probability that an enterprise selects to participate collaborative innovation in supply chain; meanwhile, the increase of all the coefficients makes the velocity with which decision-making approaches to the direction toward decision higher and higher, and when the core enterprises participate the game, they can drive the common enterprises make decision more rapidly; and for the probability that an enterprise selects to participate collaborative innovation in supply chain, data sharing profit coefficient, data sharing cost coefficient, security risk coefficient, and free rider income have threshold values. These conclusions play active roles in leading enterprises to attach importance to digitization construction and actively participate collaborative innovation in supply chain.

1. Introduction

In the wake of disseminating and applying the digital technologies of big data, cloud computing, and artificial intelligence, the modern society has been entering the digitization era [1]. The digital technology changed the basic form of existing products, the mode of new products' manufacturing procedure, and the business model and organization form, what is more, overturned the basic hypotheses of many innovation theories [2]. The digitization innovation of supply chain management has become an important way for enterprises improving competitive advantage [3].

More and more enterprises have recognized the significance of collaborative innovation in supply chain under the digitization background. For instance, by using of technology energization, JD launched the Kepler project to promote data sharing and improve the collaborative ability among the cooperative partners. Through the supply chain system driven by data, Handu Group integrated resources of many small enterprises and with group system realized the high-level collaboration and cooperation. By means of various integrative digital technologies, Tader Coal built a sharing system for the coal supply chain service so as to enhance mutual trust and promote coal trade. With the help of digital technology, all of these enterprises realized the successful transition and collaboration innovation of enterprises by means of information sharing, resource integration, and enhancing trustworthiness. Also, there are a number of famous successful enterprises such as Boeing, Ford, Huawei, and Haier that hold overwhelming leads in the innovation field by reason of the active practice of collaboration innovation together with both upstream and downstream enterprises [4, 5].

Scholars have done much research on supply chain collaboration, but there are not many literature works on supply chain collaboration innovation. Since 1990s, scholars and practitioners have been energetically pushing forward collaboration under the background of supply chain [6] and exploring the subjects of the concept of collaboration on supply chain [7–9], the concrete action of collaboration [10], influence factors of collaboration [11, 12], the game between upstream and downstream in the process of collaboration [13], and so on. Because the collaboration innovation is driven by the developments of the integration of industry and technology [14], the demand of wide-ranging stakeholder's making value, attraction for new market and consumer group, and response to new business model, scholars began new exploration around collaboration innovation in supply chain [15]. At present, scholars have relatively studied the relationship between data sharing and supply chain collaborative innovation, but few in resource integration and trust. The development in information technology has promoted the communication and real-time sharing of information among the members of supply chain [16], data sharing can significantly influence the performance of supply chain, and sharing future order information with the supplier is more beneficial than sharing only the future demand information, thus the cooperative partners in supply chain share the information of prediction and production plan, and the well coordination of business activities among enterprises is realized [17]; therefore, the collaboration innovation promotes the improvement of enterprises' performance in many aspects [18, 19]. In recent years, the scholars have been carrying on the research centered on the collaboration in the pull supply chain [20], the collaboration in supply chain in the big data era [21], the collaboration in supply chain under the new retail background [9], and so on. As the innovation process itself could be influenced by digitization, scholars hold that the accepted innovation theories are no longer suitable in use [2, 22, 23] and under the background of digitization it is necessary to find a new innovation theory. There are some scholars who study the supply chain by the game theory. The relationships between sellers and buyers have been modeled by non-cooperative and cooperative games [24]. Evolutionary dynamics has been adopted extensively to locate the optimal and the most stable point offering the best economic gains in the analysis of green supply chain contracts between the producer and the retailer [25]. There is a study that investigates the games between governments and core enterprises in greening supply chains, and this article analyzes their respective costs and benefits and studies the evolutionary game model. Game analysis shows that core enterprises' costs and benefits to implement green supply chain management as well as subsidies and penalties from governments directly affect the game results [26]. However, the evolutionary game method has not been used in the collaborative innovation of supply chain, and it has not been studied in combination with the current digital background.

Combining with the background of digitization era, this paper researches the effects of information sharing, resource integration, and trustworthiness by digital empowerment on collaboration innovation in supply chain. In consideration of the characteristics of the complexity and dynamics in supply chain, the method of evolutionary game is applied to research the question of system innovation in supply chain. In the part of numerical simulation, when verifying respectively the effect of the coefficients such as data sharing profit coefficient, resource integration, and trustworthiness, we considered whether the core enterprises' participation can produce different results of collaboration innovation.

The structure arrangement of this paper is as follows: the first part is introduction; the second part is to analyze the mechanism of collaboration innovation in supply chain under the digitization background; the third part puts forward the basic hypotheses and a evolutionary game theory model; the fourth part is to analyze the model's strategic stability; then, we start numerical simulation to verify the statements; and last, we write the research conclusion and enlightenment.

2. Analysis of the Effect Mechanism of Collaboration Innovation in Supply Chain under the Digitization Background

Whether the two companies in the supply chain collaborate to innovate is a game process. We take a total Internet group of supply chain as a natural system, which is divided into two subgroups randomly, and from each subgroup, we select randomly an enterprise to make them pair up with each other for playing the game several times. Each side of the game selects the decision to participate collaboration innovation or selects the decision not to participate collaboration innovation in supply chain. Based on the hypothesis of bounded rational man, both sides always search for the optimum strategy on the balance of income and cost.

The collaboration innovation of enterprises pursues full information sharing, mutual trustworthiness, and the realization of benefit claim [27]. Firstly, collaboration innovation in supply chain is based on information sharing. Information sharing refers to the sharing of private information owned by each participant in the supply chain. Information sharing energizes enterprises to carry on collaboration innovation in the three aspects of data sharing, technology sharing, and knowledge sharing [28]. The sharing of data, resource, and technology has great influence on the realization of product innovation by collaboration in supply chain [29]. Information sharing cannot be carried out without the support of data resource since data technology causes the progressive and disruptive innovation for collaboration in supply chain [30], and data sharing is the key factor in the realization of collaboration in supply chain, which can improve the performance of collaboration innovation in supply chain [31]. The knowledge sharing is processed in a deep level on the basis of data and technology and shapes into the sharing form for direct use easily, so as to energize enterprises with high efficiency for realization of collaboration innovation [32]. The income quantity depends on the ability of turning information into income and the quantity of shared information, i.e., the greater the quantity of shared information, the more beneficial to enterprises obtaining more comprehensive information and improving the acuity of supply chain [33], and then improving the income of supply chain. The two-way information flow is of benefit to the improvement of the performance in collaboration innovation [34]. In the context of digitalization, the most obvious manifestation is that data expand the information sharing from all aspects than that develop in the information age, so data sharing is more suitable for the current development environment than information sharing. Therefore, the income coefficient of data sharing can be introduced to express an enterprise's ability of turning data into income. Meanwhile, data sharing needs to pay cost, so the cost has become an important factor in restricting the data sharing among enterprises. The core enterprises play leading and overall planning roles that make supply chain run with high efficiency, so that the channel cost and time cost produced in the process of data sharing can be reduced [35]. Besides, data leakage in the process of data sharing caused by the poor work of information protection makes the collaborative side take the security risk of being imitated and copied and then makes the income of innovation decreased [34], and therefore, it is necessary to analyze the influence of security risk during collaborative innovation in supply chain.

Secondly, collaboration innovation in supply chain always manifests itself as a process of resource integration. Resource integration is mainly to integrate the resources owned by each participant in the supply chain in order to achieve high efficiency. Resource integration can produce the resource beaming effect, that is, the efficiency of using a large number of resources integrated is higher than the efficiency of using a kind of resource alone [36]. For the similar resources, the scale economy is applied for reducing cost and increasing income; for the complementary resources, the scope economy is applied for raising collaboration income as well as giving full play to the resource collaboration effect [37], briefly, both of them can likewise lead to success [38]. The digital resource collaboration among enterprises is of benefit to the integration of all existing logistics resources and customer resources of cooperation partners in the supply chain [39], who improve the efficiency of supply chain through standardization construction, centralized purchase, and supplier management [40, 41], as well as gain continuous income through the integration of the relationship between suppliers and customers [42]. The ability of resource integration is indicated with resource integration coefficient, so it can be found that the bigger the coefficient is, the higher the collaborative innovation income gains, and when the core enterprises exist, their resource integration ability is stronger than that of common enterprises.

Finally, as a main factor [43] that restricts cooperation intensity, trustworthiness is the core of cooperation innovation ability [44]. The higher is the degree of reciprocity and the stronger is the relationship among partners in the supply chain, the higher is the mutual trustworthiness. Digitization improves the degree of open and transparence of information and relieves the pressure of information asymmetry, as a result, enterprises obtain more smooth communication than before through explaining energization [45]. It is important to communicate in time for resolution of disputes and reach an identical opinion, and it is beneficial to the common strategy decision and collaborative innovation among enterprises, also, in the aspect of enterprise cost input, the improvement is achieved [46]. The direct and efficient communication can enhance the exchange efficiency [47], and the produced trustworthiness can increase the collaborative innovation performance [46]. Among enterprises, the higher is the trustworthiness, the higher is the desire for sharing information; what is more, in order to overcome the obstacle of information communication system, enterprises may invest again to reform their inner information system [48].

3. Basic Hypothesis and Modeling

3.1. Basic Hypothesis

Hypothesis 1. In a certain supply chain, we take an enterprise as a natural system and divide it into group 1 and group 2. Each group has several enterprises and all of them are bounded rationality. Every enterprise can have two decisions, i.e., selecting to participate or not to participate collaboration innovation in supply chain, so the strategy set of enterprise is {to participate collaboration innovation in supply chain (be simplified as "participation strategy"), not to participate collaboration innovation in supply chain (be simplified as "no participation strategy")}. In the game process, if an enterprise in this round game do not find that the profit of those enterprises participated collaboration innovation in supply chain is lower than the profit of those enterprises not participated collaboration innovation in supply chain, this enterprise will select to participate collaboration innovation in supply chain in the next round of game; in reverse, if the profit of an enterprise who did not participate collaboration innovation in supply chain is higher than the profit of those enterprises participated collaboration innovation in supply chain, still, this enterprise will not select to participate collaboration innovation in supply chain.

Hypothesis 2: When the two enterprises select "participation strategy," the collaboration effect first arises and the basis income R_1^i $(i = A, B)$ is obtained, which is greater than the communication collaboration cost among enterprises. After that, because product innovation and business model innovation bring the enterprises the collaboration innovation income and in the process of collaboration innovation there are influence of the factors of information sharing, trustworthiness, and resource integration, the information quantity P_i $(i = A, B)$, the data sharing profit coefficient α_i $(i = A, B)$, the data sharing cost coefficient β_i $(i = A, B)$, and the security risk coefficient γ_i $(i =$

A, B) are introduced. In the aspect of trustworthiness, the trustworthiness coefficient ε_{AB} is introduced, and we assume that when enterprises totally distrust each other the communication collaboration cost, which should be paid is C_0, obviously, the more is ε_{AB}, the more is the decrease in the amplitude of collaboration cost, and therefore, $1 - \varepsilon_{AB}$ can indicate the decrease proportion of communication cost. In the influence of resource integration, the resource integration ability coefficient δ_i ($i = A, B$) and extra income R_2^i ($i = A, B$) of resource integration are introduced, and we assume that in the process of resource integration the cost of input in the platform or standardization construction is C_1^i ($i = A, B$).

Hypothesis 3: In the game, when one side of enterprises selects the "participation strategy" and the other one selects the "no participation strategy," as for the enterprises not participated, the free rider behavior is inevitable, so we assume that the income from free rider is R_3^i ($i = A, B$). Because the two sides do not reach cooperation, the side that selected to participate cannot obtain collaborative innovation income; in the meantime, we assume that when the two enterprises do not reach cooperation, the equally shared collaboration cost is C_0, that is, the collaboration cost of each enterprise is $(1/2)C_0$ ($R_3^i > (1/2)C_0$).

Hypothesis 4: When the two enterprises select the "no participation strategy," each side of them just obtains existing income R_0^i ($i = A, B$).

Hypothesis 5: The probabilities that the two enterprises A and B select to participate collaborative innovation in supply chain are x and y, and the probabilities that the two enterprises select not to participate collaborative innovation in supply chain are $1-x$ and $1-y$, and $x, y \in [0, 1]$; all of them are the function of time t.

3.2. Evolutionary Game Modeling. According to the strategy selection, the income matrix of 4 kinds of selections is listed in Table 1.

According to the game payoff matrix and evolutionary game theory, when the enterprise A selects the "participation strategy," its income is

$$E_{A1} = y\left(R_0^A + R_1^A - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A\right) + (1-y)\left(R_0^A - \frac{1}{2}C_0\right). \quad (1)$$

When the enterprise A selects the "no participation strategy," its income is

$$E_{A2} = y\left(R_0^A + R_3^A - \frac{1}{2}C_0\right) + (1-y)R_A. \quad (2)$$

So, the average income of enterprise A is

$$\overline{E_A} = xE_{A1} + (1-x)E_{A2}. \quad (3)$$

When the enterprise B selects the "participation strategy," its income is

$$E_{B1} = x\left(R_0^B + R_1^B - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B\right) + (1-x)\left(R_0^B - \frac{1}{2}C_0\right). \quad (4)$$

When the enterprise B selects the "no participation strategy," its income is

$$E_{B2} = x\left(R_0^B + R_3^B - \frac{1}{2}C_0\right) + (1-x)R_B. \quad (5)$$

So, the average income of enterprise B is

$$\overline{E_B} = yE_{B1} + (1-y)E_{B2}. \quad (6)$$

We solve the replicated dynamic equation:

Table 1: Payoff matrix for both sides of the game.

Income		B: Participation (y)	B: No participation $(1-y)$
A	Participation (x)	A: $R_0^A + R_1^A - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A$ B: $R_0^B + R_1^B - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_B(R_2^B - C_1^B) + (\alpha_B - \beta_B - \gamma_B)P_B$	A: $R_0^A - (1/2)C_0$ B: $R_0^B + R_3^B - (1/2)C_0$
	No participation $(1-x)$	A: $R_0^A + R_3^A - (1/2)C_0$ B: $R_0^B - (1/2)C_0$	A: R_0^A B: R_0^B

$$F(x) = \frac{dx}{dt} = x(E_{A1} - \overline{E_A}) = x(1-x)\left[y\left(R_1^A - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0\right) - \frac{1}{2}C_0\right],$$
$$F(y) = \frac{dy}{dt} = y(E_{B1} - \overline{E_B}) = y(1-y)\left[x\left(R_1^B - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B - R_3^B + C_0\right) - \frac{1}{2}C_0\right]. \tag{7}$$

4. Analysis of Evolutionary Game Model

4.1. Analysis of Strategic Stability of the Enterprise A. When $F(x^*) = (dx/dt) = 0$, x^* is the stable point of this replicated dynamic equation. And when $F(x^*) = 0$ and $F'(x^*) < 0$, x^* is the stability strategy of this evolutionary game.

From $F(x) = 0$, we get

$$x^* = 0,$$
$$x^* = 1,$$
$$y^* = \frac{(1/2)C_0}{R_1^A - (1/2)(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0} = \frac{C_0}{2\rho_1}. \tag{8}$$

Here,

$$\rho_1 = R_1^A - \frac{1}{2}(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0. \tag{9}$$

Analyzing $F'(x) = (1-2x)[\rho_1 y - (1/2)C_0]$, we get the following conclusions:

(1) When $\rho_1 < (1/2)C_0$, $F'(x^* = 0) < 0$; therefore, $x^* = 0$ is the stability strategy of enterprise A, i.e., the enterprise A is inclined not to participate innovation in supply chain. The phase graph is shown in Figure 1.

(2) When $\rho_1 > (1/2)C_0$, $y < y^*$, then $F'(x^* = 0) < 0$; therefore, $x^* = 0$ is the evolutionary stability strategy of enterprise A. When $y > y^*$, then $F'(x^* = 1) < 0$; therefore, $x^* = 1$ is the evolutionary stability strategy of enterprise A, i.e., the enterprise A selects to participate innovation in supply chain. The phase graph is shown in Figure 2.

4.2. Analysis of Strategic Stability of the Enterprise B. From $F(y) = 0$, we get

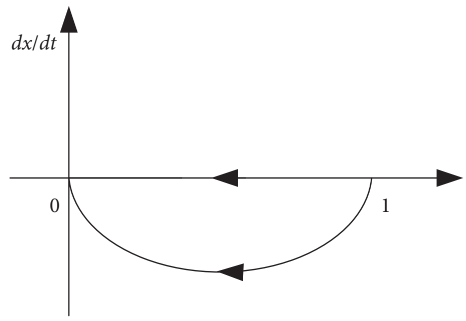

Figure 1: The replicated dynamic phase graph when $\rho_1 < (1/2)C_0$.

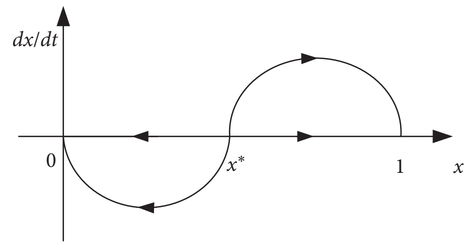

Figure 2: The replicated dynamic phase graph when $\rho_1 > (1/2)C_0$.

$$\begin{aligned} y^* &= 0, \\ y^* &= 1, \\ x^* &= \frac{(1/2)\,C_0}{R_1^B - (1/2)\,(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B - R_3^B + C_0} = \frac{C_0}{2\rho_2}. \end{aligned} \tag{10}$$

Here,

$$\rho_2 = R_1^B - \frac{1}{2}\,(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B - R_3^B + C_0. \tag{11}$$

Analyzing $F'(y) = (1-2y)[\rho_2 x - (1/2)C_0]$, we get the following conclusions:

(1) When $\rho_2 < (1/2)C_0$, $F'(y^* = 0) < 0$; therefore, $y^* = 0$ is the evolutionary stability strategy of enterprise B, i.e., the enterprise B is inclined not to participate innovation in supply chain. The phase graph is shown in Figure 3.

(2) When $\rho_2 > (1/2)C_0$, $x < x^*$, then $F'(y^* = 0) < 0$; therefore, $y^* = 0$ is the evolutionary stability strategy of enterprise B. When $x > x^*$, then $F'(y^* = 1) < 0$; therefore, $y^* = 1$ is the evolutionary stability strategy of enterprise B, i.e., the enterprise B selects to participate innovation in supply chain. The phase graph is shown in Figure 4.

4.3. Analysis of Strategic Stability of Both Sides of Game. Combining $F(x)$ and $F(y)$, compose a dynamic system in which both sides of the enterprise A and the enterprise B play game, i.e., formula (12).

$$\left\{ \begin{aligned} F(x) &= \frac{\mathrm{d}x}{\mathrm{d}t} = x\left(E_{A1} - \overline{E_{aA}}\right) = x(1-x)\left[\rho_1 y - \frac{1}{2}\,C_0\right] \\ F(y) &= \frac{\mathrm{d}y}{\mathrm{d}t} = y\left(E_{B1} - \overline{E_B}\right) = y(1-y)\left[\rho_2 x - \frac{1}{2}C_0\right] \end{aligned} \right\}. \tag{12}$$

Set $F(x) = 0$, $F(y) = 0$, we find equilibrium points $A(0,1), C(1,0), B(1,1), G(x^*, y^*)$, in which

$$\begin{aligned} x^* &= \frac{(1/2)\,C_0}{R_1^B - (1/2)\,(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B - R_3^B + C_0} = \frac{C_0}{2\rho_2}, \\ y^* &= \frac{(1/2)\,C_0}{R_1^A - (1/2)\,(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0} = \frac{C_0}{2\rho_1}. \end{aligned} \tag{13}$$

The Jacobian matrix of this system is

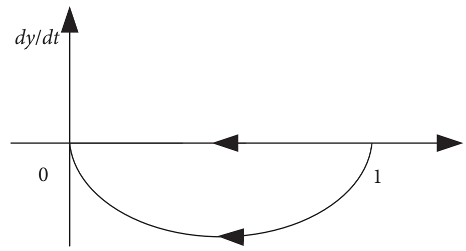

FIGURE 3: The replicated dynamic phase graph when $\rho_2 < (1/2)C_0$.

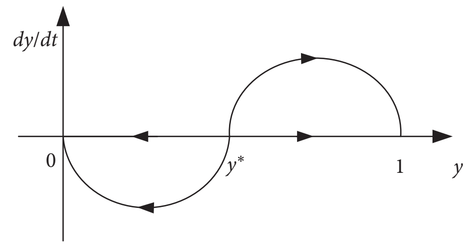

FIGURE 4: The replicated dynamic phase graph when $\rho_2 > (1/2)C_0$.

$$J = \begin{pmatrix} (1-2x)\left[y\rho_1 - \frac{1}{2}C_0\right] & x(1-x)\rho_1 \\ y(1-y)\rho_2 & (1-2y)\left[x\rho_2 - \frac{1}{2}C_0\right] \end{pmatrix}. \tag{14}$$

The determinant of Jacobian matrix is

$$\begin{aligned} \operatorname{Det} J = {} & (1-2x)\left[\rho_1 y - \frac{1}{2}C_0\right](1-2y)\left[\rho_2 x - \frac{1}{2}C_0\right] \\ & - x(1-x)y(1-y)\rho_1\rho_2. \end{aligned} \tag{15}$$

The trace of Jacobian matrix is

$$\operatorname{Tr} J = (1-2x)\left(\rho_1 y - \frac{1}{2}C_0\right) + (1-2y)\left(\rho_2 x - \frac{1}{2}C_0\right). \tag{16}$$

The collaborative innovation income obtained when both enterprises select the "participation strategy" is greater than that obtained when only one enterprise participates, and the income from free rider can be calculated with the expression about ρ_1 (9) and the expression about ρ_2 (11), $\rho_1 > 0$, $\rho_2 > 0$; therefore, the correlation properties of these five equilibrium points can be calculated with expression (15) and expression (16), i.e., the trace of Jacobian matrix, the sign of determinant, and the stability of results are shown in Table 2.

Table 2 shows that among the five equilibrium points, point $O(0,0)$ and point $C(1,1)$ satisfy the condition of $\operatorname{Det} J > 0, \operatorname{Tr} J < 0$. They are evolutionary stable points and correspond, respectively, to the evolutionary game strategy {not to participate collaborative innovation in supply chain, not to participate collaborative innovation in supply chain} and {to participate collaborative innovation in supply chain, to participate collaborative innovation in supply chain}.

TABLE 2: Analysis of stability of local equilibrium points.

Equilibrium points	Det J's Sign	Tr J's Sign	Result
$O(0,0)$	+	−	ESS
$A(0,1)$	+	+	Instability
$B(1,0)$	+	+	Instability
$C(1,1)$	+	−	ESS
$G(x^*, y^*)$	−	0	Saddle point

Point $A(0,1)$ and point $B(1,0)$ are unstable points, $G(x^*, y^*)$ is the critical point, namely the saddle point, and the polygonal line of the three points converge to the evolutionary stable points $O(0,0)$ and $C(1,1)$. Based on the analysis of the stability of evolutionary game, the evolution phase graph of the enterprises in supply chain participating collaborative innovation in supply chain is drawn, which delineates the dynamic evolutionary process, as shown in Figure 5. As for the enterprises in supply chain, whether to select to participate collaborative innovation in supply chain chiefly is dependent upon the comparison between the total gained income and paid cost; therefore, the income and payoff matrix concerning enterprises participating collaborative innovation in supply chain and variation of every coefficient will influence the selection of strategy and finally converge to the corresponding equilibrium point.

The selection of strategy by both sides of game correlates with the area of quadrangle AOBG and quadrangle ACBG. The quadrangle AOBG indicates the probability that both sides select "no participation strategy." The quadrangle AOBG indicates the probability that both sides select "participation strategy," and the sum of the two parties is 1. Let S indicate the area of quadrangle AOBG, and expression (17) shows S. To analyze the factors that influence the variation of area, the evolutionary direction of system can be inferred.

$$\begin{aligned} S &= S_{OGB} + S_{OGA} = \frac{1}{2}\left(x^* + y^*\right) = \frac{1}{2}\left(\frac{C_0}{2\rho_2} + \frac{C_0}{2\rho_1}\right) = \frac{1}{4}\left(\frac{C_0}{\rho_2} + \frac{C_0}{\rho_1}\right) = \\ & \frac{1}{4}\left(\frac{C_0}{R_1^B - (1/2)(1-\varepsilon_{AB})C_0 + \delta_B\left(R_2^B - C_1^B\right) + (\alpha_B - \beta_B - \gamma_B)P_B - R_3^B + C_0} + \frac{C_0}{R_1^A - (1/2)(1-\varepsilon_{AB})C_0 + \delta_A\left(R_2^A - C_1^A\right) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0}\right). \end{aligned} \tag{17}$$

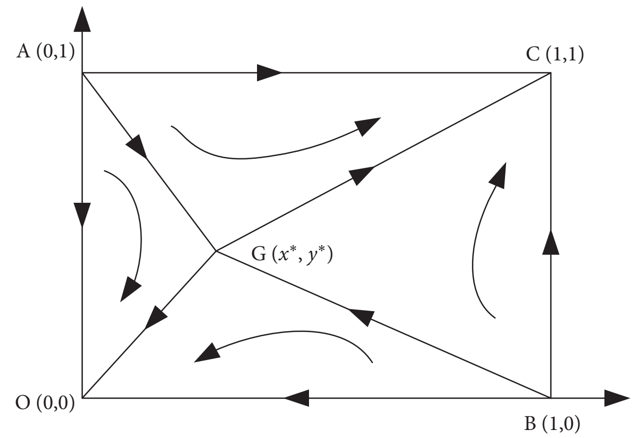

Figure 5: Phase graph of evolutionary game of enterprises participating collaborative innovation in supply chain.

Statement 1. The increase of data sharing profit coefficient improves the probability of an enterprise selecting to participate collaborative innovation in supply chain, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial \alpha_A) = (-P_1 C_0/4(R_1^A - (1/2)(1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)\ P_A - R_3^A + C_0)^2) < 0$, similarly, $(\partial S/\partial \alpha_B) < 0$, it will be found that related to α_i, S appears monotone progressive decrease. It shows that with the increase of the income coefficient of data sharing, the saddle point G moves to point (0, 0), and the system evolves toward (1, 1); the probability of an enterprise selecting "participation strategy" increases, and both sides of game tend to participate collaborative innovation in supply chain at the same time. The bigger is the data sharing profit coefficient, the stronger is the capacity that the shared information generates income; therefore, the increase of the data sharing profit coefficient makes an enterprise gain more income and urges an enterprise to participate collaborative innovation in supply chain.

According to $(\partial^2 S/\partial \alpha_A^2) = (2P_1^2 C_0/4(R_1^A - (1/2)(1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, similarly, $(\partial^2 S/\partial \alpha_B^2) > 0$, it will be found that with the increase of the income coefficient of data sharing, the velocity of an enterprise selecting the final strategy becomes higher and higher. The bigger the data sharing profit coefficient is, the more collaborative innovation income an enterprise gains, and therefore, the time of making decision becomes less, that is, the velocity becomes higher and higher.

Statement 2. The increase of cost coefficient of data sharing makes the probability of an enterprise selecting to participate collaborative innovation in supply chain decrease, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial \beta_A) = (P_1 C_0/4(R_1^A - (1/\ 2)(1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^2) > 0$, similarly, $(\partial S/\partial \beta_B) > 0$, it will be found that related to β_i, S appears monotone progressive increase. It shows that with the increase of the cost coefficient of information sharing, the saddle point G moves to point (1, 1), and the system evolves toward (0, 0); the probability of an enterprise selects "no participation strategy" increases, and both sides of game approach to not participating collaborative innovation in supply chain. The higher is the cost of information sharing, the lower is the desire of an enterprise participating collaborative innovation in supply chain, and if the cost of data sharing of an enterprise is too high, the enterprise will select directly not to participate collaborative innovation in supply chain; therefore, the cost of data sharing hinders the decision of an enterprise participating collaborative innovation in supply chain.

According to $(\partial^2 S/\partial \beta_A^2) = (P_1^2 C_0/2(R_1^A - (1/2)(1-\varepsilon_{AB})C_0 + \delta_A\ (R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, similarly, $(\partial^2 S/\partial \beta_B^2) > 0$, it will be found that with the increase of the cost coefficient of data sharing, the velocity of an enterprise selecting the final strategy becomes higher and higher. The bigger the data sharing cost coefficient is, the more the cost an enterprise must pay; in order to reduce cost investment, the time of making decision should be reduced, that is to say, the velocity becomes higher and higher.

Statement 3. The increase of security risk coefficient makes the probability of an enterprise selecting to participate collaborative innovation in supply chain decrease, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial \gamma_A) = (P_1 C_0/4\ (R_1^A - (1/2)(1-\varepsilon_{AB})\ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^2) > 0$, similarly, $(\partial S/\partial \gamma_B) > 0$, it will be found that related to γ_i, S appears monotone progressive increase. It shows that with the increase of the security risk coefficient, the saddle point G moves to point (1, 1), and the system evolves toward (0, 0); the probability of an enterprise selects "no participation strategy" increases, and both sides of game approach to not to participate collaborative innovation in supply chain. In the process of information sharing, the security risk brings the risk of information leakage to enterprises; therefore, in face of risk an enterprise always shows an evasive state.

According to $(\partial^2 S/\partial \gamma_A^2) = (2P_1^2 C_0/4(R_1^A - (1/2)(1-\varepsilon_{AB})\ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, similarly, $(\partial^2 S/\partial \gamma_B^2) > 0$, it will be found that with the increase of the security risk coefficient, the velocity of an enterprise selecting the final strategy becomes higher and higher. The bigger the security risk coefficient is, the greater the risk an enterprise faces up to, and on this condition, the enterprise will select not to participate more rapidly and clearly.

Statement 4. The increase of resource integration coefficient makes the probability of an enterprise selecting to participate collaborative innovation in supply chain increase, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial\delta_A) = (-(R_3^A - C_1)C_0/4(R_1^A - (1/2)\ (1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^2) < 0$, similarly, $(\partial S/\partial\delta_B) < 0$, it will be found that related to δ_i, S appears monotone progressive decrease. It shows that with the increase of the resource integration coefficient, the saddle point G moves to point (0, 0), and the system evolves toward (1, 1); the probability of an enterprise selects "participation strategy" increases, and both sides of game tend to participate the cooperation of collaborative innovation in supply chain. The capacity of resource integration includes the capacity for an enterprise to integrate with the logistics resource and customer resource in supply chain and the capacity of supplier's management. Enterprises reduce operation cost and improve logistics efficiency through standardization construction and centralized purchase mode. Therefore, the improvement of the capacity of source integration can make enterprises approach to participate in supply chain collaborative innovation.

According to $(\partial^2 S/\partial\delta_A^2) = (2(R_3^A - C_1)^2 C_0/4(R_1^A - (1/2)\ (1-\varepsilon_{AB})C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, similarly, $(\partial^2 S/\partial\delta_B^2) > 0$, it will be found that with the increase of the source integration coefficient, the velocity of an enterprise selecting the final strategy becomes higher and higher. The bigger the source integration coefficient is, the more the income an enterprise gains in the process of source integration; therefore, the enterprise will select participating cooperation quickly.

Statement 5. The increase of trustworthiness makes the probability of an enterprise selecting to participate collaborative innovation in supply chain increase, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial\varepsilon_{AB}) = ((-(1/2)C_0^2)/4(R_1^A - (1/2)\ (1-\varepsilon_{AB})\ \ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^2) < 0$, it will be found that S appears monotone progressive decrease related to ε_{AB}. It shows that with the increase of the trustworthiness, the saddle point G moves to point (0, 0), and the system evolves toward (1, 1); the probability of enterprises selecting "participation strategy" increases, and both sides of game approach to participate the cooperation of collaborative innovation in supply chain. The higher the trustworthiness is, the less the cost an enterprise pays in supplier management, and the higher is the desire to share information with each other, correspondingly, the communication cost is decreased; what is more, in order to overcome the obstacle of information communication system, an enterprise may invest again to reform its inner information system, and the effect of trustworthiness of one enterprise will win the trustworthiness from the other enterprise as well, as a result, more enterprises are absorbed in supply chain and the innovation within a greater extent is launched. Therefore, the enhancement of the trustworthiness among enterprises is beneficial to carrying on collaborative innovation in supply chain with high efficiency.

According to $(\partial^2 S/\partial\varepsilon_{AB}^2) = ((1/2)C_0^3/4(R_1^A - (1/2)(1-\varepsilon_{AB})\ \ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, it will be found that with the increase of the trustworthiness, the velocity of an enterprise selecting the final strategy becomes higher and higher. The higher the trustworthiness is, the better the ability of cooperation among enterprises is, and communication becomes better and faster, as a result, enterprises gain more income, and therefore, enterprises will select to participate quickly.

Statement 6. The increase of free rider income makes the probability of an enterprise selecting to participate collaborative innovation in supply chain decrease, and the velocity of approaching to the decision direction becomes higher and higher.

Proof. According to $(\partial S/\partial R_3^A) = (C_0/4(R_1^A - (1/2)(1-\varepsilon_{AB})\ \ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^2) > 0$, similarly, $(\partial S/\partial R_3^B) > 0$, it will be found that S appears monotone progressive increase related to R_3. It shows that with the increase of the trustworthiness, the saddle point G moves to point (1, 1), and the system evolves toward (0, 0); the probability of enterprises selecting "participation strategy" decreases, and both sides of game approach to not to participate the cooperation of collaborative innovation in supply chain. Enterprises always start from maximizing profits. Therefore, when free rider income increases, enterprises will select free rider income that can be obtained without paying any cost and therefore will not participate in supply chain collaborative innovation.

According to $(\partial^2 S/\partial R_3^{A^2}) = ((1/2)C_0^3/4(R_1^A - (1/2)\ (1-\varepsilon_{AB})\ \ C_0 + \delta_A(R_2^A - C_1^A) + (\alpha_A - \beta_A - \gamma_A)P_A - R_3^A + C_0)^3) > 0$, similarly, $(\partial^2 S/\partial R_3^{B^2}) > 0$, it will be found that with the increase of the free rider income, the velocity of an enterprise selecting the final strategy becomes higher and higher; the higher the free rider income is, the more the income an enterprise obtains without any cost, and therefore, an enterprise will firmly select the "no participation" strategy and make decision in less time.

5. Numerical Simulation

Because there are several enterprises in the supply chain, and in every network of supply chain, there are core enterprises and common enterprises, and furthermore, the collaborative innovation among enterprises may take place between core enterprises and common enterprise as well as between common enterprises, in order to observe comprehensively the different game evolution among every sort of enterprise, we select one core enterprise and two common enterprises to conduct simulation. We assume enterprise A is a core enterprise, enterprise B and enterprise C are common enterprises and select numbers for them, considered that the capacity of the core enterprise is better than the common enterprise, we let the parameter value corresponding to enterprise A is bigger than those corresponding to enterprise B and enterprise C; the parameter values of common enterprises B and C are approximate, and we let the parameter value of enterprise B is slightly bigger than that of enterprise C. Then we pair enterprise A with enterprise B and pair enterprise B with enterprise C to conduct simulation game, in order to verify the correctness

Table 3: Simulation parameter valuation.

i	R_0^i	R_1^i	R_2^i	R_3^i	C_1^i	C_0	P_i	α_i	β_i	γ_i	δ_i	ε_{ij}
A	6	5	12	4	2	2	20	0.8	0.4	0.2	0.6	
B	5	3	6	3	1	2	10	0.4	0.2	0.1	0.4	$\varepsilon_{AB} = \varepsilon_{CB} = 0.4$
C	4	2.5	4.5	2	0.5	2	10	0.3	0.1	0.1	0.2	

of statements and analyze if the participation of the core enterprises has different influence on collaborative innovation in supply chain. Simulation parameter valuation is shown in Table 3.

Substituting the number into the replicated dynamic equation (12), we obtain the replicated dynamic equation of game between enterprise A and enterprise B:

$$\begin{aligned} \frac{dx}{dt} &= x(1-x)(12.4y-1), \\ \frac{dy}{dt} &= y(1-y)(4.4x-1). \end{aligned} \quad (18)$$

The replicated dynamic equation of game between enterprise B and enterprise C:

$$\begin{aligned} \frac{dx}{dt} &= x(1-x)(3.7y-1), \\ \frac{dy}{dt} &= y(1-y)(4.4x-1). \end{aligned} \quad (19)$$

5.1. The Influence of the Income Coefficient α_i on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, we analyze the influence of the change in simulation α_i on the enterprises A, B, and C. When α_i takes the values of 0.2, 0.4, 0.6, and 0.8, we get the results shown in Figure 6–9, and Statement 1 gets verified.

From Figures 6 and 7, it can be found that when core enterprises and common enterprises conduct collaborative innovation, no matter what value α_i takes, enterprise B will select "participation strategy." When $\alpha_A \leq 0.2$, the core enterprise A will select "no participation strategy," and only when the information coefficient is relatively big, it will select "participation strategy." The appearance of this threshold value tallies with the actual situation. The core enterprise always has ambitious aim and undertakes a lot of work such as construction of digital platform, which demand a high investment. As for the fixed cost, if the predicted data sharing income is relatively low, enterprises will not select participating collaborative innovation in supply chain, and if the predicted data sharing income increased, they will naturally select "participation strategy." The common characteristic of both enterprises A and B is that with the progressive increase of data sharing profit coefficient, the velocity of the probability of "participation strategy" approaching 1 becomes higher and higher, which indicates that enterprises tend to select to participate supply innovation comparatively.

From Figures 8 and 9, it can be found that when the two enterprises A and B participate collaborative innovation,

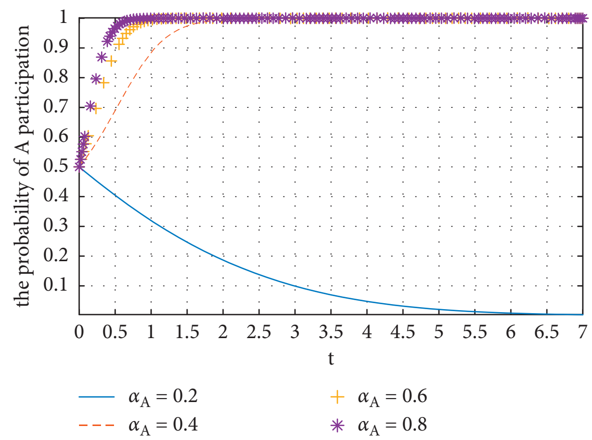

Figure 6: Influence of α_A on the core enterprise A.

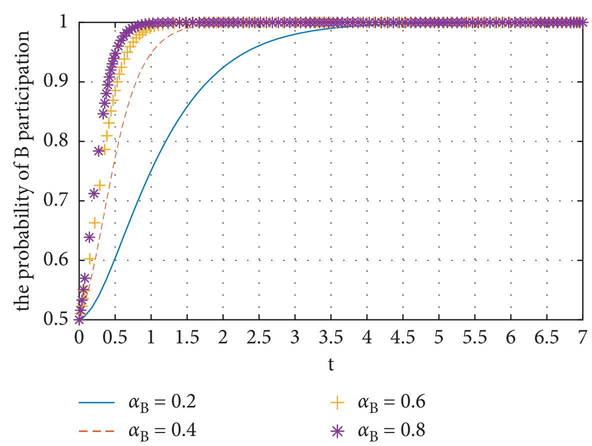

Figure 7: Influence of α_B on the common enterprise B.

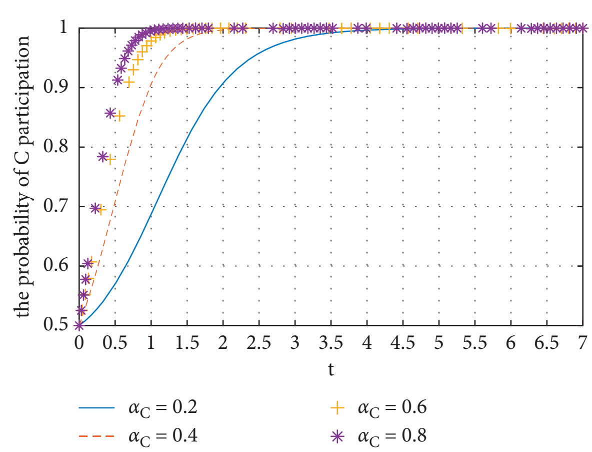

Figure 8: Influence of α_C on the common enterprise C.

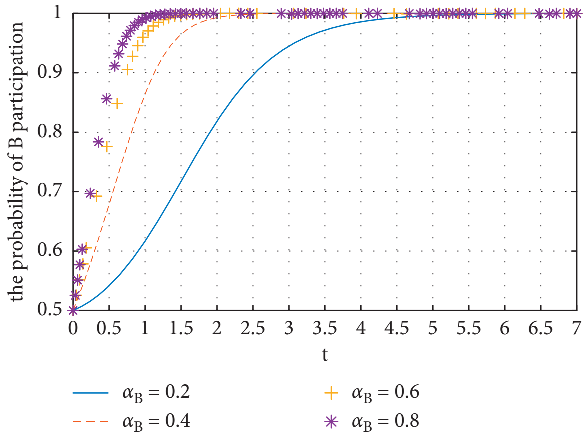

FIGURE 9: Influence of α_B on the common enterprise B.

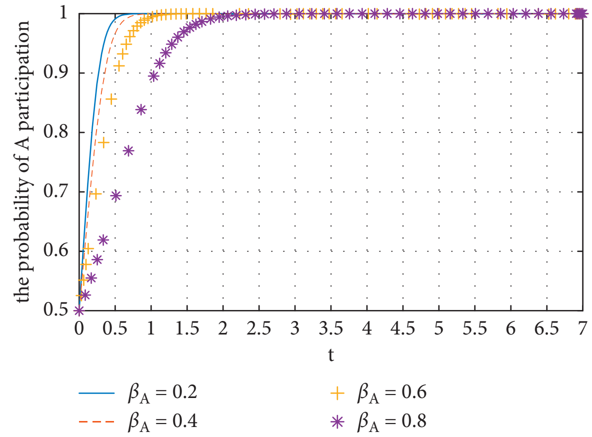

FIGURE 10: Influence of β_A on the core enterprise A.

both of them make a completely similar selection that approaches to "participation strategy." With the increase of the income coefficient of information sharing, the velocity of the probability of "participation strategy" approaching 1 becomes higher and higher. As for the velocity of the probability of "participation strategy" approaching 1, enterprise C is faster than enterprise B, maybe it is because that the base of enterprise C is slightly worse compared with enterprise B and, in the aspects of digital technology and information technology, it has not much advantage in itself and it selects cooperation quickly in order to promote its growth and increase of income.

Comparing the displays of enterprise B under the two conditions, no matter if there are core enterprises, it will select participating collaborative innovation in supply chain. When there are core enterprises, the velocity of the probability of "participation strategy" approaching 1 is higher than that in the condition without core enterprises. Maybe it is because that the core enterprise whose capacity of digitization technology is strong in itself, possesses more information, and can lead the cooperative enterprises to turn the advantage of data sharing into income so as to promote collaborative innovation in supply chain, and the desire of common enterprises to select "participation strategy" becomes more obvious. Yet, when both sides are common enterprises, their information quantity and information capacity in themselves are poor, and the income produced in data sharing is less, and therefore, the enterprises may select "participation strategy" slowly.

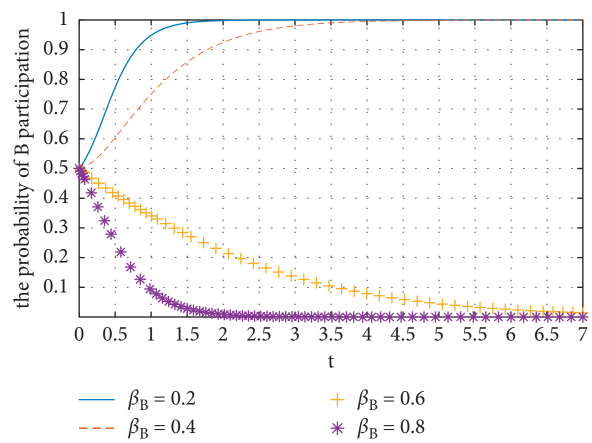

FIGURE 11: Influence of β_B on the common enterprise B.

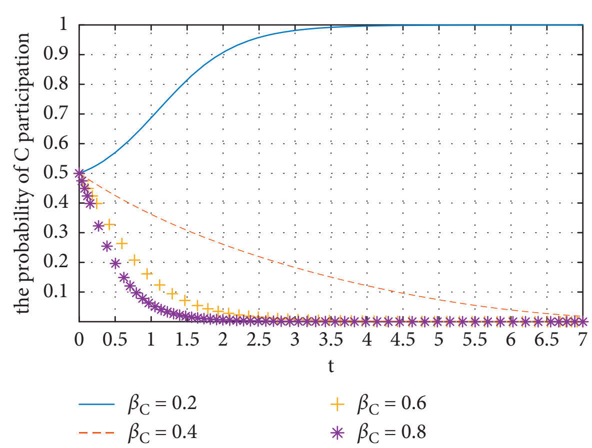

FIGURE 12: Influence of β_C on the common enterprise C.

5.2. The Influence of Cost Coefficient β_i on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, the influence of the change in simulation β_i on the enterprises A, B, and C is analyzed. When β_i takes the values of 0.2, 0.4, 0.6, and 0.8, the evolution results shown in Figures 10–13 are obtained, and the numerical simulation verifies Statement 2; also, it has been found, when the enterprises B and C select the strategy, there is a threshold value of β_i.

From Figures 10 and 11, it can be found that when enterprise A and enterprise B play game concerning collaborative innovation in supply chain, against different cost coefficients of information sharing, the core enterprise A will select participating collaborative innovation in supply chain, while the common enterprise B will weigh the value of cost coefficient. When the cost coefficient is relatively big, the common enterprises will select "participation strategy,"

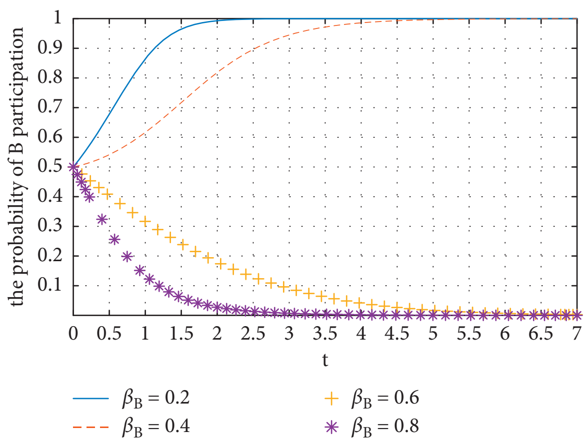

Figure 13: Influence of β_B on the common enterprise B.

and with the increase of the cost coefficient of information sharing, the velocity of enterprises approaching selection of "no participation strategy" becomes higher and higher. When the cost of data sharing is low, the common enterprises will select to participate collaborative innovation in supply chain, and with the decrease of the cost coefficient of information sharing, the velocity of enterprises approaching selection of "participation strategy" becomes higher and higher. This is entirely consistent with the practice in which the core enterprises have great confidence in the future income; meanwhile, the sensitivity for cost of the common enterprise is higher than that of the core enterprise.

From Figures 12 and 13, it can be found that when the two common enterprises B and C play the game, for the decision of enterprise, there is a threshold value; when β_i is small, enterprises will select "participation strategy," and with the increase of β_i, all enterprises will select "no participation strategy," between the enterprises the threshold value of enterprise C is less than that of enterprise B. By analyzing the reason, we know: the cost sensitivity of the two enterprises is high, and the cost affordability for enterprise C is poorer than that for enterprise B, so the threshold value, which influences decision, becomes low and the velocity of making decision becomes high, so only if it is thought that the income of data sharing can offset the paid cost, the two enterprises will select "participation strategy."

Comparing Figures 11 and 13, we can find that for enterprise B the threshold value and the tendency of selection have little change, but when playing the game with a core enterprise, it will make decision more rapidly. It indicates that for the common enterprises selecting "participation strategy," the cost of data sharing is a very big threshold and the amount of cost directly influences the selecting direction; in addition, there is a big gap between the common enterprises and the core enterprise, the sharp contrast makes enterprise B to do comparison and resolution more easily, and therefore, it will make decision more rapidly.

5.3. The Influence of Security Risk Coefficient γ_i on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, the influence of the change in simulation γ_i on the enterprises A, B, and C selecting strategy is analyzed. When γ_i takes the values of 0.2, 0.4, 0.6, and 0.8, the evolution results shown in Figures 14–17 are obtained, and the results of numerical simulation verify Statement 3; also, it has been found that in every graph, the coefficient γ_i has a threshold value and in the enterprises the difference of threshold is great.

From Figures 14 and 15, it can be found that when enterprise A and enterprise B play game, and when the security risk coefficient is relatively big, both of them will select "no participation strategy," and with the decrease of the security risk coefficient, enterprises tend to select "participation strategy," and in addition, the threshold value of enterprise A (between 0.6 and 0.8) is bigger than that of enterprise B (between 0.4 and 0.6). Under the background of digitization, for the data security question leading various risks, it will hinder enterprises from selecting to participate collaboration innovation in supply chain, and only when the security risk coefficient is not big, the enterprises can select "participation strategy." The threshold value of the core enterprise is bigger than that of the common enterprises; maybe it is because that the risk-bearing capacity of the core enterprise is stronger.

From Figures 16 and 17, it can be found that the game between enterprise B and enterprise C is similar to the game between enterprise A and enterprise B. Furthermore, comparing Figures 15 and 17, it can be found that the presence of core enterprise has little influence on the decision of the common enterprises, and they make decision based on their own actual situations; after all, their own risk must be borne by themselves. But when there are core enterprises, the common enterprises will make decision more rapidly. It indicates the promoting and leading effect of the core enterprises on collaborative innovation in supply chain, and the common enterprises clearly know how the gap between the two sides is, so they will make decision more rapidly.

5.4. The Influence of Resource Integrative Capacity Coefficient δ_i on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, the influence of the change in simulation δ_i on the enterprises A, B, and C selecting strategy is analyzed. When δ_i takes the values of 0.2, 0.4, 0.6, and 0.8, the evolution results shown in Figures 18–21 are obtained, and the results of numerical simulation verify Statement 4.

From Figures 18 and 19, it can be found that when the enterprise B plays game with the enterprise A, both of them will select "participation strategy," so with the increase of resource integration coefficient, the velocity of the probability of "participation strategy" approaching 1 becomes higher and higher, and the core enterprises are faster than the common enterprise. It indicates that both the two enterprises believe resource integration can bring forth income; besides, having strong capacity, the core enterprises make decision more rapidly. Furthermore, comparing Figures 19 and 20, it can be found that when there are core

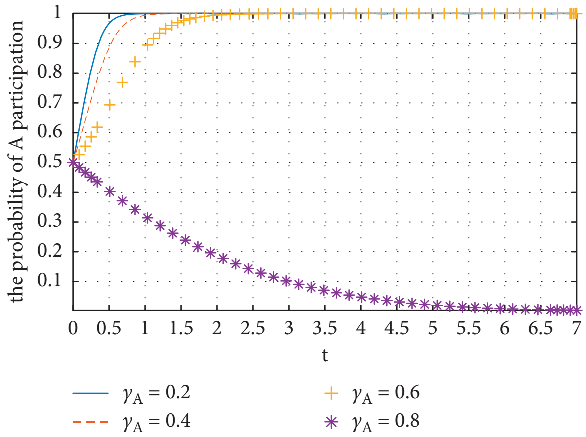

FIGURE 14: Influence of γ_A on the core enterprise A.

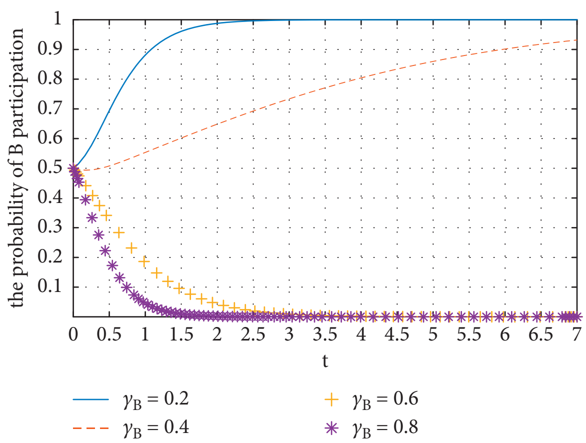

FIGURE 15: Influence of γ_B on the common enterprise B.

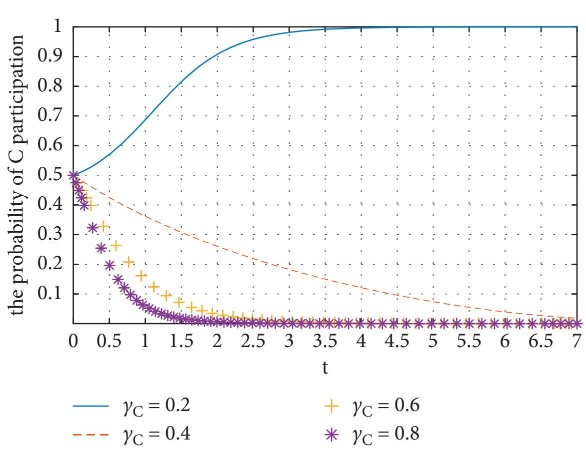

FIGURE 16: Influence of γ_C on the common enterprise C.

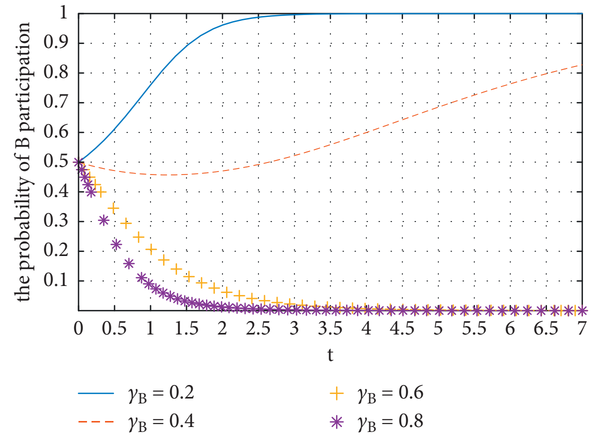

FIGURE 17: Influence of γ_B on the common enterprise B.

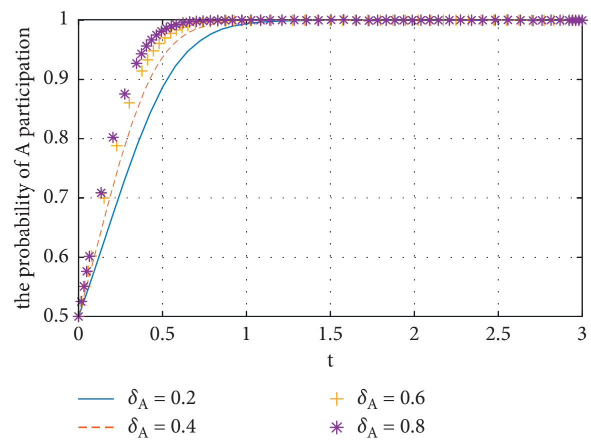

FIGURE 18: Influence of δ_A on the core enterprise A.

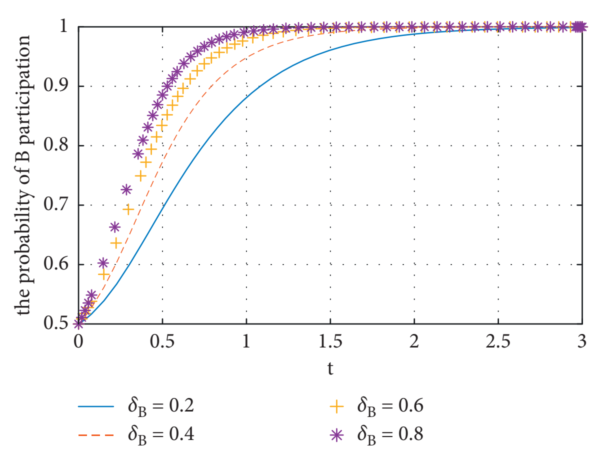

FIGURE 19: Influence of δ_B on the common enterprise B.

enterprises, the velocity with which the probability of the common enterprises selecting "participation strategy" approaching 1 becomes higher and higher, and it indicates that, in the aspect of resource integration, the core enterprise really has an obvious leading effect on the common enterprises.

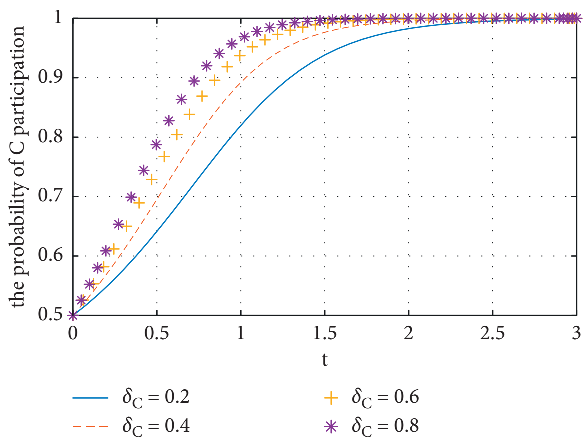

Figure 20: Influence of δ_C on the common enterprise C.

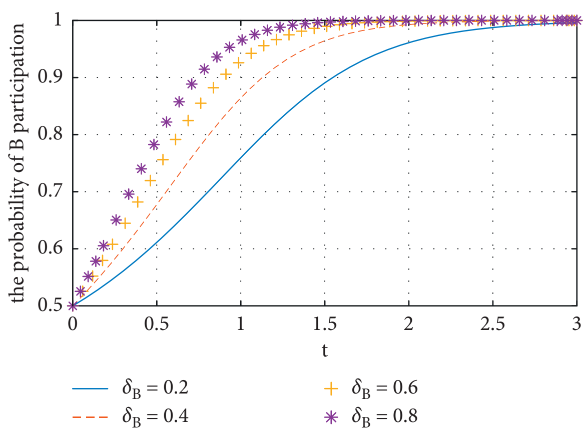

Figure 21: Influence of δ_B on the common enterprise B.

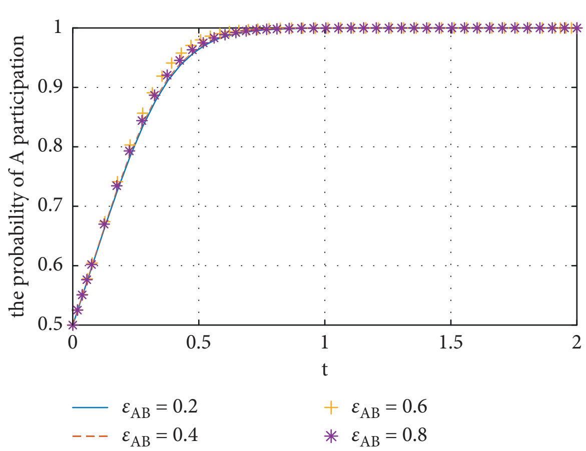

Figure 22: Influence of ε_{AB} on the enterprise A.

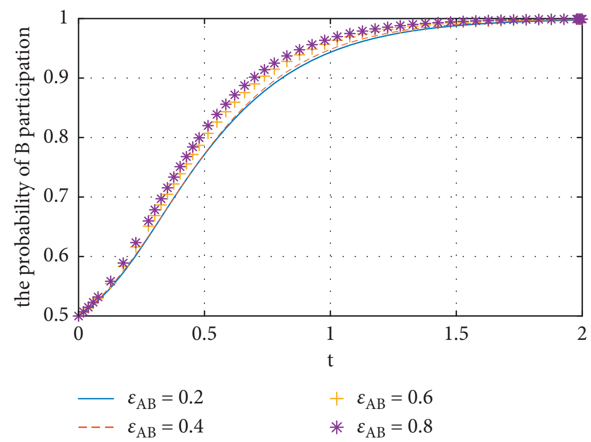

Figure 23: Influence of ε_{AB} on the enterprise B.

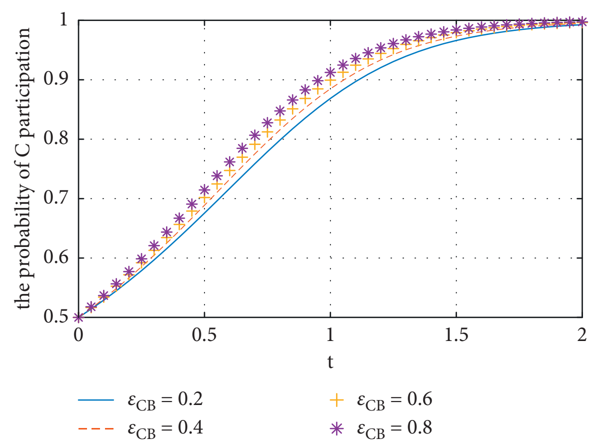

Figure 24: Influence of ε_{CB} on the enterprise C.

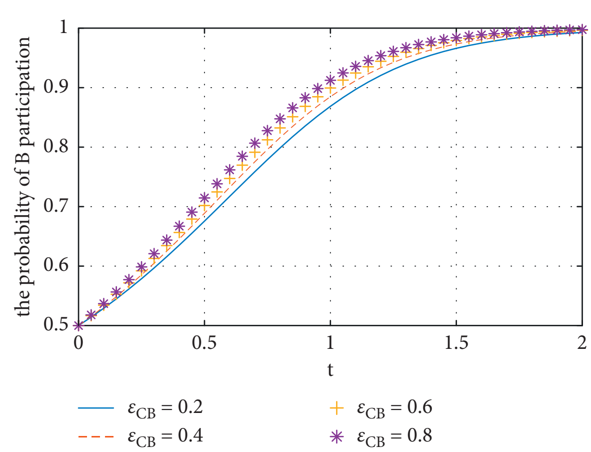

Figure 25: Influence of ε_{CB} on enterprise B.

5.5. The Influence of Trustworthiness Coefficient ε on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, the influence of the change in simulation ε on the enterprises A, B, and C selecting strategy is analyzed. When ε takes the values of 0.2, 0.4, 0.6, and 0.8, the evolution results shown in Figures 22–25 are obtained, and the results of numerical simulation verify Statement 4.

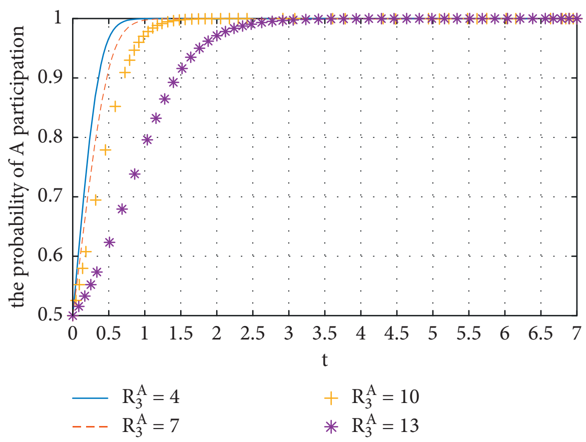

Figure 26: Influence of R_3^A on the core enterprise A.

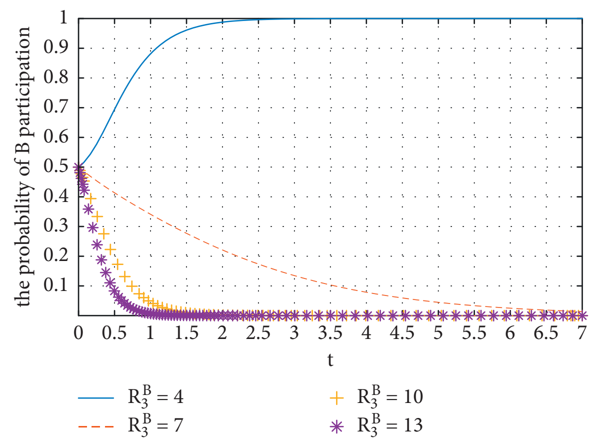

Figure 27: Influence of R_3^B on the common enterprise B.

From Figures 22 and 23, it can be found that when the enterprise A plays game with the enterprise B, the velocity with which the probability approaching 1 of enterprise A selecting "participation strategy" is significantly higher than that of enterprise B; additionally, comparing Figure 23 and 25, it can be found that when the enterprise B plays game with the core enterprise A, the velocity of the probability approaching 1 of its selecting "participation strategy" is higher than that when it plays game with the common enterprise C. In the same way, it indicates the leading effect of the core enterprises.

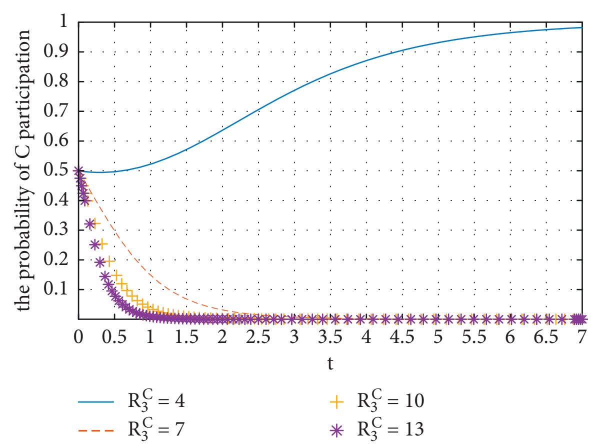

Figure 28: Influence of R_3^C on the common enterprise C.

5.6. The Influence of Free Rider Income R_3^i on the Results of Both Game Sides Evolution. Under the condition that the other factors will not be changed, the influence of the change in simulation R_3^i on the enterprises A, B, and C selecting strategy is analyzed. When R_3^i takes the values of 4, 7, 10, and 13, the evolution results shown in Figures 26–29 are obtained, and the results of numerical simulation verify Statement 6; also, it can be found that when enterprises B and C select the strategy, the γ_i coefficient has threshold value between 4 and 7.

From Figures 26 and 27, it can be found that when the enterprise A plays game with the enterprise B, the core enterprise A always selects "participation strategy," and with the increase of free rider income, the velocity of the probability approaching 1 of the core enterprise's participation will become slow, and it indicates its strong unwillingness to free rider behavior. With the increase of free rider income, the common enterprise B will change its strategy, and only when free rider income is not more, it will select "participation strategy." Once free rider income reaches a certain degree, enterprises will select "no participation strategy"; after all, since an enterprise can obtain income without cost, attracted by income the common enterprises will select free rider without any hesitation.

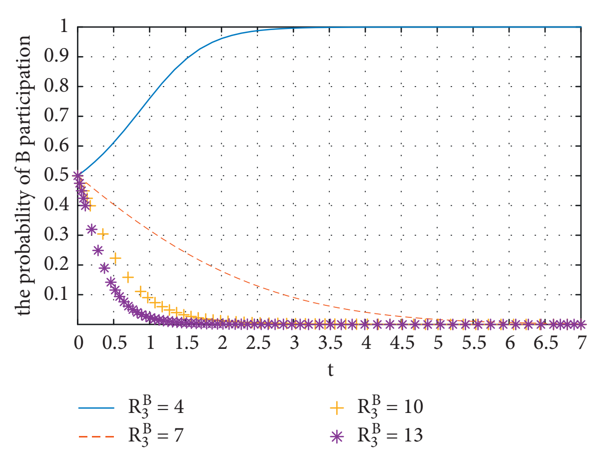

Figure 29: Influence of R_3^B on the common enterprise B.

From Figures 28 and 29, it can be found that when the two common enterprises B and C play game, as long as free rider income amounts to a value which exceeds the lowest threshold value, they will select "no participation strategy." In addition, the velocity with which the enterprise C approaches the selection of "no participation strategy" is higher than that of the enterprise B, maybe it is because that in the several aspects of capacity the enterprise C is slightly poor and has strong tendency toward free rider for obtaining income without paying cost. Furthermore, comparing

Figures 27 and 29, it can be found that the presence of core enterprise has a little influence on the threshold value for the common enterprises making decision. The common enterprises balance collaborative innovation income against free rider income and will make decision finally. But when the core enterprises participate in the game, the enterprise B will make decision more rapidly, likewise, it is because that the enterprise B can realize quickly that the core enterprise A has significant advantage in capacity over itself, so it will make decision soon.

6. Conclusion and Enlightenment

On the base of the analysis of the effect mechanism on collaborative innovation in supply chain, in consideration of the influence of both sides of game in correlative factors such as information sharing, resource integration, and trustworthiness on income and cost of an enterprise, this paper builds a dynamic evolution game model of enterprises participating collaborative innovation to solve the model and analyze the stability of game strategy of both sides as well as to prove the relative statements theoretically and verify them with the method of numerical simulation.

6.1. The Main Research Conclusion. The results of research are as follows:

(1) The increase of data sharing profit coefficient, resource integration coefficient, and trustworthiness coefficient increase the probability of enterprises participating collaborative innovation in supply chain, and the velocity of enterprises approaching the direction of decision becomes higher and higher.

(2) The increase of data sharing cost coefficient, security risk coefficient, and free rider income causes the decrease of the probability of enterprises participating collaborative innovation in supply chain, and the velocity of enterprises approaching the direction of decision becomes higher and higher.

(3) The numerical simulation shows that, for the probability the core enterprises or the common enterprises participating collaborative innovation in supply chain, the income coefficient of information sharing, the cost of information sharing, security risk coefficient, and free rider income have threshold values.

(4) The core enterprises participating the game can drive the common enterprises make decision more quickly.

6.2. The Main Enlightenments. The research in this paper brings the following enlightenments:

6.2.1. Attach great importance to digitization construction. Data sharing income and resource integration income are the cardinal driving forces. The digitization construction in enterprises has significant effect on the promotion of the degree of data sharing and the strength of resource integration. It is the foundation stone of enterprises to reinforce enterprises in comprehension of digitization innovation as well as to cultivate and improve digitization capacity of enterprise. Collaborative innovation in supply chain depends on the increase of the digitization level in every enterprise, and innovation in supply chain needs active participation and joint promotion.

6.2.2. Play the leading role of core enterprises. The core enterprises in supply chain have a great advantage in the aspects of technology, resource, and management capacity. While leading and encouraging all enterprises to participate collaborative innovation in supply chain, the government should pay attention to the leading effect from the core enterprises, especially the platform enterprises under the background of digitization, and find out the core enterprises to be spurred timely and then impel the core enterprises to lead collaborative innovation in supply chain.

6.2.3. Government gives subsidies for breaking out threshold values. In general, a threshold value is a critical value of the difference between the expected income and cost, which determines the direction enterprises making decision. As the government plays an important leading role in making industrial policies and promoting the development of collaborative innovation in supply chain, in the specific analysis of different industry, it should give some proper subsidies to the enterprises that have the potential for innovation but still hesitate for being perplexed with cost, so as to urge enterprises to breakout the boundary of threshold values and take the strategy of participating collaborative innovation in supply chain sooner, as a result, the efficiency of the whole network of supply chain will be increased finally.

6.2.4. Exert the effect of data encryption technology and protect achievement in innovation. The free rider behavior is disadvantageous to the trustworthiness construction and the long-term healthy development of supply chain. The data encryption technology in the construction of digitization platform should be utilized to the full, and in contract, the permissions of the resources such as information should rationally set in order to protect innovation patents and achievements.

6.3. Insufficient Research. The research of this paper has rather more theoretical value and practical significance; though, there are some deficiencies to be deeply researched, for instance, not verifying the related conclusions with actual data of enterprises and the lack of further analysis of the specific situation of the threshold value upon enterprises making decision and the leading effect exerted by the core enterprises.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

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Research Article

Distributed Load Shedding considering the Multicriteria Decision-Making Based on the Application of the Analytic Hierarchy Process

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This paper shows an analytic hierarchy process (AHP) algorithm-based approach for load shedding based on the coordination of the load importance factor (LIF), the reciprocal phase angle sensitivity (RPAS), and the voltage electrical distance (VED) to rank the load buses. This problem is important from a power system point of view, and the AHP method is able to support the decision-making process in a simple and intuitive way in a three-criterion environment. This satisfies the multicriteria decision-making to meet economic-technical aspects. The ranking and distributed shedding power at each demand load bus are based on this combined weight. The smaller overall weights of the load buses show the lesser importance of the load bus, the smaller reciprocal phase angle sensitivity, and the closer voltage electrical distance. Therefore, these load buses cut a larger amount of capacity, and vice versa. By considering the generator control, the load shedding consists of the primary and secondary control features of the generators to minimize the load shedding capacity and restore the system frequency value back to the allowable range. The efficiency of the suggested load-shedding scheme was verified via the comparison with the under-frequency load shedding (UFLS). The latter result is that the load shedding power of the suggested approach is 22.64% lower than the UFLS method. The case studies are experienced on the IEEE 9-generator; the 37-bus system has proven its effectiveness.

1. Introduction

In the load-shedding issue, the ranking of loads according to the priority of shedding is essential for adjusting the power balance, restoring frequency to bring economic, technical efficiency to customers. Therefore, it is necessary to determine which loads need to be classified in the list of loads to be shed and their priority order. The ranking of these loads should satisfy many aspects that require an analysis of the economic and technical consequences. However, the calculation of economic and technical analysis is very complicated, and most power companies in the world still base on the evaluation of electrical system experts. However, it is very difficult for experts to prioritize these loads, especially when a load needs to be considered in many different criteria.

Studies on optimizing load shedding considering multiobjective constraints are mainly to solve the problem of minimizing the load shedding power. The proposal of a multiobjective optimization model considering load-shedding risk [1] is of interest to many researchers operating power systems. The multiobjective constraints are mostly technical constraints, such as conditions for power constraints of generating sets, power carrying capacity of the line, and the voltage at the nodes. However, in current times, the load shedding must meet many different goals, including achieving the technical requirements and economic goals including restoring frequency, load importance factor, the damage caused by power shedding, and priority level. The distributed shedding power at each demand load buses so that it is optimal and reduces the damage to the power supplier as well, such as customer power consumption. Solving this multicriteria load-shedding problem needs the application of algorithms for system experts.

The calculation of the load-shedding power is an essential factor to return the frequency back to the value within the permissible range and prevent the frequency degradation in the power system [2, 3]. The load-shedding power is usually calculated based on frequency degradation [4], calculating the amount of load-shedding power; if the calculation is insufficient, it will not be possible to restore the frequency to the permissible value, and vice versa will cause excessive load shedding. Studies on load shedding mainly calculate it based on the rotation motion of the rotor [5]. However, these methods do not consider the actual operating conditions such as primary and secondary controls of generating sets.

The techniques of load shedding are distributed into three fundamental areas of study [6]: conventional load shedding, adaptive load shedding, and intelligent load shedding techniques. Conventional load shedding is a method of load shedding by using underfrequency load-shedding (UFLS) or under-voltage load-shedding (UVLS) relays. This is the most common method used for frequency control and voltage stabilization of the power grid. According to the IEEE standard, UFLS must be implemented quickly to prevent the electrical system frequency attenuation and power system blackout [7]. Many works used UFLS and UVLS [8–11]. These studies have the advantage of a low-cost, simple working principle. However, they have the main disadvantage that they do not estimate the amount of unbalanced power in the system. This result causes excessive load shedding, affects the quality of electricity, or leads to the discontinuation of electricity services or consumers [12]. In [13, 14], the high-priority loads were considered during load shedding, but the secondary frequency control was not added. Reference [15] showed the UFLS using decision trees to decide whether the load needs to be cut or not and the amount of load capacity to be cut. The decision tree was built based on the frequency derivative, the load demand, and the system's reserve capacity. However, this method has not considered the important factor of the load in the electricity system. The adaptive load-shedding method uses the swing rotor equation to calculate the amount of load shedding [5]. Rate of change of frequency (ROCOF) relay is used to perform load shedding [16]. The method proposed in [12] used both frequency deviation and voltage parameters to improve the accuracy of the frequency and voltage stability. In [17], a semi-adaptive multistage UFLS plan with ROCOF element and AHP method is proposed. The AHP method is based on two main criteria including the total amount of load shed and the minimum point of frequency response to rank the importance of load shedding. However, assessing the importance of loads based on the AHP algorithm has not been considered. In [18], the artificial neural network (ANN) and power flow tracing were used to evaluate the total active power imbalance. The load priority was considered in this study. However, the 0–1 variable is introduced to represent. The load priority of the load at bus k was allowed to be shed; the value of a is set to 1. Otherwise, the value of a was set to 0. This shows that the baseload and the ranking of load shedding priority have not been considered in this situation.

The intelligent load-shedding methods include the application of intelligent algorithms such as artificial neural network (ANN) [19–21], adaptive neural-fuzzy inference system (ANFIS) [22, 23], fuzzy logic control (FLC) [24], genetic algorithm (GA) [25], and particle swarm optimization (PSO) [26, 27] to calculate and select the shed load. These approaches can easily solve nonlinear, multiobjective problems in power systems that conventional methods cannot solve with the desired speed and acceptable accuracy [19, 28]. For ANN, the output is the total quantity of active power that needs to be cut. This output is not an actual signal because it does not determine the number of loads and the load capacity to be shed in each step. Multiobjective optimization methods using GA or PSO algorithms only have constraints on technical conditions. These methods do not have a combination of multiple methods including economic technical parameters when studying the load ranking. In [29], the weight coefficient in the load shedding objective equation was adjusted to satisfy the actual needs. Furthermore, reference [30] coordinated the optimization load-shedding method based on sensitivity analysis. The weighted sum of economic expense and equilibrium index was taken as the objective function to establish the load-shedding optimization model. However, this model has not considered the important factor of the load and has not yet ranked the load in the order of priority load.

This paper focuses on the coordination of various objectives during the load-ranking process. In this paper, a new load shedding method is presented based on the calculation of primary and secondary control of the generator to determine the minimum amount of shedding power. It coordinates criteria to consider the aspects to respond to load shedding in the direction of decision-making multicriteria. This satisfies the technical and economic factors to optimize the distribution of the power shedding at each load bus. There is an easier method for experts to approach the critical issues of load shedding criteria. When giving opinions, they often rely on technology characteristics and operating realities to be able to make verbal comments. Experts make it easy for a comparison of pairs and common languages like Load 1 is more important than Load 2, or Criterion 1 is more important than Criterion 2. In addition, the evaluation of the important rank of the load in the frequency control problem is also considered under many criteria with different importance levels. The paper proposes an approach based on consultation with experts when expressed in words. Each load will be considered under many criteria.

The efficiency of the suggested load-shedding technique was proved through the test on the 9-generator, 37-bus system. The calculations are evaluated with a traditional underfrequency load-shedding method. The results have shown that the suggested approach has a lower amount of load shedding capacity than the UFLS method. Therefore, the proposed method can minimize the damage and inconvenience caused to electricity customers. The recuperation time and rotor deviation angle are still guaranteed within the permissible values and sustained the power system stability. In addition, the proposed method demonstrates the combination of multimethod taking into account both technical and economic criteria that have not been carried out by previous studies. Therefore, in large disturbance situations such as large outage generators, this proposed method can be used to teach operators and improve their skills.

2. Materials and Methods

2.1. Calculate the Overall Weights and Rank the Load Buses to Load Shedding Based on the AHP Algorithm. It is supposed that there are m loads to be shed in the electrical system diagram. These loads need to be ranked for load shedding based on coordination of three criteria including LIF, RPAS, and VED. The problem is that in the case of outage generators and load shedding is required, ranking and distributing the amount of load-shedding power to these loads require the satisfaction of multiple criteria simultaneously. To achieve that, it requires technical and economic consequences analysis. However, these calculations and analysis are very complicated and time-consuming. Therefore, it is necessary to collect reviews of power system experts in this regard. Experts easily give a verbal comment when comparing each pair of criteria and using common language, such as Criterion 1 is more important than Criterion 2. In this section, the AHP method is able to support the decision-making process in a simple and intuitive way in a three-criterion environment to calculate the overall weights of criteria and rank the load buses to load shedding. The ranking of the load buses is based on the AHP method which includes three stages: establishing the hierarchical structure, determining the weights of criteria, and calculating the overall weights.

2.1.1. Stage 1: Establishing the Hierarchical Structure. This step targets to solve the problem of the ranking of load buses into a hierarchical structure [31–34]. Accordingly, a three-level hierarchical structure is proposed for calculating the overall weights, as shown in Figure 1. In this study, three types of criteria are proposed: LIF, RPSA, and VED. The three criteria are described in detail in the following sections.

(1) First Criterion: *The Reciprocal Phase Angle Sensitivity (RPAS) from the Load Buses to the Outage Generator*. The concept of the RPAS between two buses is defined as follows [35–39]:

$$D_p(i,j) = \left(J_{P\theta}^{-1}\right)_{ii} + \left(J_{P\theta}^{-1}\right)_{jj} - \left(J_{P\theta}^{-1}\right)_{ji} - \left(J_{P\theta}^{-1}\right)_{ij}. \quad (1)$$

In the power system, the goal is to concentration on the priority of load shedding at the nearby outage generator location. To do this, the idea of the RPAS between two buses is applied. Two buses close to each other always have exceptionally little RPAS. The smaller the RPAS between the load buses and the outage generator, the closer the load bus is to the outage generator. Therefore, when a disturbance occurs in an area on the grid, adjusting the grid in the disturbance area will achieve the best effect. Thus, minimizing the control errors in the disturbance area will have little effect on other areas in the system. Additionally, in load shedding, the delineation of a serious disturbance and load shedding around the disturbance area make the impact of the disturbance on a smaller system a more effective load-shedding method.

The following steps show the calculation of the reciprocal phase angle sensitivity:

Step 1: Extract the Jacobian matrix $[J_{P\theta}]$

Step 2: Inverse elements in the Jacobian matrix $[J_{P\theta}]$, calculate the elements in the matrix $[J_{P\theta}^{-1}]$

Step 3: Apply formula (1) to calculate $D_{p(i,\ j)}$

The weight of the load bus based on the RPAS between the load bus and the outage generator is calculated by the following formula:

$$W_{D_P(i,j)} = \frac{D_P(i,j)}{\sum_1^m D_P(i,j)}, \quad (2)$$

where $W_{D_P(i,j)}$is the weight of the RPAS from the i-bus to the outage generator and $D_P(i,j)$is the RPAS from the i-load bus to the outage generator.

(2) Second Criterion: *The Voltage Electrical Distance (VED) from the Load Buses to the Outage Generator*. The VED can be obtained by following steps [40–43]:

Step 1: Turn all generator buses into PQ buses for calculating $[\partial V/\partial Q]$.

Step 2: Calculate $[\partial V/\partial Q]$in all buses. This value is the inverse of the Jacobian matrix that indicates the effect on a voltage variation at neighboring buses of reactive power injection at a bus.

$$\Delta V_i = -[\partial V/\partial Q]\Delta Q_j = -J_{ij}^{-1}\Delta Q_j, \quad (3)$$

where $J_{ij}^{-1}$is sensitivity matrix$[\partial V_i/\partial Q_j]$.

Step 3: Calculate α_{ij}using the sensitivity matrix of step 2. The voltage changes in the bus i due to voltage change in bus j are as follows:

$$\Delta V_i = \left[J_{ij}^{-1}/J_{jj}^{-1}\right]\Delta V_j = \alpha_{ij}\Delta V_j, \quad (4)$$

where α_{ij} is defined as $[J_{ij}^{-1}/J_{jj}^{-1}]$.

Step 4: Calculate the VED using $(\alpha_{ij} \times \alpha_{ji})$, which is reflected by the symmetrical distance.

$$D_V(i,j) = D_V(j,i) = -\text{Log}\left(\alpha_{ij} * \alpha_{ji}\right), \quad (5)$$

where α_{ji} is defined as $[J_{ij}^{-1}/J_{jj}^{-1}]$.

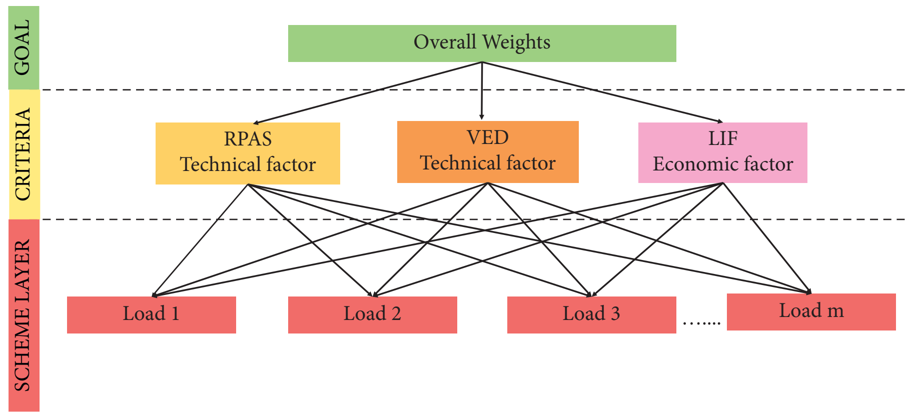

FIGURE 1: Three-level hierarchical structure for load buses ranking.

After calculating the VED, the weight of the load buses based on the VED between the load buses and the outage generator is calculated by the following formula:

$$W_{D_V(i,j)} = \frac{D_V(i,j)}{\sum_1^m D_V(i,j)}, \quad (6)$$

where $W_{D_P(i,j)}$ is the weight of the VED from the i-load bus to the outage generator and $D_V(i,j)$ is the VED from the i-load bus to the outage generator.

The VED is the physical relationship between two buses in the power system. Formula (5) shows that the closer the distance, the smaller D_V or the largerα_{ij}. On the other hand, formula (4) evaluates the voltage interactions between bus i and bus j. The bigger α_{ij} is, the greater the voltage attenuation at bus i when a disturbance occurs at bus j. Thus, when an outage generator occurs, the amplitude of the voltage fluctuation near this generator is large, leading to an attenuation voltage at nodes with a small VED also increasing. To ensure the voltage profile returns to its stability margin, the amount of load shedding at each bus can be calculated on the principle that the smaller the VED, the larger the load shedding power, and vice versa. The relationship between the generator and the loads is shown in Figure 2.

With: $D_V(k,1) < D_V(k,2) < D_V(k,3) < \ldots < D_V(k,n)$.

Prioritized load shedding: Load 1 $\longrightarrow$ Load 2 $\longrightarrow$ Load 3 $\longrightarrow \ldots \longrightarrow$ Load n.

(3) Third Criterion: The Load Importance Factor (LIF). The parameters of the LIF weight, W_{LIF}, were calculated by the fuzzy AHP algorithm and suggested to be in [34]. The LIF shows how important the loads are to each other when the assessor considers mainly the economic aspect. In other words, the larger the W_{LIF} is, the more damage when load shedding is.

2.1.2. Stage 2: Determining the Weights of Criteria. Based on the established hierarchy structure, there are three steps to determine the weights of criteria. Firstly, pair-wise comparison or judgment matrices are formed to measure the relative importance of each two criteria. The pair-wise comparison scale proposed by Saaty [44] is applied, as showed in Table 1. A pair-wise comparison matrix is described by the following equation. The value of p_{ij} is equal to the reciprocal of p_{ij} in the pair-wise comparison matrix.

$$P = \begin{bmatrix} 1 & p_{12} & \cdots & p_{1n} \\ 1/p_{12} & 1 & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/p_{1n} & 1/p_{2n} & \cdots & 1 \end{bmatrix}, \quad (7)$$

where P is a pair-wise comparison matrix and p_{ij} is the importance of the i-th criteria relative to the j-th criteria.

Secondly, the largest eigenvalue and the eigenvector of a pair-wise comparison matrix are calculated. The relation among the largest eigenvalue, eigenvector, and pair-wise comparison matrix is defined by the following equation. The eigenvector is then normalized to obtain the weight vector of corresponding criteria.

$$P\omega = \lambda_{\max}.\omega, \quad (8)$$

where P is a pair-wise comparison matrix, $\lambda_{\max}$ is the largest eigenvalue of the pair-wise comparison matrix, and ω is the corresponding eigenvector.

Thirdly, the consistency index and consistency ratio of a pair-wise comparison matrix are evaluated, as the inconsistency may happen due to subjective expert judgment. They are defined by the following equations. A pair-wise comparison matrix is satisfied if the stochastic consistency ratio, $\mathrm{CR} < 0.10$.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}, \quad (9)$$

$$CR = \frac{\mathrm{CI}}{\mathrm{RI}}, \quad (10)$$

where CI is the consistency index of a pair-wise comparison matrix, CR is the consistency ratio of the matrix, RI is the random index of the matrix, $\lambda_{\max}$ is the largest eigenvalue of the matrix, and n is the number of criteria in the matrix.

2.1.3. Stage 3: Calculating the Overall Scores. The overall score of each load bus is calculated by using equation (11). The higher the overall score of load bus is, the more

TABLE 1: Pair-wise comparison scale of criteria.

Numerical rating	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the goal
3	Moderate importance	A criterion is favored slightly over the other
5	Strong importance	A criterion is favored strongly over the other
7	Very strong importance	A criterion is favored very strongly over the other
9	Extreme importance	A criterion is favored extremely over the other
2, 4, 6, 8	Intermediate values between two adjacent scale values	Make a compromise between two adjacent judgments

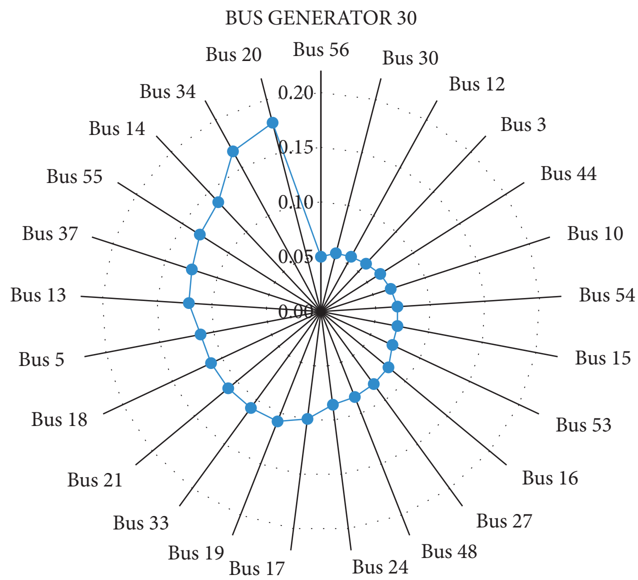

FIGURE 2: The VED relationship between generator 30 and the loads.

important the load bus is. It means that the higher the load is ranked, the less the load shedding distributed power to that load bus is done.

$$\mu_{A_i^{\sim}}(\mu_1, \mu_2, \mu_i \ldots, \mu_n) = \sum_{i=1}^{n} W_i W_{D,j}, \quad (11)$$

where $\mu_{A_i^{\sim}}$ is the overall score of each load bus, W_i is the weight of the i-th criterion, and $W_{D,j}$ are the values represented by W_{LIF}, $W_{D_v(i,j)}$ $W_{D_P(i,j)}$.

2.2. Calculate the Minimum Load-Shedding Power and Distribute Load-Shedding Power at the Load Buses. After the overall weights are calculated for each load bus, the distributed shedding power at each demand load bus can be implemented according to the following flow chart in Figure 3.

Distributing the shedding power at the load buses requires two processes. In the first process, from the grid configuration and the location of the outage generator, the overall weights are calculated with the support of the AHP algorithm; the results are presented in equation (11). In the second process, when there is an outage generator and load shedding has to be implemented; the calculation of the load shedding power taking into account the process of primary and secondary frequency controls reduces the amount of shedding. This minimizes damages to customers due to power outages.

2.2.1. Primary and Secondary Frequency Controls in Power System. The process of frequency control when there is a disturbance in the power system consists of stages: level 1 control or primary frequency control and level 2 control or secondary frequency control [45]. In case after performing the level 2 control, the frequency has not returned to the allowable value, the load shedding control must be implemented to restore the frequency to the allowable value. The generator frequency control process includes primary and secondary frequency controls described in [46, 47]. The process of this control is shown in Figure 4.

In summary, in the case of an outage of the generator or a power imbalance between the load and the generator, the power system implements primary and secondary frequency controls. After the implementation of the secondary frequency control adjustment process, the electrical system's frequency has not yet recovered to the permissible value, the load shedding will be implemented to restore the frequency. This is the last mandatory solution to avoid grid blackout and power system collapse.

2.2.2. Establish the Minimum Load-Shedding Power. The calculation of the minimum load shedding power ensures the minimum amount of power is shed while restoring the power system frequency to the permissible value and minimize damage to electricity users. The computation takes into account the primary control and the secondary control of the generator group in accordance with the actual operation.

The relationship between the load power variations with frequency variation is determined by the following equation:

$$\Delta P_D = -\frac{\Delta f}{f_n}.P_L.D, \quad (12)$$

where P_L is the active power of the load, ΔP_D is the change of load power according to frequency change, and D is the percentage characteristic of the change of load according to the percentage change of frequency, D value ranges from 1% to 2%. It is determined experimentally in power systems [48]. For example, a value of $D = 2\%$ means that a 1% change in frequency will cause a 2% change in load.

In the power system with n generators and m loads, when the power system has an outage of the generator, the primary frequency control of $(n-1)$ remaining generators is

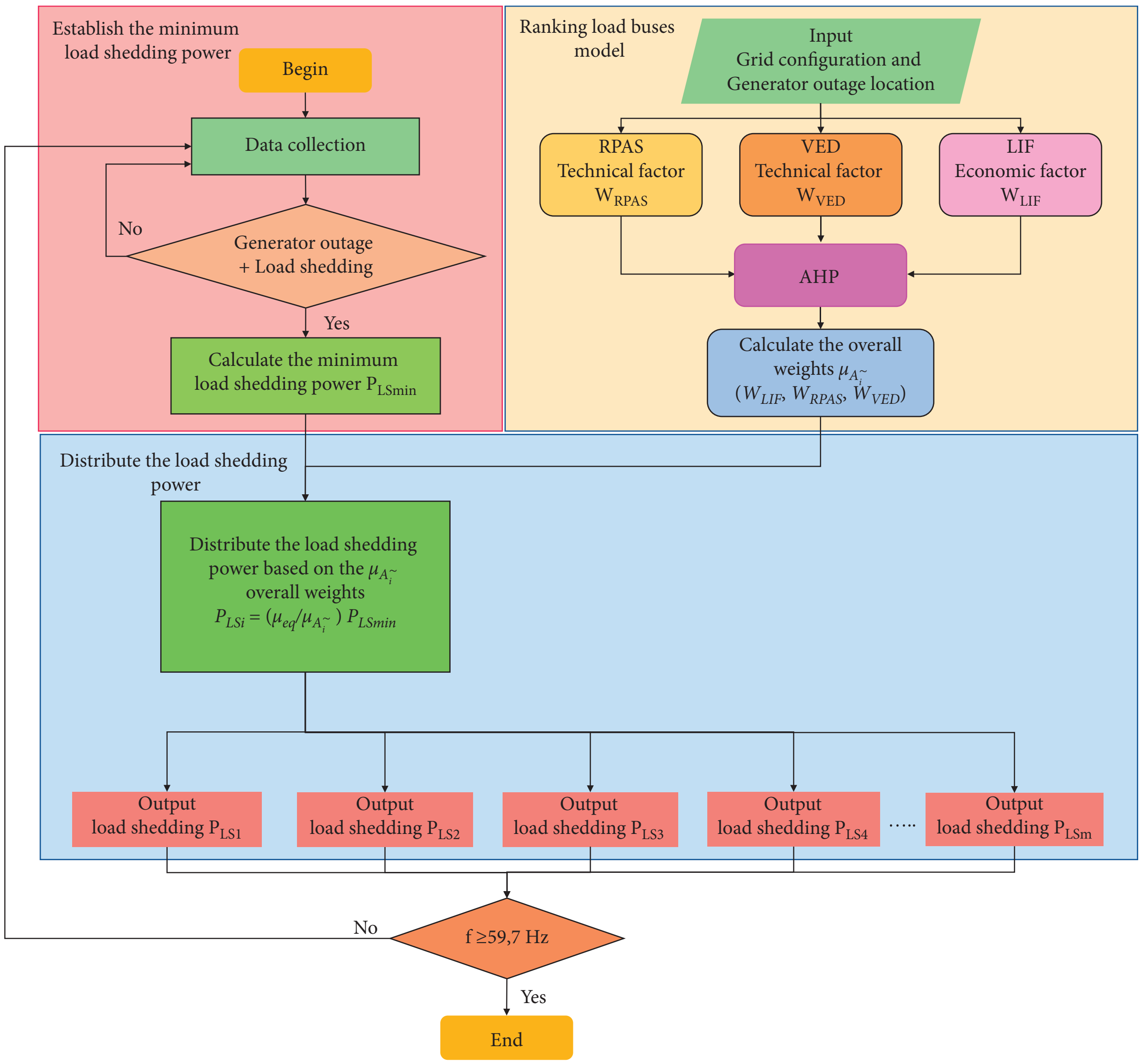

FIGURE 3: The flow chart of the load ranking of the shedding power process that satisfies many criteria.

performed with the amount of power adjustment according to the following expression:

$$\sum_{i=1}^{n-1}\Delta P_{\text{Primary control}} = \sum_{i=1}^{n-1}\frac{-P_{G_{n,i}}}{R_i}.\frac{\Delta f_1}{f_0}, \qquad (13)$$

where $\Delta P_{\text{Primary control}}$is the primary control power of the i-th generator, $P_{Gn,i}$is the rated power of the i-th generator, $\Delta f_1 = f_1 - f_0$is the frequency attenuation, and f_0 is the rated frequency of the power system.

When an outage of the generator occurs, the difference between the generator power and the P_L load power results in a frequency difference; in particular, the frequency is attenuated. The amount of load power depending on the frequency will be reduced by the amount of ΔP_D, and the value of ΔP_D is presented in formula (12).

The status of power balance is presented in the following formulas:

$$P_L - \Delta P_D = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1}\Delta P_{\text{Primary control}}, \qquad (14)$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = \Delta P_D + \sum_{i=1}^{n-1}\frac{-P_{G_{n,i}}}{R_i}.\frac{\Delta f_1}{f_0}, \qquad (15)$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = -\left(\frac{\Delta f}{f_0}\right).P_L.D + \sum_{i=1}^{n-1}\frac{-P_{G_{n,i}}}{R_i}.\frac{\Delta f_1}{f_0}, \qquad (16)$$

$$P_L - \sum_{i=1}^{n-1} P_{G_i} = -\left(\frac{\Delta f_1}{f_0}\right)\left(P_L.D + \sum_{i=1}^{n-1}\frac{P_{G_{n,i}}}{R_i}\right). \qquad (17)$$

Set $\Delta P_L = P_L - \sum_{i=1}^{n-1} P_{G_i}$and $\beta = P_L.D + \sum_{i=1}^{n-1} P_{G_{n,i}}/R_i$. From formula (17), we have

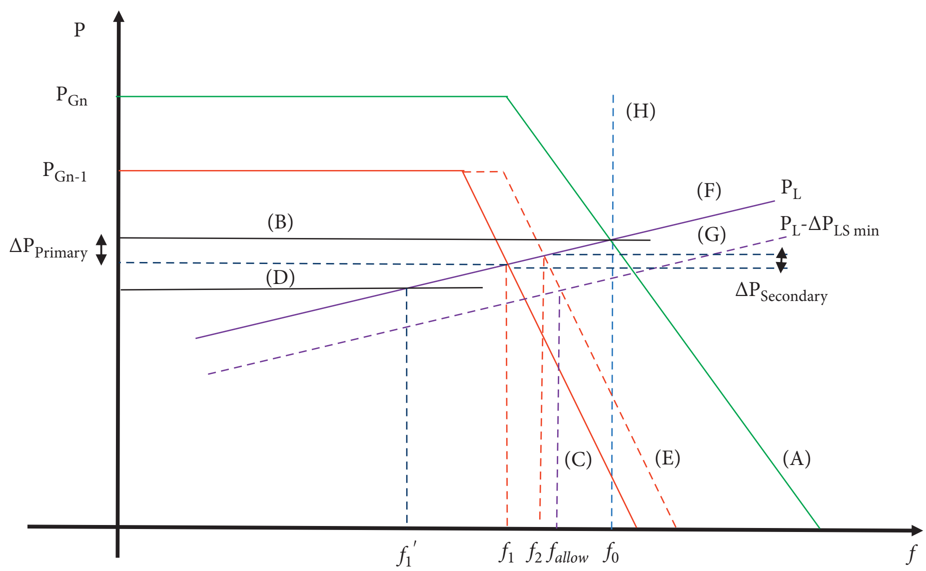

Figure 4: The relationship between frequency deviation and output power deviation [34]. Characteristic lines (A), (C), and (E) show the characteristic of the output power of a generator within a governor relating to the normal operating case, after the outage of the generator and after controlling the primary and secondary; characteristic lines (F) and (G) show the characteristic of the load power in the normal operating conditions and during load shedding, respectively; and characteristic lines (B) and (D) show the characteristic of the output power of a generator without a governor corresponding to the normal operating case, after the outage of the generator. PG_n and PG_{n-1} are the total value of the output power in the normal operating conditions and during the outage of the generator, respectively. f_0 is the rated frequency in the normal operating conditions. f_1' is the frequency when the outage of the generator (in case of the generator without a governor); f_2 is the frequency of the system after the primary and secondary control; and f_{allow} is the restored frequency (59.7 Hz for power grids with a rated frequency of 60 Hz).

$$\Delta P_L = \frac{-\Delta f_1}{f_n}.\beta. \tag{18}$$

In the case of considering the power of the secondary control to restore the frequency, the new status of power balance with the new frequency value f_2, equation (14) becomes:

$$P_L - \Delta P_D = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} + \Delta P_{\text{Secondary control max}}, \tag{19}$$

where $\Delta P_{\text{Secondary control max}}$ is the maximum amount of secondary control power generated by the power system. This amount of secondary control power is determined by the following equation:

$$\Delta P_{\text{Secondary control max}} = \sum_{j=1}^{m} \left(P_{Gm,j} - \Delta P_{\text{Primary control},\, j} \right), \tag{20}$$

where $P_{Gm,j}$ is the maximum generating power of the secondary frequency control generator j and $\Delta P_{\text{Primary control},\, j}$ is the primary control power of the secondary control generator j.

After including the secondary control process and the system frequency has not yet restored to the fallow the allowable value, then load shedding is required to recover the frequency; the minimum amount of load shedding power P_{LSmin} is calculated by the following equations:

$$P_L - \Delta P_D - P_{LS\,\text{min}} = \sum_{i=1}^{n-1} P_{G_i} + \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} + \Delta P_{\text{Secondary control max}}, \tag{21}$$

$$\Delta P_{LS\,\text{min}} = P_L - \Delta P_D - \sum_{i=1}^{n-1} P_{G_i} - \sum_{i=1}^{n-1} \Delta P_{\text{Primary control}} - \Delta P_{\text{Secondary control max}}, \tag{22}$$

$$\Delta P_{LS\,\text{min}} = P_L - \sum_{i=1}^{n-1} P_{G_i} + \frac{\Delta f_{cp}}{f_0}.P_L.D + \sum_{i=1}^{n-1} \frac{P_{G_{n,i}}}{R_i}.\frac{\Delta f_{allow}}{f_0} - \Delta P_{\text{Secondary control max}}, \tag{23}$$

where $\Delta f_{\text{allow}} = f_0 - f_{\text{allow}}$ is the allowable frequency attenuation.

Formula (22) is abbreviated into the following formula:

$$\Delta P_{LS\min} = \Delta P_L + \frac{\Delta f_{\text{allow}}}{f_0}.\beta - \Delta P_{Seconda\ ry\ control\max}. \tag{24}$$

2.2.3. Distribute Load-Shedding Power at the Load Buses. After calculating the overall weights and the $P_{LS\ \min}$, the load-shedding power at each load bus can be distributed in the same way as the principle of load sharing in the parallel circuit as follows:

$$P_{LSi} = \frac{\mu_{eq}}{\mu_{A_i^{\sim}}}.P_{LS\min}, \tag{25}$$

with

$$\mu_{eq} = \frac{1}{\sum_{i=1}^{n} 1/\mu_{A_i^{\sim}}}, \tag{26}$$

where P_{LSi} is the amount load shedding power at the buses, μ_{eq} is the equivalent weight of all load buses, $\mu_{A_i^{\sim}}$ is the overall weights at the i-th bus, and P_{LSmin} is the total minimum load shedding power.

2.3. Case Studies. The efficiency of the suggested approach is experienced on the IEEE 37-bus 9-generator system [47, 49], which is shown in Figure 5. All test cases are simulated using PowerWorld GSO 19 software. The calculations are compared with the traditional load shedding method using an underfrequency load-shedding relay.

In the studied case, the generator JO345 # 1 (bus 28) is facing an outage and disconnected from the grid. Using formula (18), the established frequency value is calculated when the JO345 # 1 generator (bus 28) faces an outage at 59.6 Hz. The frequency value after the outage of generator JO345 # 1 (bus 28) is less than the allowed value.

Therefore, it is important to execute the process of the generator control and re-establish frequency. The primary frequency control is performed automatically. The reaction of the governor is performed immediately after the generator JO345 # 1 (bus 28) has been outage. The primary control power values for each generator turbine are shown in Table 2.

Because the recovery frequency is less than the allowed value, the secondary frequency control process should be implemented after the primary control. Secondary standby generator control power will be mobilized to perform secondary control. In the IEEE 37-bus 9-generator power system diagram, the SLACK 345 (SLACK bus) was chosen as the secondary frequency control generator. In this case, using equation (20), the amount of secondary control power calculated is 10.72 MW. A graphical simulation of the frequency of the system after the implementation of the secondary control is illustrated in Figure 6.

$$\begin{aligned}
\Delta P_{LS\min} &= \Delta P_L + \frac{\Delta f_p}{f_0}.\beta - \Delta P_{\text{Secondary control max}},\\
\Delta P_L &= P_L - \sum_{i=1}^{n-1} P_{G_i} = 9.5394 - 8.31780 = 1.2216,\\
\beta &= P_L.D + \sum_{i=1}^{n-1} \frac{P_{Gi}}{R_i} = 9.5394 \times 0.02 + 187.4 = 187.590788,\\
\Delta P_{LS\min} &= 1.2216 + \frac{(-0.3)}{60} \times 187.590788 - 0.1072 = 0.1764\,\text{pu}.
\end{aligned} \tag{27}$$

Thus, after carrying out the secondary control process, the recovery frequency is 59.66 Hz and has not been back to the allowed value. Therefore, the ultimate solution is load shedding to restore the frequency to the allowable value. Application of formula (24) calculates the minimum amount of load shedding power to restore the frequency to the permissible value.

In a 60 Hz power system, the permissible frequency attenuation Δfallow is 0.3 Hz.

$\Delta f_{\text{allow}} = -0.3$ Hz. Therefore, when calculated in relative units (pu), then $\Delta f_{\text{allow}} = -0.3/60$ (pu).

In summary, the minimum load shedding power $P_{LS\min}$ is 17.64 MW.

We implemented the same calculation steps above for a few other case studies. We calculated the value of the system frequency, the amount of primary and secondary control power and the load power to be reduced. Calculation results for these case studies are shown in Table 3.

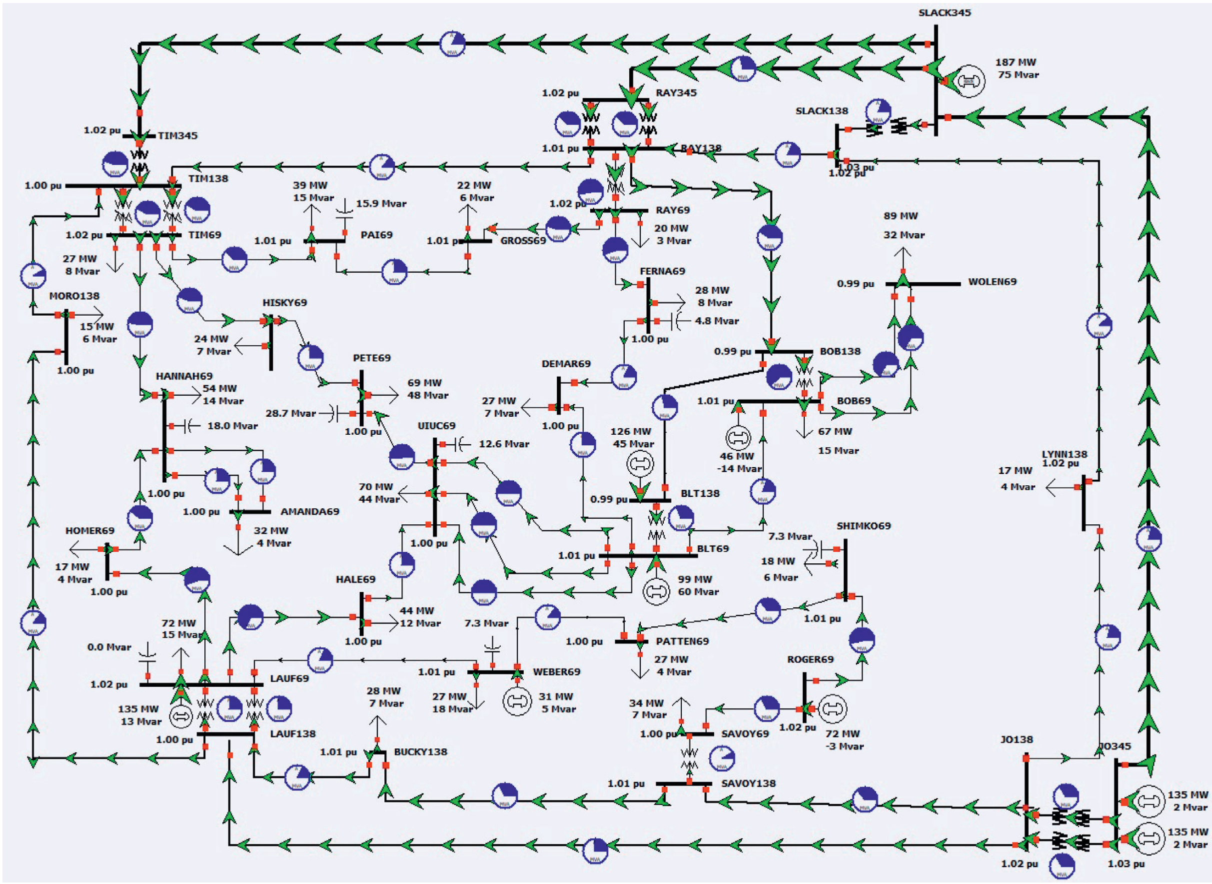

Figure 5: The IEEE 37-bus 9-generator system [47, 49].

Table 2: The parameter values and primary control power of the generator.

Number of generator	Name of generator	P_G (MW)	P_G (pu)	R	$\Delta P_{\text{Primary control}}$(pu)	$P_{G,n}/R$
1	WEBER69	31.5	0.315	0.05	0.035	7
2	JO345#1	0	0	0.05	0	0
3	JO345#2	135	1.35	0.05	0.15	30
4	SLACK345	187.2	1.872	0.05	0.22	44
5	LAUF69	135	1.35	0.05	0.15	30
6	BOB69	46	0.46	0.05	0.052	10.4
7	ROGER69	72	0.72	0.05	0.08	16
8	BLT138	126	1.26	0.05	0.14	28
9	BLT69	99	0.99	0.05	0.11	22
Total		831.7	8.317		0.937	187.4

The results of these calculations are the basis for the distribution of the amount of load-shedding power at the load buses based on the overall weights of the criteria.

After computing the minimum amount of load-shedding power, the next step calculates the load importance factor (LIF), the reciprocal phase angle sensitivity (RPAS), and the voltage electrical distance (VED). Using formulas (2) and (6), calculate the reciprocal phase angle sensitivity (RPAS) and the voltage electrical distance (VED). The parameters of the load importance factor (LIF) were calculated by fuzzy AHP algorithm and published by the authors in [34].

The overall weights for multimethod coordination criteria will be calculated using theory at stage 2: determining the weights of criteria section and expert opinion, obtaining P matrix as follows:

$$P = \begin{bmatrix} 1 & 3 & 2 \\ 1/3 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix}. \tag{28}$$

The eigenvector is calculated based on the matrix P; its value is shown below:

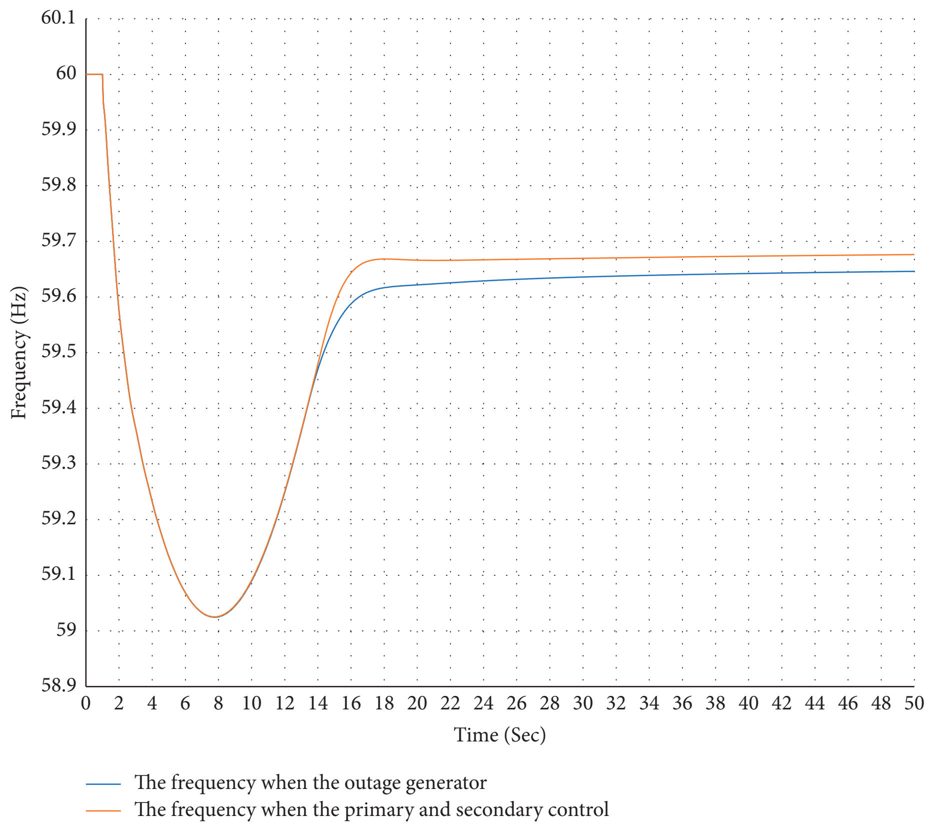

Figure 6: The frequency of the system when the JO345#1 generator outages.

Table 3: The results of generator outage case study.

Generator outage	Frequency after generator outage (Hz)	Frequency within the permissible range	Shed load (MW)
WEBER69	59.97	Yes	0
JO345#1	59.56	No	38.57
JO345#2	59.56	No	38.57
SLACK345	59.62	No	13.89
LAUF69	59.86	Yes	0
BOB69	59.79	Yes	0
ROGER69	59.61	No	18.2
BLT138	59.70	Yes	0

$$W = [W_1, W_2, W_3]^T = [0.53962;\ 0.16342;\ 0.29696]^T. \tag{29}$$

Equations (8)–(10) are used to calculate the largest eigenvalues (λ_{max}), the consistency index (CI), and the stochastic consistency ratio (CR), respectively. The calculation results are presented as follows:

$$\begin{aligned} \lambda_{max} &= 3.009, \\ CI &= 0.0046, \\ CR &= 0.0079. \end{aligned} \tag{30}$$

The above results show that the values of stochastic consistency ratio $CR = 0.00775 < 0.1$, so the proposed judgment matrix is reasonable.

After obtaining the weighted values of the criteria, the next step applies formula (11) to determine the values of the overall weights of each load bus and applies formula (25) to calculate the amount of power needed to be shed at each busload; the values are shown in Table 4 and Figure 7. The smaller overall weights of the load bus indicate that the load bus is of minor LIF, the RPAS is small, and the VED is small and, therefore, that the load will prioritize the shedding load with a large amount of load shedding power, and vice versa.

The suggested approach is compared to an under-frequency load-shedding relay approach. These values are shown in Table 5 [34].

It can be seen that the proposed load-shedding method has less amount of shedding (65.19 MW) than the UFLS, thereby minimizing the damage caused by power outages a lot. Simultaneously, satisfying the goal of combining a variety of economic and technical methods: The Load Importance Factor

Table 4: Ranking of load shedding and the amount of load-shedding power at buses when the JO345#1 (bus 28) generator outage.

Ranking of load shedding	Bus	RPAS	VED	Load importance factor (W_{LIF})	Weight of RPAS (W_{RPAS})	Weight of VED (W_{VED})	Overall weights ($\mu_{\tilde{A}_i}$)	Shed load (MW)
1	Bus 03	0.06046	2.98914	0.00012	0.02513	0.03331	0,01406	1,33759
6	Bus 05	0.11244	3.39848	0.00012	0.04674	0.03787	0,01895	0,99271
9	Bus 10	0.06680	4.40264	0.00164	0.02777	0.04906	0,01999	0,94090
3	Bus 12	0.05650	3.49661	0.00211	0.02349	0.03896	0,01655	1,13679
13	Bus 13	0.12095	4.80471	0.00388	0.05028	0.05354	0,02621	0,71773
10	Bus 14	0.13660	3.13791	0.00359	0.05678	0.03497	0,02160	0,87077
5	Bus 15	0.07069	3.66261	0.00236	0.02939	0.04081	0,01820	1,03365
8	Bus 16	0.08001	3.80214	0.00427	0.03326	0.04237	0,02032	0,92565
21	Bus 17	0.09936	4.31684	0.05642	0.04130	0.04810	0,05148	0,36537
23	Bus 18	0.11118	3.72396	0.18097	0.04621	0.04150	0,11753	0,16004
22	Bus 19	0.10774	4.56991	0.09891	0.04478	0.05092	0,07581	0,24810
24	Bus 20	0.17781	3.21071	0.19005	0.07391	0.03578	0,12526	0,15017
25	Bus 21	0.10988	4.32333	0.19508	0.04568	0.04818	0,12704	0,14806
7	Bus 24	0.08637	3.53451	0.00418	0.03590	0.03939	0,01982	0,94898
16	Bus 27	0.08158	3.83314	0.02274	0.03391	0.04271	0,03050	0,61677
2	Bus 30	0.05542	1.93331	0.01184	0.02304	0.02154	0,01655	1,13661
4	Bus 33	0.10895	2.52799	0.00337	0.04529	0.02817	0,01758	1,06978
18	Bus 34	0.16743	3.22803	0.02305	0.06960	0.03597	0,03450	0,54529
12	Bus 37	0.12353	3.82862	0.00339	0.05135	0.04266	0,02289	0,82173
15	Bus 44	0.06433	2.56398	0.03384	0.02674	0.02857	0,03112	0,60451
17	Bus 48	0.08365	4.05141	0.02334	0.03477	0.04515	0,03169	0,59364
14	Bus 53	0.07244	4.01952	0.01916	0.03011	0.04479	0,02856	0,65857
19	Bus 54	0.07037	3.72225	0.04441	0.02925	0.04148	0,04106	0,45812
20	Bus 55	0.13139	4.64896	0.04441	0.05462	0.05181	0,04827	0,38967
11	Bus 56	0.04985	2.00815	0.02675	0.02072	0.02238	0,02447	0,76880
	Total			1	1	1	1	17.64

(economic), the Reciprocal Phase Angle Sensitivity, and the Voltage Electrical Distance. Here, the recovery frequency value of the proposed method is lower than the UFLS method. However, this value is still within the allowable parameters and acceptable range (59.7 Hz). Moreover, the voltage value and the recovery time of the rotor angle after load shedding are better quality than before the load shedding.

The frequency, rotor angle, and voltage comparison between the proposed method and the UFLS method are presented in Figures 8 –10.

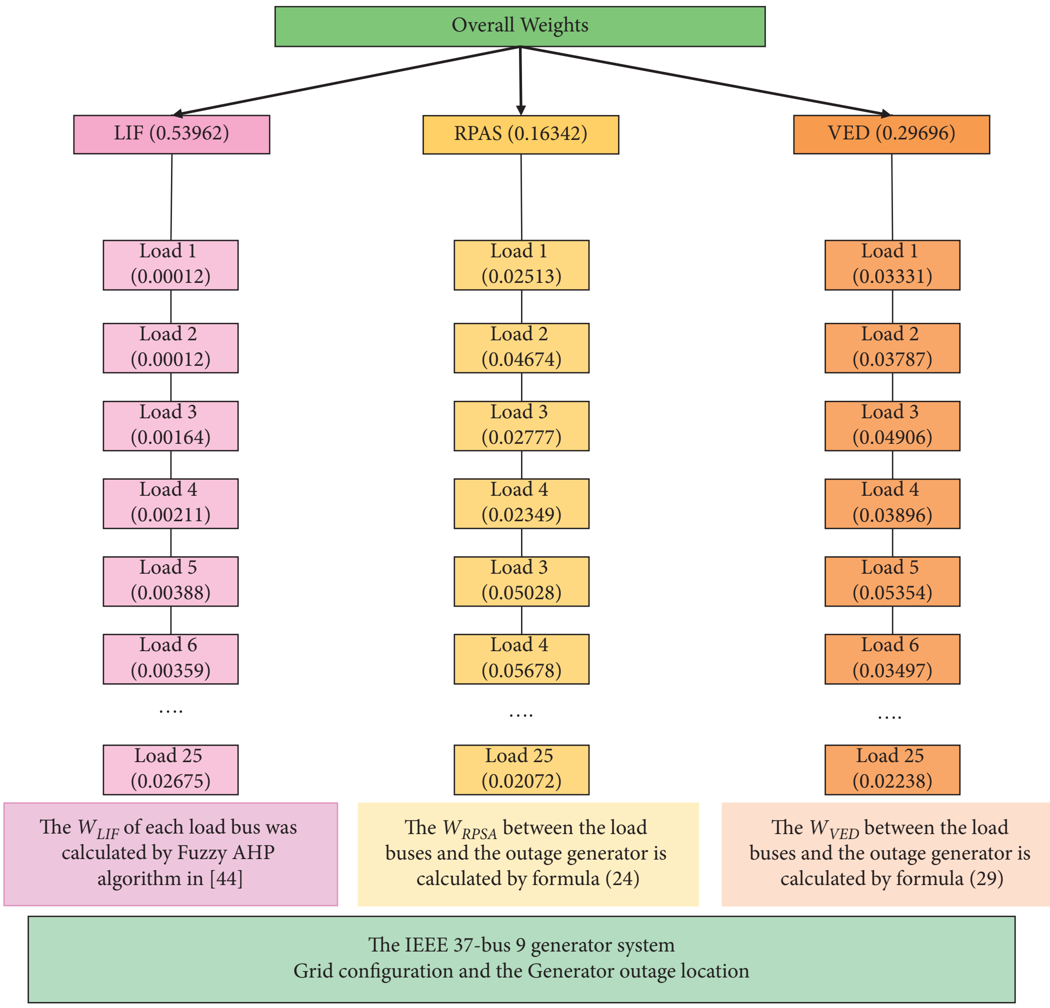

Figure 7: The value of the weights in the IEEE 37-bus 9-generator system hierarchy structure.

Table 5: The UFLS scheme using load-shedding table [47].

The steps UFLS	Frequency (Hz)	Time delay (s)	The amount of load shedding (the percent of total load) (%)	The total amount of load shedding (%)
A	59.7	0.28	9	9
B	59.4	0.28	7	16
C	59.1	0.28	7	23
D	58.8	0.28	6	29
E	58.5	0.28	5	34
F	58.2	0.28	7	41
J	59.4	10	5	46

3. Discussion

The AHP method is quite simple and intuitive in a three-criterion environment. It easily supports the calculation of the overall weights of the criteria. In this study, the pair-wise comparison matrixes are formed by one expert. If there are many experts, some group decision-making methods can be accepted to aggregate the pair-wise comparison matrixes determined by these experts [50]. For example, a weighted geometric mean method can be used as a tool to do this aggregation. In addition, if the value of the pair-wise comparison is uncertain, the combined use of AHP with fuzzy methods is also one of the possible solutions [34].

For a very large power system, when there is a failure of one generator, the space of influence on the technical parameters of the entire grid is negligible. It is only significant when very serious problems occur and the large-power system is divided into smaller systems or islands. In particular, in the larger power grid, areas far from the outage generator are not affected much. It only affects the areas near and around the outage generator. Therefore, this situation does not need to take the entire grid into consideration. In

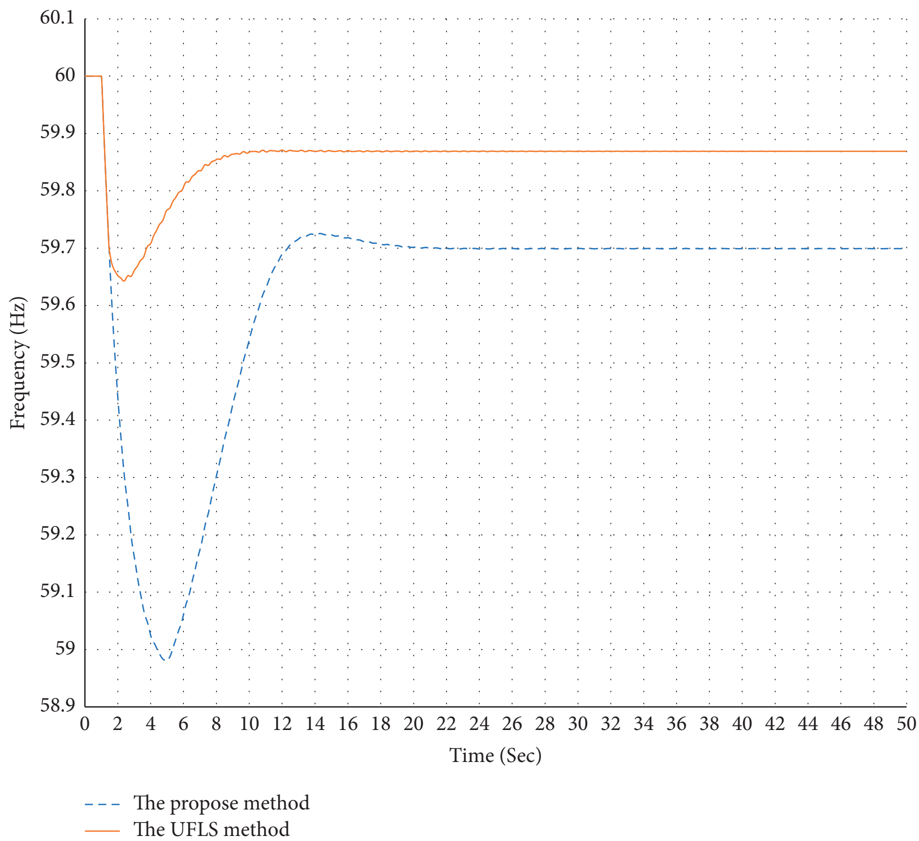

Figure 8: The frequency comparison between the proposed method and the traditional met.

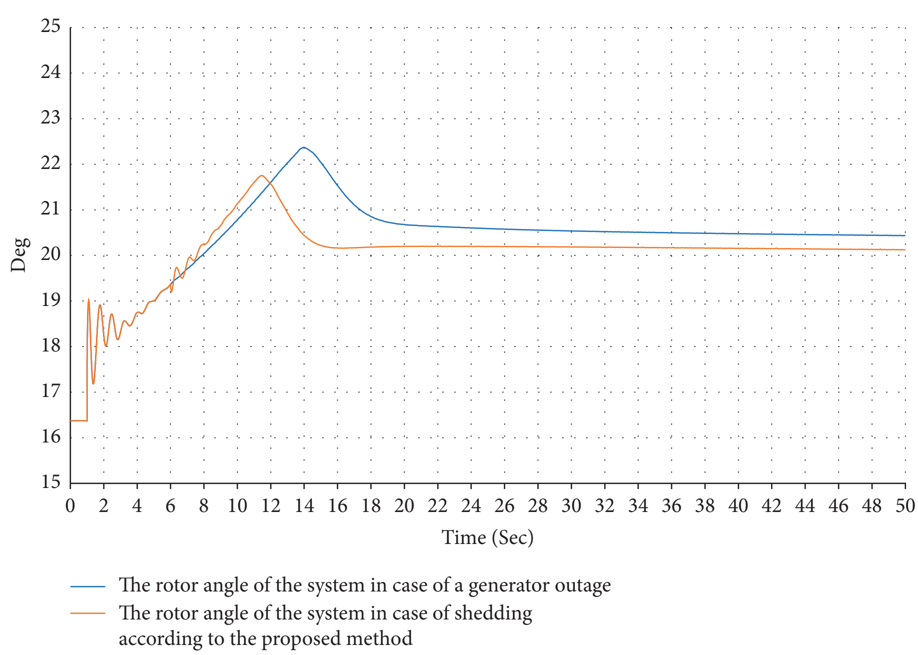

Figure 9: Compare the rotor angle when generator outage and when load shedding according to the proposed method.

this case, the problem should only be considered in a range around the "observation area" that is affected by the outage generator. The determination of RPAS and VED will support determining this influence gap. However, the RPAS and VED values for each grid configuration need to be studied further. At this time, the opinion of the power system expert will support limiting "observation areas" and "inter-observation areas".

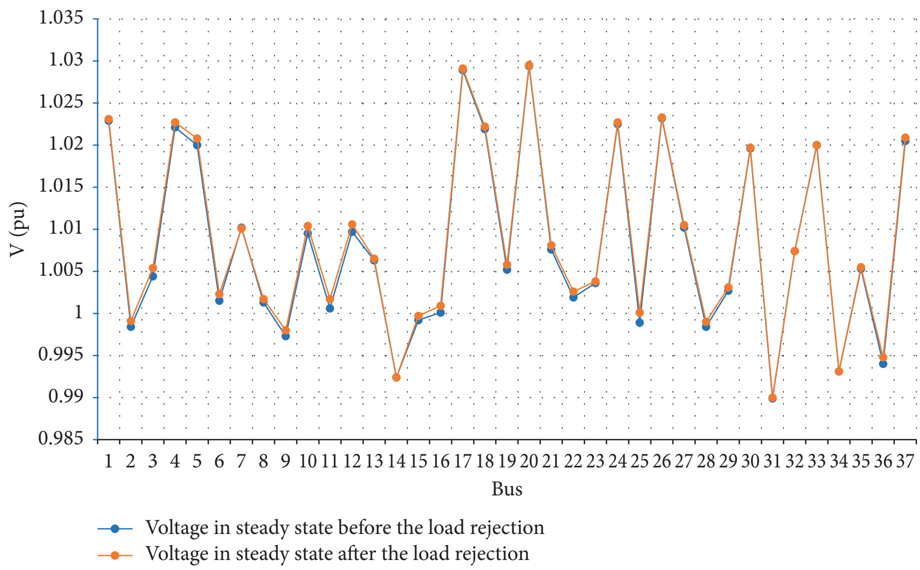

FIGURE 10: Compare the voltage when generator outage and after load shedding according to the proposed method.

4. Conclusions

The calculation of overall weights includes the following criteria: Reciprocal Phase Angle Sensitivity (RPAS), Voltage Electrical Distance (VED), and Load Importance Factor (LIF). It ensures multicriteria decision-making that meets economic and technical factors. The analytic hierarchy process algorithm is applied to calculate the weights of the criteria, thereby contributing to combining the weights of the criteria together to determine the combined weight. This weight is used to rank and distributed shedding power to the load buses.

The computation of the amount of load shedding includes the generator control processes that makes the load-shedding power less than the UFLS method and restores the frequency to the allowed value.

The distributed shedding power at each demand load bus based on the overall weights W ensures multimethod coordination of economic and technical criteria and reduces technical and economic losses to power companies and customers.

The efficiency of the suggested approach has been verified on the 37-bus 9-generator system under case studies. This implementation is better than that of the traditional UFLS method. The results proved that the suggested approaches solutions to reduce amount of shedding power while still meeting the technical and economic operating conditions of the network. In future work, the load-shedding scheme should reflect the following aspects minimizing the economic and technical losses of both power companies and customers. To solve this multiobjectives problem, we need to apply algorithms such as genetics algorithm and PSO.

The feasibility of the proposed technique has been shown on the 37-bus system with 9 generators under various experiments. This presentation is superior to that of the traditional UFLS method. The discoveries show that the proposed strategy brings about a decreased measure of load shedding while at the same time fulfilling the specialized technical-economic operating conditions of the network. Later in work, the load-shedding issue ought to consider the accompanying components minimizing the economic and technical losses of both influence organizations and clients. To resolve this multiobjective issue, we need to apply calculations like genetics algorithm and PSO.

Data Availability

The data of expert opinion in the formulation of the judgment matrix and parameter values and primary control power of the generator used to support the findings of this study are included within the article. The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All the authors contributed to the study's conception and design. Topical guidance was performed by Nghia T. Le. Material preparation, data collection, and analysis were performed by An T. Nguyen, Trang H. Thi, Vu Nguyen Hoang Minh, Anh H. Quyen, and Binh T. T. Phan. The first draft of the manuscript was written by Nghia T. Le, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

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Research Article

A Novel Hybrid MCDM Model for the Evaluation of Sustainable Last Mile Solutions

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Modern social trends are intensively transforming supply chains and the last mile as their most complex and most expensive segment. For the realization of the last mile, various solutions can be defined which combine initiatives, technologies, and concepts of city logistics. The successful implementation of these solutions depends on the characteristics of the city, the goals of stakeholders, and the ability to achieve economic, social, and environmental sustainability. In accordance with that, this paper defines innovative sustainable last mile solutions and evaluates their potential application in the real-life logistics system of the city. As evaluation requires consideration of a large number of criteria, this is a problem of multicriteria decision-making, and for solving it, a novel hybrid model that combines Delphi, FARE (Factor Relationship), and VIKOR (Višekriterijumska Optimizacija i Kompromisno Rešenje) methods in the fuzzy environment has been developed. The applicability of the model is demonstrated in the example of evaluating the last mile solution for the central business district of the City of Belgrade. A combination of microconsolidation centers and autonomous vehicles is obtained as the most favorable solution.

1. Introduction

Globalization, growth of consumer society, the shift of production paradigm based on individualization, personalization and shorter product life, development of the industry 4.0 based on technological progress, automation, digitalization, networking and new forms of communication, development of e-commerce, sustainability, and other modern trends intensively transform the ways of realization of goods and transport flows. Requirements for efficient realization of supply chains are becoming increasingly strict, which is especially expressed in the realization of the last mile as their most complex and most expensive segment. The last mile is realized in the urban environments that are characterized by various economic, geographical, sociological, cultural, historical, and demographic features, architectural heritage, habits, and perceptions of the population, etc. [1]. In addition, there are various stakeholders in the cities (users, logistics providers, residents, and city administration) whose goals define the requirements for planning and implementation of the last mile in accordance with the principles of economic, social, and environmental sustainability. Accordingly, the subject of this paper is the creation of sustainable last mile solutions (LMSs) by combining different initiatives, technologies, and concepts of city logistics (CL). The goal is to evaluate and rank them and analyze the possibility of their application in the real-life logistics system of the city.

As it requires consideration of a large number of criteria, the problem of multicriteria decision-making (MCDM) is defined in the paper. The existing literature demonstrated many examples of combining different MCDM methods, but there are no examples of combining the FARE (Factor Relationship) with Delphi and VIKOR (Višekriterijumska Optimizacija i Kompromisno Rešenje) methods. Furthermore, the scientific literature lacks articles that define innovative, sustainable LMSs and evaluate them from a multicriterial perspective. This article fulfills these research gaps by defining innovative and potentially sustainable LMSs and evaluating them through a wide set of defined criteria with a novel hybrid model that combines Delphi, FARE, and VIKOR methods in the fuzzy environment. The applicability of the model is demonstrated in the example of ranking sustainable LMSs in the City of Belgrade. A combination of microconsolidation centers and autonomous vehicles was obtained as the most favorable solution in relation to the observed criteria.

The paper is organized as follows: Section 2 provides an overview of the literature on the methods that make up the MCDM model and the initiatives, technologies, and concepts that form the sustainable LMSs. After that, in Section 3, the structure of the defined model is given and the steps of its application are described. Section 4 describes the LMSs applicable in the City of Belgrade, as well as the criteria for their evaluation. The application of the model for solving the defined problem and the sensitivity analysis are also presented in the same section. Sections 5 and 6 discuss the achieved results and the conclusions and directions for future research, respectively.

2. Literature Review

This section provides an overview of the literature on recent applications of MCDM methods, the methods that make up the proposed hybrid MCDM model, concepts, technologies, and initiatives that could be combined to form sustainable solutions for the realization of the last mile, as well as the criteria for their evaluation.

2.1. Overview of Recent MCDM Method Applications. Using MCDM methods for solving multicriterial problems is a popular topic in the existing literature [2]. Besides the conventional form, the developed MCDM models in the literature were also applied in various uncertainty environments—fuzzy, grey, rough, neutrosophic, etc. [3]. Novel MCDM methods [4] and hybrid models [5] are regularly proposed in the literature for solving decision-making problems in various fields.

The long-established and widely accepted MCDM methods, such as AHP, TOPSIS, and VIKOR, find extensive application to this day. In recent years, the AHP method was used for selecting routes for oversized cargo transport [6], identifying the most relevant sustainability issues [7], selecting sustainable projects [8], etc. The TOPSIS method found its application for reverse logistics performance evaluation [9], policy selection for developing electric vehicle systems [10], supplier selection [11], etc. The VIKOR method was recently used for risk evaluation [12], selection of supplier portfolio of key outsourcing parts [13], selection of industrial robots [14], etc. The existing literature is also abundant in newly introduced methods such as CODAS [15], KEMIRA [16], PIPRECIA [17], and MARCOS [18]. Aside from applying MCDM methods independently, many literature articles propose and develop hybrid MCDM models by combining two or more MCDM methods. Various MCDM models can be found in the literature, such as DEMATEL-AEF-VIKOR [19], SERVQUAL-AHP-TOPSIS [20], DANP-FUCOM-VATOPSIS [21], SSC-VIKOR [22], SWARA-MARCOS [23], and KEMIRA-BWM-MOORA [24].

2.2. Overview of the Methods That Make Up the MCDM Model. The paper proposes a novel hybrid MCDM model that combines the fuzzy Delphi, fuzzy FARE, and fuzzy VIKOR methods. The fuzzy FARE method was used in the first part of the model to evaluate and determine the weights of the criteria. As the evaluation of the criteria is performed by several decision-makers (stakeholders' representatives), the Delphi method was used to consolidate their evaluations. The fuzzy VIKOR method was used in the second part of the model to evaluate, rank, and select the most favorable alternative in relation to the defined criteria.

The FARE method was developed by Ginevičius [25], and it is based on defining the relationship between all decision-making elements (criteria, subcriteria). In the first phase of the application, the method requires a minimum amount of initial data (evaluations) by the experts on the existence of influences between individual decision-making elements, as well as their direction and strength [26]. In later phases, the influences between other elements of decision-making are analytically determined on the basis of these evaluations. In this way, there is a drastic reduction in the required evaluations by experts [27]. The main advantages of the method, compared to the other methods based on the pairwise comparison of decision-making elements, e.g., AHP and ANP, are a small number of necessary evaluations, elimination of contradictions that occur in the comparison matrices, high reliability, consistency, and stability of the obtained results, etc. [26–28]. Due to the stated advantages, FARE was chosen in this paper for evaluation and determination of the criteria weights. However, as with other methods based on expert evaluation, the problem may arise due to ambiguous or unclear assessments, which can be solved by applying fuzzy logic. Therefore, the fuzzy extension of the FARE method, performed by Roy et al. [29], was used in the paper. The FARE method has found wide application in the literature and has so far been used, either alone or in a combination with other methods, either in conventional form or in the fuzzy environment, in various areas for evaluation and selection of 3PL providers [29], selection of production materials [30], evaluation of mechanical processes [27], evaluation of the impact of technology transfer on the value creation [31], selection of political candidates [5], evaluation of visibility in freight vehicles [32], etc.

The Delphi method was developed by Dalkey and Helmer [33] and is generally used to iteratively process decision-makers' opinions until a consensus is reached on the subject of the research [34]. The method is defined as a process of group communication in which the convergence of opinions on a specific real-life problem is achieved. It is suitable for forming consensus through a series of questionnaires which in several iterations collect data from a group of selected respondents (experts). The main advantages of the method are anonymity, iteration, controlled feedback, statistical group responses, and stability in the decisions of decision-makers on a given topic [35]. The main disadvantages of the method are the need for multiple repetitions of the questionnaire in order to achieve convergence of evaluations and high costs of data collection, especially for large and complicated problems and ambiguity and uncertainty in the assessment by experts [35, 36]. One way to overcome these shortcomings is to extend the Delphi method to the fuzzy environment, which was performed by Murry et al. [37]. The Delphi method, alone or in combination with other methods, in conventional form or in the fuzzy environment, has been used in various fields to evaluate renewable energy development projects [38], locate terminals [39, 40], select plant layout [41], define typical structures of intermodal terminals [42], evaluate battery storage systems [43], plan intermodal terminals [44], etc.

The VIKOR method was developed by Opricovic [45] and is based on the ranking and selection of alternatives in relation to numerous, in most cases conflicting, and mutually incomparable decision-making criteria and determines a compromise solution to the problem. The obtained compromise solution can be accepted by the decision-maker because it achieves the majority maximum group utility and minimum individual regret of the opposing parties. The main advantages over other methods most commonly used to rank alternatives, e.g., ELECTRE, PROMETHEE; TOPSIS, etc., are stability, simplicity in the use of cardinal information, obtaining a unique solution, obtaining the final order of alternatives, obtaining the solution that is closest to the ideal solution, etc. [46–49]. As with the previous methods, one of the biggest problems of the conventional VIKOR method is the impossibility of adequate perception of inaccuracies in the evaluations of decision-makers, which is solved by applying fuzzy logic. The fuzzy extension of the VIKOR method was performed by Opricovic [50]. The VIKOR method is very popular and has been widely used in the literature in various areas for machine tool selection [51], evaluation of sustainable city logistics initiatives [52], health services [53], intermodal transport technology [54], risk management projects [55], CL conceptions [56], etc.

There are no examples in the literature of combining the FARE method with Delphi or VIKOR methods, either in conventional form or in the fuzzy environment. Accordingly, the development of a novel MCDM model that combines these three methods in the fuzzy environment is one of the main contributions of this paper.

2.3. Last Mile Solution Sustainability. Based on different initiatives, measures, technologies, concepts, approaches, etc., a large number of practical solutions can be defined in CL, and even within a single solution, it is possible to define several different scenarios [57]. CL solutions are not universal—solutions that are proven good for particular urban areas can perform significantly worse in others [56, 58, 59]. The key to finding high-quality solutions for CL problems is in the compromise between the goals of stakeholders as well as in the balance among the identified demands and available resources [60]. A portion of the existing literature research focused on the selection of adequate last mile delivery solutions from a set of individual technologies and measures (e.g., [61–63]). Some research focused on the selection of the most appropriate initiatives from the defined CL initiative groups (e.g., [64, 65]). Most of the existing research focused on individual initiatives and technologies, but there are also examples that analyzed more complex CL solutions, defined by combining different initiatives, measures, and technologies.

The paper [66] analyzed the application of different drone-based CL solutions through a wider set of CL performances. The paper highlights that multiechelon CL solutions can achieve sustainability but require the definition of appropriate regulatory frameworks, especially for the application of autonomous vehicle technologies. Different CL solutions that take into account specific characteristics of the city and the environment are analyzed in the paper [56]. The goal was to find the best CL solution for the City of Belgrade for all stakeholders, but with regard to all the factors that describe the urban area. The solutions combined different categories of logistics centers, the concepts of consolidation, and the application of environment-acceptable transportation technologies. The problem of selecting the most appropriate solution for the logistics system in the central business district of Belgrade is solved in [67]. Different multiechelon systems, with different consolidation levels and the application of different transport technologies, are taken into account. The paper in [68] focused on the selection of the most appropriate CL solution for the City of Brussels where different configurations of urban consolidation centers and their combination with several vehicle categories, toll charging, and time access restrictions are taken into account. The selection of the most appropriate horizontal cooperation model between urban consolidation centers for the City of Bucharest is covered in the paper [69], while the paper in [70] analyzes the sustainability of the urban consolidation center in Copenhagen in scenarios that vary according to the measures of access restrictions for commercial vehicles, toll charging, and the number of public sector subsidies. In the paper [71], a last mile delivery solution that combines parcel lockers and electro-powered cargo cycles is analyzed for the case of Hannover.

A review of the most analyzed initiatives, technologies, and concepts of CL, as well as some of the new ones that stand out as the potential future solutions, is presented in Table 1.

The presence of multiple stakeholders, with often conflicting goals, gives a multicriterial dimension to the problems of selecting the most appropriate CL solutions [129]. Various criteria can be defined for solving CL problems, and those most widely used are presented in Table 2.

There are no papers in the literature that deal with defining innovative and complex sustainable solutions for the realization of the last mile, nor their evaluation by applying a wide set of criteria. This is done below on a real-life example and represents one of the main contributions of this paper.

Table 1: Review of CL initiatives, concepts, and technologies.

Initiative/technology/concept	Type	Literature
Cooperation	—	[72, 73]
Consolidation	Urban consolidation centers	[69, 70, 74–76]
	Microconsolidation	[77, 78]
Crowdsourcing	—	[79–86]
Inland waterway transport	—	[87–90]
Rail transport	Regular tram lines	[91–93]
	Integrated rail systems	[94]
	Cargo-hitching	[95, 96]
Parcel lockers	—	[71, 97–100]
Eco-vehicles	Electric	[101]
	Hydrogen	[102]
	Hybrid	[103]
	Cargo bicycles	[104–107]
	Cargo bikes	[108, 109]
	Scooters	[110]
	Rickshaws	[111]
Autonomous vehicles	Ground autonomous vehicles	[112–115]
	Aerial autonomous vehicles (drones)	[66, 112, 116–123]
Underground logistics systems	—	[124–129]

Table 2: Relevant criteria review.

Criteria group	Criteria	References
Technical	Efficiency (loading factor, trip effectiveness, volume of goods handled)	[61, 62, 65, 66, 129]
	Reliability, flexibility, customer coverage	[61, 64, 65]
	Service quality, service level, delivery time	[56, 57, 61–63, 65–67, 69, 129]
	Possibility of implementation, operative barriers, issues related to the lack of infrastructure	[56, 62]
	Modal split of transport work	[56, 66]
	Goods flow transformation degree	[56, 66, 67]
	Traceability, Information security	[62]
Economic	Costs (operational, implementation, land and equipment acquisition, staff training, insurance, taxes)	[56, 57, 61–68, 70, 129]
Social	Freeing of public space, consistency with urban planning, the attractiveness of the city zone	[56, 61, 64, 65, 67, 68]
	Congestions, vibrations, noise, safety, mobility	[56, 57, 61, 63–65, 67, 68, 129]
	Cooperation of stakeholders	[62]
	Accessibility	[61, 64, 65, 129]
Environmental	Air pollution, energy conservation, waste generation	[56, 57, 61, 64–68, 70, 129]

3. Proposed Hybrid MCDM Model

For solving the problem of evaluating the sustainable LMSs, a novel hybrid MCDM model was developed in this paper that combines the fuzzy Delphi-based fuzzy FARE and the fuzzy VIKOR method. The structure of the proposed model is presented in Figure 1, while the steps of the model, which is universally applicable and which can, after minimal adjustments, be used to solve the problems in different areas, are described in detail as follows:

Step 1: define the problem structure; i.e., form the sets of alternatives and criteria for their evaluation and identify the stakeholders interested in solving the problem.

Step 2: define the fuzzy scale for the evaluations of criteria and alternatives by the decision-makers. Linguistic evaluations and corresponding triangular fuzzy values are presented in Table 3.

Step 3: obtain the criteria weights by applying the fuzzy Delphi-based fuzzy FARE method. Also we have the following:

Step 3.1: form the criteria evaluation matrices $\widetilde{A}_h$ based on the linguistic evaluations by the decision-makers that represent various stakeholders, and transform them into triangular fuzzy values using the relations given in Table 3:

$$\widetilde{A}_h = \left[\widetilde{a}_{ijh}\right]_{n\times n}, \quad \forall h = 1, \ldots, p, \tag{1}$$

where $\widetilde{a}_{ijh} = (l_h, m_h, u_h)$ is the evaluation of the strength of impact (importance) of the criterion i in relation to the criterion j by the decision-maker h, l_h,

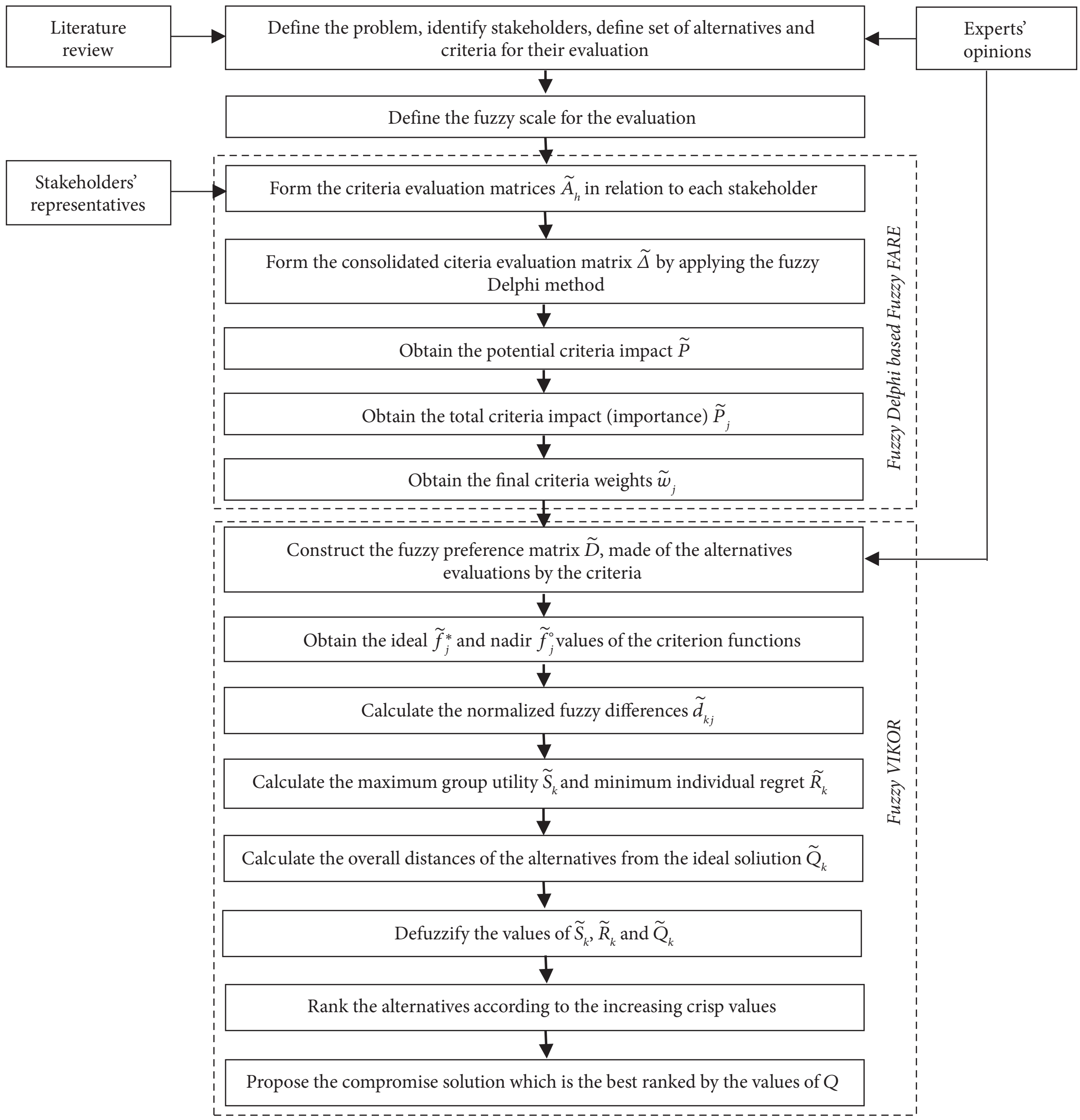

Figure 1: Structure of the proposed MCDM model. The model consists of two main parts, Fuzzy Delphi-based fuzzy FARE for obtaining criteria weights and fuzzy VIKOR for ranking the alternatives.

Table 3: Fuzzy scale from the evaluations.

Linguistic evaluation	Abbreviation	Fuzzy scale
None	N	(1, 1, 2)
Very low	VL	(1, 2, 3)
Low	L	(2, 3, 4)
Fairly low	FL	(3, 4, 5)
Medium	M	(4, 5, 6)
Fairly high	FH	(5, 6, 7)
High	H	(6, 7, 8)
Very high	VH	(7, 8, 9)
Extremely high	EH	(8, 9, 10)

m_h, and u_h are lover, middle, and upper values of the triangular fuzzy evaluation $\widetilde{a}_{ijh}$, n is the number of criteria taken into account, and p is the number of decision-makers performing the evaluations. When forming the matrix $\widetilde{A}_h$ the following condition must be met:

$$\tilde{a}_{jih} = -\tilde{a}_{ijh}, \tag{2}$$

and the evaluation is considered consistent if the following is fulfilled:

$$\sum_{j=1}^{n} u_h = -\sum_{j=1}^{n} l_h, \quad \forall h = 1, \ldots, p. \tag{3}$$

Step 3.2: form the consolidated criteria evaluation matrix $\tilde{\Delta}$ by applying the fuzzy Delphi method [130]:

$$\tilde{\Delta} = \left[\tilde{\delta}_{ij}\right]_{n\times n}, \tag{4}$$

$$\tilde{\delta}_{ij} = (\alpha, \beta, \gamma), \tag{5}$$

$$\alpha = \min(l_h), \quad h = 1, \ldots, p, \tag{6}$$

$$\beta = \left(\prod_{h=1}^{p} m_h\right)^{1/p}, \quad h = 1, \ldots, p, \tag{7}$$

$$\gamma = \max(u_h), \quad h = 1, \ldots, p, \tag{8}$$

where α, β, and γ are lower, middle, and upper values of consolidated fuzzy evaluation $\tilde{\delta}_{ij}$, respectively, and $\alpha \le \beta \le \gamma$.

Step 3.3: obtain the potential criteria impact in the following way:

$$\tilde{P} = \tilde{H}(n-1), \tag{9}$$

where $\tilde{P}$ is the potential impact (importance) of all criteria for the defined problem, and $\tilde{H}$ is the highest value of the scale used for the evaluations.

Step 3.4: obtain the total impact (importance) of criterion $\tilde{P}_j$ by applying the following equation:

$$\tilde{P}_j = \sum_{i=1}^{n} \tilde{\delta}_{ij}, \quad \forall j = 1, \ldots, n, \ j \ne i. \tag{10}$$

Step 3.5: obtain the final fuzzy criteria weights $\tilde{w}_j$ by applying the following equation:

$$\tilde{w}_j = \frac{\tilde{P}_j^r}{\tilde{P}_H}, \quad \forall j = 1, \ldots, n, \tag{11}$$

where $\tilde{P}_H$ is the total potential impact (importance) of the considered set of criteria obtained in the following way:

$$\tilde{P}_H = n \times \tilde{P} \tag{12}$$

and $\tilde{P}_j^r$ is the real total impact of the criterion j obtained in the following way:

$$\tilde{P}_r^j = \tilde{P}_j + \tilde{P}, \quad \forall j = 1, \ldots, n, \tag{13}$$

Step 4: evaluate the alternatives by applying the fuzzy VIKOR method. The procedure is adapted from the paper [131], and the steps are described as follows.

Step 4.1: construct the fuzzy preference matrix ($\tilde{D}$). It is necessary to perform the evaluation of the alternatives (LMSs), in relation to the criteria using the triangular fuzzy values given in Table 3:

$$\tilde{D} = \left[\tilde{f}_{kj}\right]_{o\times n}, \tag{14}$$

where $\tilde{f}_{kj} = (l_{kj}, m_{kj}, u_{kj})$ denotes triangular fuzzy evaluations of the alternative k in relation to the criterion j. o is the total number of alternatives taken into consideration.

Step 4.2: obtain the ideal $\tilde{f}_j^* = (l_j^*, m_j^*, u_j^*)$ and nadir $\tilde{f}_{j^\circ} = (l_j^\circ, m_j^\circ, u_j^\circ)$ values of all criterion functions which represent the evaluations of the alternatives by the criteria depending on whether they are the benefit or cost criteria. The set of benefit criteria is denoted as J^b, while the set of cost criteria is denoted as J^c.

$$\begin{aligned} \tilde{f}_j^* &= \max_k \tilde{f}_{kj}, \quad \tilde{f}_{j^\circ} = \min_k \tilde{f}_{kj}, \quad \text{for } j \in J^b, \\ \tilde{f}_j^* &= \min_k \tilde{f}_{kj}, \quad \tilde{f}_j^\circ = \max_k \tilde{f}_{kj}, \quad \text{for } j \in J^c. \end{aligned} \tag{15}$$

Step 4.3: calculate the normalized fuzzy differences $\tilde{d}_{kj}$:

$$\tilde{d}_{kj} = \frac{\tilde{f}_j^* \ominus \tilde{f}_{kj}}{u_j^* - l_{j^\circ}}, \text{for } j \in J^b \tilde{d}_{kj} = \frac{\tilde{f}_{kj} \ominus \tilde{f}_j^*}{u_{j^\circ} - l_j^*} \text{ for } j \in J^c. \tag{16}$$

Step 4.4: calculate the values of $\tilde{S}_k = (S_k^l, S_k^m, S_k^u)$, representing the normalized fuzzy difference, i.e., maximum group utility, and the values of $\tilde{R}_k = (R_k^l, R_k^m, R_k^u)$ representing the maximum fuzzy difference, i.e., minimum individual regret, by applying the following equations:

$$\tilde{S}_k = \sum_{j=1}^{n} \tilde{w}_j \otimes \tilde{d}_{jk}, \tag{17}$$

$$\tilde{R}_k = \max_j \tilde{w}_j \otimes \tilde{d}_{jk}. \tag{18}$$

Step 4.5: calculate the values of $\tilde{Q}_k = (Q_k^l, Q_k^m, Q_k^u)$, i.e., the overall distances of the alternatives from the ideal solution, by applying the following equation:

$$\tilde{Q}_k = \nu \frac{\tilde{S}_k \ominus \tilde{S}^*}{S^{\circ u} - S^{*l}} \oplus (1-\nu) \frac{\tilde{R}_k \ominus \tilde{R}^*}{R^{\circ u} - R^{*l}}, \tag{19}$$

where $\tilde{S}^* = \min_k \tilde{S}_k$, S^{*l} is the lower value of the triangular fuzzy number $\tilde{S}^*$, $S^{\circ u} = \max_k S_k^u$, $\tilde{R}^* = \min_k \tilde{R}_k$, R^{*l} is the lower value of the triangular fuzzy number $\tilde{R}^*$, and $R^{\circ u} = \max_k R_k^u$. Value ν refers to the weight of the strategy of "the majority of criteria" (or "the maximum group utility"), whereas $1-\nu$ is the weight of the individual regret.

Step 4.6: defuzzify the values of $\widetilde{S}_k$, $\widetilde{R}_k$, and $\widetilde{Q}_k$ using the following equation [132]:

$$\text{crisp}(\widetilde{T}) = \frac{\left(T^l + 4T^m + T^u\right)}{6}, \tag{20}$$

where $\widetilde{T} = (T^l, T^m, T^u)$ is any triangular fuzzy number.

Step 4.7: rank the alternatives (LMSs), according to the increasing crisp values. The results are three ranking lists $\{\text{LMS}\}_S$, $\{\text{LMS}\}_R$, and $\{\text{LMS}\}_Q$ according to crisp(S), crisp(R), and crisp(Q), respectively.

Step 4.8: propose as a compromise solution the alternative $\text{LMS}^{(1)}$ which is the best ranked by the values of Q, if the following two conditions are satisfied:

Co.1. "Acceptable Advantage": $\text{Adv} \geq DQ$ where $\text{Adv} = [Q(\text{LMS}^{(2)}) - Q(\text{LMS}^{(1)})]/[Q(\text{LMS}^{(o)}) - Q(\text{LMS}^{(1)})]$ is the advantage rate of the alternative $\text{LMS}^{(1)}$, ranked as the first, in relation to the alternative $\text{LMS}^{(2)}$, ranked as the second one in the list $\{\text{LMS}\}_Q$, and $DQ = 1/(o-1)$ represents the threshold from which the advantage rate (Adv) has to be higher.

Co.2. "Acceptable Stability in decision-making": Alternative $\text{LMS}^{(1)}$ must also be the best ranked by S and/or R.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of the following:

CS1. Alternatives $\text{LMS}^{(1)}$ and $\text{LMS}^{(2)}$ if only the condition Co.2 is not satisfied

CS2. Alternatives $\text{LMS}^{(1)}$, $\text{LMS}^{(2)}$, ..., $\text{LMS}^{(M)}$ if the condition Co.1 is not satisfied; $\text{LMS}^{(M)}$ is determined by the relation $[Q(\text{LMS}^{(M)}) - Q(\text{LMS}^{(1)})]/[Q(\text{LMS}^{(o)}) - Q(\text{LMS}^{(1)})] < DQ$ for maximum M (the positions of these alternatives are "in closeness")

4. Evaluation of the Sustainable Last Mile Solutions

For solving the problem of evaluating the sustainable LMS, a novel hybrid MCDM model was developed in this paper that combines the fuzzy Delphi-based fuzzy FARE and the fuzzy VIKOR method. The structure of the proposed model is presented in Figure 1.

4.1. Proposed Sustainable Last Mile Solutions for the Central Business District of Belgrade. By combining the reviewed initiatives and technologies, it is possible to define a wide set of solutions, but only those that are applicable and in line with the principles of sustainability are taken into consideration (Figure 2). It is assumed that the concepts of cooperation and flow consolidation at the outskirts of urban areas are an integral element of logistics in the city; therefore, they are not explicitly highlighted in the description of the analyzed LMSs. All proposed solutions also include two freight villages (FVs) whose development is planned at the outskirts of Belgrade.

The first solution (LMS_1) is a combination of the ideas of parcel lockers and crowdsourcing (Figure 2(a)). Goods delivery from FVs to parcel lockers, located in the immediate proximity of the end users, is performed with the road freight vehicles. Flow generators independently collect their goods at the assigned parcel lockers, where they can obtain discounts/benefits/financial compensation by taking the role of crowd agents and delivering the goods to the other generators in their surroundings. By utilizing parcel lockers, the providers are relieved of the responsibilities in the last phase of the delivery, and at the same time, the uncertainties that exist in the classic crowdsourcing models are reduced. The implementation of this solution requires the deployment of parcel lockers in the central business district and the development of the software platform used for the communication between logistics providers and crowd agents. The required investments for the development of LMS_1 are relatively low, but delivery reliability is problematic due to the crowd agents' autonomy.

The solution LMS_2 considers the development of microconsolidation centers in the delivery zone which enables the modal shift of transport work on autonomous vehicles (Figure 2(b)). Goods delivery from FVs to microconsolidation centers is performed with road freight vehicles, while the last phase is performed with ground autonomous vehicles and drones. This solution requires the development of logistics infrastructure (microconsolidation centers) in the central business district and the definition of regulatory frameworks for the application of autonomous vehicles. By transforming the delivery system into a two-phased system, efficiency and reliability are improved while negative environmental impacts are reduced. On the other hand, the application of autonomous technologies requires the definition of specific regulations and opens a wide variety of questions, especially those regarding safety.

The third solution (LMS_3) also performs the delivery through two phases, but with road freight vehicles in the role of mobile depots, where the last phase of the delivery is performed with drones (Figure 2(c)). Road freight vehicles visit convenient locations (special parking slots) near flow generators from where the drones are launched to execute the last delivery phase. This solution requires the synchronization between ground vehicles and drones in the delivery process and also the adoption of regulations that would define the application of drones in urban areas. Besides, drone-based delivery is sensitive to unfavorable weather conditions (strong wind, rain, and storm) that are present during the winter months in the City of Belgrade.

The solution LMS_4 delivers goods from FVs to the central business district with rail transportation (regular cargo tram lines), where the last phase of the delivery is performed with light commercial vehicles—cargo bicycles and scooters (Figure 2(d)). The solution utilizes the existing infrastructure, but to improve the flexibility of the solution, the transportation of goods outside regular time schedules is made possible through the idea of cargo-hitching (with regular passenger tram lines). This solution greatly eliminates road transportation and improves the logistics system's efficiency by redistributing the transport work on rail

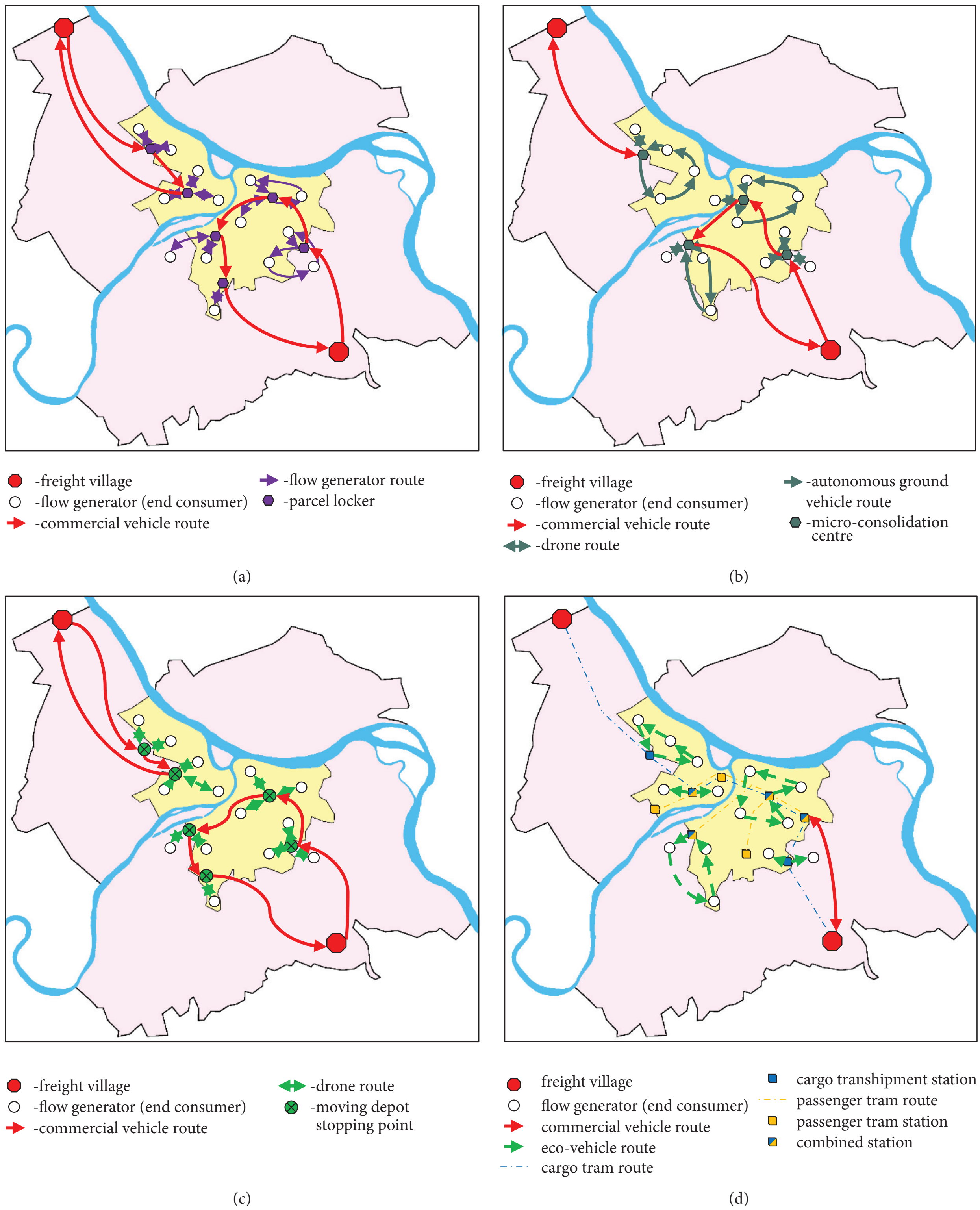

Figure 2: Continued.

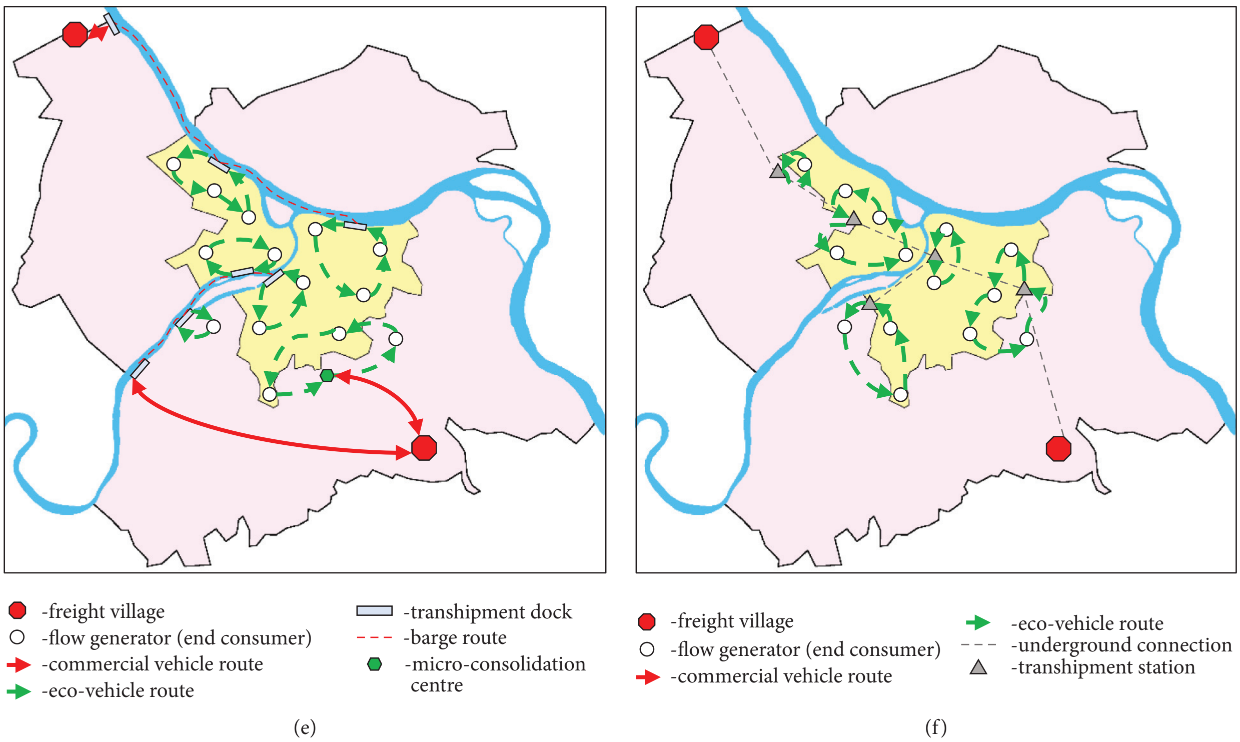

Figure 2: Last mile delivery solutions for the central business district of Belgrade. Six different solutions are created, namely, (a) LMS_1, (b) LMS_2, (c) LMS_3, (d) LMS_4, (e) LMS_5, and (f) LMS_6.

transportation. The weakness of this solution is its operational complexity, the demand for installing transshipment stations in the central business district, the general nonflexibility of rail transportation, and mixing passenger and goods flows through the concept of cargo-hitching.

In the solution LMS_5, inland waterways of the rivers Sava and Danube are used for the transportation of goods to the central business district of Belgrade (Figure 2(e)). Along the riverbeds, transshipment stations that enable the transfer of goods on eco-delivery vehicles (bikes, cycles, and smaller electrovehicles) are located. Goods transportation between FVs and the nearest transshipment stations is performed with the road shuttle connections. This solution eliminates road freight transportation in coastal urban areas, but some locations remain outside the delivery zone of transshipment stations. To provide service for these locations, the development of microconsolidation centers in particular urban zones is required. Goods delivery to microconsolidation centers is performed with road freight vehicles, from where the last phase of the delivery is performed with eco-vehicles. The solution utilizes the natural infrastructural resources—inland waterways—but requires the development of additional infrastructure—coastal transshipment stations and microconsolidation centers. Although this solution improves the efficiency of logistics activities, inland waterway transportation is generally nonflexible and sensitive on unfavorable weather conditions.

The solution LMS_6 refers to the utilization of an underground logistics system for goods transportation between FVs and the central business district (Figure 2(f)). Since the City of Belgrade is characterized by significant spatial dispersion of generators, it is impossible to include all generators in an underground system. Instead, transshipment stations that enable the modal shift on light freight vehicles—bikes, bicycles, scooters, and electrovehicles—used in the last delivery phase, are developed on strategically important locations. Underground logistics systems reduce negative environmental impacts of logistics and improve mobility in urban areas. On the other hand, the solution generates high infrastructural investments, and the development of underground systems is not even possible in historical parts of the city. Aside from the aforementioned, this solution can be the key to achieving logistics sustainability in city areas that are yet to be constructed.

4.2. Criteria for the Evaluation of the Last Mile Solutions. For the evaluation of the LMSs for the central business district of Belgrade, ten criteria are defined and explained in the following text. The criteria are selected according to the literature review, analysis of the CL participants in Belgrade, and the authors' experience in the field.

Efficiency (C_1) represents the rationalization level of logistics activities within a solution. It refers to the utilization of loading space in commercial vehicles, the average traveled distance per delivery, overall delivery completion times, fuel and energy consumption, etc.

Operation complexity of delivery (C_2) depends on the goods flow transformation degree and the applied technologies. In solutions that transform the logistics system into multiechelon systems, with or without transportation modal shift, the complexity of delivery operations is higher.

Flexibility (C_3) refers to the possibility of the logistics system's adaptation to unexpected changes in demand characteristics. The solutions that imply the use of rail and inland waterway transportation have lower flexibility, while the solutions that rely more on road transportation are more flexible.

Reliability (C_4) refers to the availability of services and goods in acceptable time intervals. Solutions with systems whose activity execution greatly depends on weather conditions (barges and drones) and traffic conditions are less reliable because of frequent delays and bottlenecks.

Implementation possibility (C_5) of a solution refers to its compatibility with existing urban plans for the observed area. This criterion also reflects on the need for defining new laws, regulations, and measures that cover the application of newer delivery technologies (such as drones and autonomous vehicles), as well as on the administrative procedures that precede the implementation of such solutions.

Implementation costs (C_6) refer to the number of infrastructural investments required for the development and implementation of an LMS.

Modal redistribution of transport work (C_7) implies the stimulation (subsidies) for the use of alternative transportation means (rail, inland waterway, or drones) in the LMSs.

Freeing of public space (C_8) describes to what level the solution contributes to the freeing of public spaces (roads, sidewalks, plazas, promenades, parks, green areas, lots, etc.) for the development of more attractive content.

Environmental impact (C_9) refers to the reduction of logistics activities' negative environmental impact—air-pollutant emissions and ecosystem degradation, which follow the implementation of modern LMSs.

Mobility (C_{10}) refers to the conditions that enable the uninterrupted realization of goods and passenger flows in the urban areas. By reducing the participation of road transportation in overall transport, urban mobility rises.

4.3. Evaluation of the Last Mile Solutions. The first step in applying the model, in addition to defining a set of alternatives and criteria for their evaluation, involves identifying stakeholders interested in solving the problem. The evaluation of the criteria was performed from the aspect of four CL stakeholders: residents (Res.), users (Use.), logistics service providers (Pro.), and city administration (Adm.). Residents are people who live, work, and shop in the city. They strive to minimize traffic congestion, noise, air pollution, and traffic accidents near the place of residence, work, and shopping. Shippers and recipients are the users of the services who send or receive goods and generally require the provider to maximize the level of service, which means shorter delivery/collection times, greater reliability and flexibility, and better information at a lower cost of service. Providers strive to minimize the cost of collecting or delivering goods to customers, while maximizing profits. The city administration aims at economic development of the city and increasing employment opportunities on the one side and reducing traffic congestion, improving living conditions, and increasing traffic safety on the other [133]. In accordance with their preferences, stakeholders' representatives evaluated the importance of the criteria with linguistic assessments (Table 4).

By applying the relations given in Table 3, the evaluations were transformed to the fuzzy values, thus forming the criteria evaluation matrices (1), while satisfying conditions (2) and (3). For the matrices obtained in such way, the consolidated criteria evaluation matrix is formed by applying equations 4–(8). By applying equation (9), the potential criteria impact was calculated, and by applying equation (10), the total impact (importance) of criteria was determined. The final criteria weights were obtained by applying equations (11)–(13). The following criteria weights were obtained: ($\widetilde{w}_1$; $\widetilde{w}_2$; $\widetilde{w}_3$; $\widetilde{w}_4$; $\widetilde{w}_5$; $\widetilde{w}_6$; $\widetilde{w}_7$; $\widetilde{w}_8$; $\widetilde{w}_9$; $\widetilde{w}_{10}$) = (0.050, 0.102, 0.200; 0.050, 0.096, 0.193; 0.050, 0.100, 0.197; 0.050, 0.104, 0.206; 0.051, 0.103, 0.198; 0.051, 0.105, 0.217; 0.050, 0.092, 0.167; 0.050, 0.096, 0.192; 0.050, 0.097, 0.198; 0.051, 0.107, 0.213).

The evaluation of alternatives in relation to the criteria (Table 5) was performed in the next step. Evaluations were converted into fuzzy values using the relations given in Table 3, thus forming a fuzzy preference matrix (14). By applying equation (15), the ideal and nadir values of all criterion functions were obtained and then the normalized fuzzy differences by applying equation (16).

By applying equations (17) and (18), the values of maximum group utility and minimum individual regret were obtained, and then the overall distances of the alternatives from the ideal solution by applying equation (19) (value of 0.5 was taken for parameter v). These values were then defuzzified using equation (20), and the final ranking of the alternatives was performed. The results of the conducted ranking process are presented in Table 6.

LMS_2 is selected as the best ranked alternative since it is ranked as the first one according to the Q, S, and R, thus satisfying the condition Co.2. The condition Co.1 is also satisfied since Adv = 0.346 ≥ DQ = 0.200.

4.4. Sensitivity Analysis. In order to examine the stability of the obtained solution, a sensitivity analysis was performed. Eight scenarios have been defined in which individual model parameters have been changed. In the first four scenarios (Sc.1–Sc.4), the ranking of alternatives was performed based on the criteria weights obtained by the evaluation of representatives of each stakeholder, namely, providers, users, administration, and residents, respectively. In the next three scenarios (Sc.5–Sc.7), one of the three most important criteria, C_{10}, C_6, and C_4, was excluded from the model, respectively. In the last scenario (Sc.8), all three most important criteria were excluded from the model. The obtained results of ranking by scenarios and changes in relation to the baseline scenario (Sc.0) are presented in Table 7, while the graphical representation of the sensitivity analysis is presented in Figure 3.

Table 4: Criteria evaluation by the stakeholders' representatives (Res., Use., Pro., and Adm.).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	(/,/,/,/)	(FL,VL,/,L)	(/,/,L,VL)	(/,/,L,VL)	(/,L,FL,/)	(VL,L,VL,/)	(FL,H,FH,/)	(/,FH,EH,/)	(/,M,EH,/)	(/,N,H,/)
C_2	(/,/,N,/)	(/,/,/,/)	(/,/,L,/)	(/,/,L,/)	(/,VL,FL,/)	(/,VL,VL,/)	(/,FH,FH,/)	(/,M,EH,/)	(/,FL,EH,/)	(/,/,H,/)
C_3	(N,L,/,/)	(FL,FL,/,VL)	(/,/,/,/)	(/,/,N,/)	(/,M,VL,/)	(VL,M,/,/)	(FL,EH,FL,/)	(/,VH,H,/)	(/,H,H,/)	(/,L,M,/)
C_4	(FL,L,/,/)	(H,FL,/,VL)	(FL,N,/,N)	(/,/,/,/)	(L,M,VL,/)	(M,M,/,/)	(H,EH,FL,/)	(/,VH,H,/)	(/,H,H,/)	(/,L,M,/)
C_5	(VL,/,/,M)	(M,/,/,H)	(VL,/,/,FH)	(/,/,/,FH)	(/,/,/,/)	(L,N,/,/)	(M,M,L,L)	(/,FL,FH,VL)	(/,L,FH,L)	(/,/,FL,N)
C_6	(/,/,/,H)	(L,/,/,EH)	(/,/,VL,VH)	(/,/,VL,VH)	(/,/,L,L)	(/,/,/,/)	(L,M,M,M)	(/,FL,VH,FL)	(/,L,VH,M)	(/,/,FH,L)
C_7	(/,/,/,L)	(N,/,/,M)	(/,/,/,FL)	(/,/,/,FL)	(/,/,/,/)	(/,/,/,/)	(/,/,/,/)	(/,/,FL,/)	(/,/,FL,/)	(/,/,VL,/)
C_8	(M,/,/,FL)	(VH,/,/,FH)	(M,/,/,M)	(VL,/,/,M)	(FL,/,/,/)	(FH,/,/,/)	(VH,VL,/,VL)	(/,/,/,/)	(/,/,/,VL)	(/,/,/,/)
C_9	(FH,/,/,L)	(EH,/,/,M)	(FH,/,/,FL)	(L,/,/,FL)	(M,/,/,/)	(H,/,/,/)	(EH,L,/,N)	(VL,VL,N,/)	(/,/,/,/)	(/,/,/,/)
C_{10}	(FH,/,/,M)	(EH,VL,/,H)	(FH,/,/,FH)	(L,/,/,FH)	(M,L,/,/)	(H,L,/,/)	(EH,H,/,L)	(VL,FH,L,VL)	(N,M,L,L)	(/,/,/,/)

Table 5: Evaluation of the alternatives in relation to the criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
LMS_1	L	EH	VH	L	EH	EH	VL	H	L	VH
LMS_2	FH	VH	H	H	H	H	FH	FH	H	M
LMS_3	VL	H	EH	M	L	VH	L	H	VL	VL
LMS_4	H	M	FH	VH	VH	M	H	M	FH	FH
LMS_5	EH	VL	L	VL	FL	FH	EH	VH	EH	H
LMS_6	VH	FH	VL	EH	VL	VL	VH	EH	VH	EH

Table 6: Final ranking of the alternatives.

		LMS_1	LMS_2	LMS_3	LMS_4	LMS_5	LMS_6
	S^l	0.049	0.025	0.123	0.045	0.059	0.035
	S^m	0.328	0.284	0.478	0.320	0.353	0.303
S	S^u	1.105	1.022	1.404	1.101	1.166	1.066
	Crisp ($\widetilde{S}$)	0.411	0.364	0.573	0.405	0.440	0.386
	Rank	4	1	6	3	5	2
	R^l	0.028	0.011	0.028	0.017	0.028	0.029
	R^m	0.072	0.048	0.083	0.064	0.081	0.082
R	R^u	0.184	0.160	0.213	0.192	0.206	0.217
	Crisp ($\widetilde{R}$)	0.083	0.061	0.096	0.077	0.093	0.095
	Rank	3	1	6	2	4	5
	Q^l	−0.286	−0.334	−0.257	−0.314	−0.281	−0.289
	Q^m	0.191	0.117	0.272	0.169	0.221	0.205
Q	Q^u	0.837	0.749	1.018	0.856	0.915	0.905
	Crisp ($\widetilde{Q}$)	0.219	0.147	0.308	0.203	0.253	0.240
	Rank	3	1	6	2	5	4

Based on the presented results, it can be seen that there are no significant changes in the ranking of alternatives in any of the scenarios. Alternative LMS_2 is the best and LMS_3 the worst ranked in all scenarios. LMS_4 ranks second in all scenarios except Sc.3 and Sc.7. Other alternatives changed the rank, but without significant deviations. Sensitivity analysis proved that the obtained solution in Sc.0 is sufficiently stable and can be adopted as the final.

5. Discussion

The possibility of applying the defined MCDM model was successfully demonstrated in the previous section. It has been shown that the FARE method is very suitable for obtaining criteria weights because it results in consistent values based on a small number of pair vise comparisons of criteria. This characteristic would be even more pronounced

Table 7: Sensitivity analysis results.

	Sc.0	Sc.1	Sc.2	Sc.3	Sc.4	Sc.5	Sc.6	Sc.7	Sc.8
Q_{LMS_1}	0.219	0.285	0.290	0.244	0.302	0.235	0.249	0.199	0.246
Q_{LMS_2}	0.147	0.138	0.155	0.169	0.209	0.144	0.166	0.148	0.157
Q_{LMS_3}	0.308	0.400	0.361	0.362	0.422	0.290	0.336	0.308	0.319
Q_{LMS_4}	0.203	0.201	0.199	0.238	0.282	0.208	0.213	0.210	0.223
Q_{LMS_5}	0.253	0.353	0.357	0.225	0.303	0.265	0.269	0.216	0.240
Q_{LMS_6}	0.240	0.304	0.320	0.321	0.239	0.259	0.225	0.252	0.255

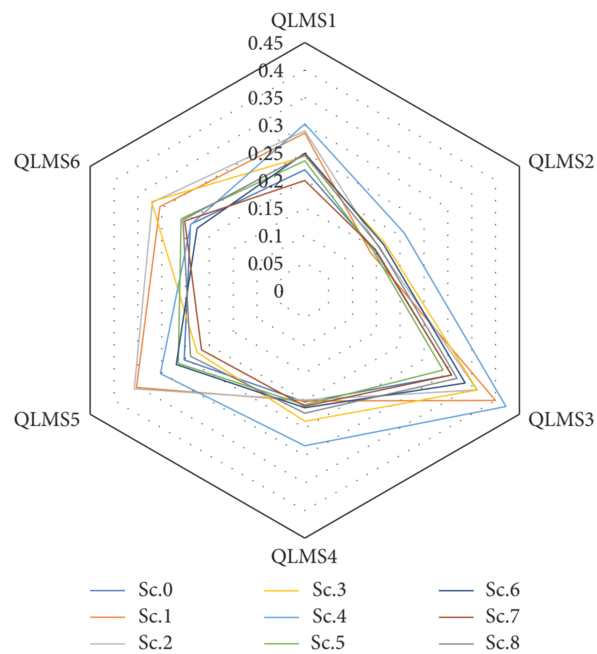

Figure 3: Sensitivity analysis. Eight scenarios, each differing according to the model parameters, were compared to the baseline scenario in order to examine the stability of the obtained solution.

in the case of considering a greater number of criteria. The Delphi method made it possible to easily consolidate the evaluation of criteria by the representatives of different stakeholders, which is the first step in finding a compromise solution. The VIKOR method has enabled the ranking of alternatives based on the values that determine their distance from the ideal solution much more precisely, compared to some other methods. The combination of these methods in the fuzzy environment, which enabled an adequate perception of ambiguity and inaccuracy in the evaluations of decision-makers, further contributed to the quality of the obtained results. The implications of the developed model are the possibility of its application for ranking any initiatives, technologies, concepts, or solutions of city logistics, as well as for solving other MCDM problems in the field of logistics and industrial engineering, as well as in other areas.

The defined MCDM model was applied in this paper for the evaluation of LMS for the central business district of Belgrade. LMS_2—the combination of the concept of microconsolidation of flows and autonomous vehicle technologies—is evaluated as being the best one. By locating microconsolidation centers in the immediate proximity of the flows generators, technical limitations of autonomous vehicles are overcome, and the efficiency of their application is improved. By transforming the system into a two-echelon system, the interdependence of flow performance is reduced in different levels—the transportation of goods to the microconsolidation centers and the delivery of goods to the generators. This means that after the delivery of goods to a microconsolidation center, the freight vehicle continues its task, while, at the same time, the last phase of the delivery is being adapted for the autonomous vehicles, thus improving the flexibility of the system. By selecting LMS_2, significant positive effects on logistics sustainability in urban areas are expected—better activity efficiency, reduction of negative effects (air-pollutant emissions, noise, vibrations, traffic congestions), the improvement in attractiveness of the central business district, and the promotion of the application of modern goods delivery technologies. The implementation of this solution is practically feasible, while the application of different autonomous vehicle classes (ground vehicles and drones) provides greater flexibility during the system's planning as well. Certainly, the implementation of the solution is preceded with solving all relevant problems on the strategical and tactical decision levels (the required number of microconsolidation centers, their locations and capacities, dimensioning the required number of autonomous vehicles in microconsolidation centers, etc.) and appropriate preparations for solving operational problems (vehicle routing and synchronization) during its exploitation. Besides, the application of such solutions opens a wide variety of questions regarding the definition of required regulatory frameworks for autonomous technologies, which have not received adequate treatment in the world so far.

The main theoretical implications of the paper are the development of a framework for the establishment of sustainable last mile solutions and efficient mathematical tool, in the form of a hybrid MCDM model, which can be used for solving the problems in the field of logistics, as well as any other. The main practical implications, on the other side, are the definition of the set of solutions that could serve as a good base for policy-making and plan development, in Belgrade or any other city, as well as the application of the developed model for selecting sustainable solutions for city logistics and last mile delivery by the decision-makers and practitioners.

6. Conclusion

The aim of this paper was to rank sustainable solutions for the realization of the last mile. The solutions defined in the paper are combinations of initiatives, technologies, and concepts of city logistics, and their application depends on the goals of different stakeholders. Accordingly, a set of criteria was defined for the evaluation of the solutions, and a novel MCDM model which combines Delphi, FARE, and VIKOR methods in the fuzzy environment was developed for solving the problem. The applicability of the defined model was demonstrated by ranking the sustainable LMSs for the central business district of Belgrade. A combination of microconsolidation centers and autonomous vehicles was obtained as the most favorable solution.

The main contributions of the paper are the definition of the innovative sustainable last mile solutions, the creation of a wide set of criteria for their evaluation, and the development of a novel hybrid MCDM model. In future research, the defined solutions could be upgraded, e.g., with some newly developed technologies of Industry 4.0. The potential effects of the application of defined solutions on the realization of logistics processes could also be examined in more detail, primarily in Belgrade, but also in some other cities. The defined MCDM model is universally applicable, and with certain adjustments, it could be used to solve various problems, so an important direction of future research is its application to solve problems in this or other areas. In addition, the model, or some of its parts, could serve as a basis for the development of some new MCDM models in the future.

Data Availability

All data underlying the findings of the study are included within the paper.

Disclosure

The research was performed as part of the employment of the authors at the University of Belgrade, Faculty of Transport and Traffic Engineering, and Chalmers University of Technology.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Determination of Moving Speed of School Age Children

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School age children (pedestrians) can move at different speeds, which are conditioned by certain parameters. Not all parameters have the same effect on the pedestrian speed. According to the literature, gender and age are the most researched parameters that have an impact on the speed of pedestrians. However, a small number of authors have dealt with the influence of movement regimes (slow, normal, fast, run, and rush) on pedestrian speed, while at the same time taking into account age and gender. For that reason, this article measured the speed of movement of school age children by movement regimes, taking into account age and gender. Within the same movement regime, the influence of age, sex, height, and weight on the speed of movement was investigated. Experimental measurements of the speed of movement of pedestrians aged 7 to 20 years were performed. Based on the results of measurements and statistical analyzes, recommendations on the average speed of movement regimes, age, and gender are given.

1. Introduction

The speed of pedestrians depends on a number of parameters. This article primarily deals with the research of the speed of pedestrian movement according to the movement regimes combined with the knowledge of age and gender. A review of previous research in this area shows that there are certain gaps:

(i) A small number of authors have dealt with measuring pedestrian speeds depending on the regime of movement, taking into account gender and age

(ii) Majority of the previous work dealt with only one usual (normal) movement regime, taking into account both age and gender

(iii) Sample sizes by categories are relatively small, so the question of statistical reliability of the obtained results arises

(iv) During measurement, age was not always known

(v) When measuring in advance, the movement regime of pedestrians was not known

(vi) The accuracy of the measuring equipment affected the obtained results

(vii) Wide speed limit (min-max) for the same movement regime

(viii) In the presentation of measured results, the minimum, maximum, and average values are given, without statistical analyzes and conclusions about the reliability of the obtained results, etc.

Having in mind all the above, it is clear that in the previous research on the speed of movement of school age children, there are gaps that need to be explored. Research (measurements) of the speed of movement of school age children were performed in experimental conditions, on the test area. During the preparation of the experiment, the aim was to eliminate the gaps and shortcomings that have been observed in previous research.

Pedestrian speed in practice is used as an input data in many situations (studies). Very often, the speed of pedestrians cannot be determined by known engineering methods, so in these cases, the recommendations given in the literature are used. The previously stated fact clearly speaks of the importance of the reliable speed measurements.

The main goal of this article is to measure the speed of movement of school age children, with predefined movement regimes with the knowledge of key parameters that affect it within the same mode, in order to obtain more reliable results and give recommendations regarding speed in different regimes.

In addition to the presentation of measured results, the article describes in detail the measurement procedure and the used measuring equipment. The literature review provides an overview of articles that have dealt with similar issues and the results obtained by other authors. Statistical analysis showed that there is a relationship between the pedestrians' speed of movement of certain age and gender within the same movement regime. In the discussion and conclusion, recommendations were given regarding the pedestrian speed, depending on the movement regime, taking into account gender and age.

2. Literature Overview

A large number of authors have researched and measured the parameters of pedestrian flows, and the obtained results can be used for various purposes. The basic parameters of pedestrian flows are flow density and speed [1]. The speed of pedestrian depends on the characteristics of pedestrians (age, gender, and physical abilities), infrastructure (length, width, type of pedestrian object) as well as weather and other external conditions [2]. Similar conclusions were reached by Peters et al. [3] and Xie et al. [4]. Based on the results of research conducted in India, Subramanyam and Prasanna Kumar [5] showed that the speed of movement of male pedestrians is higher by 0.17 m/s compared with the speed of movement of female pedestrians. Bansal et al. [6] concluded that pedestrian speed is affected by age, group size, and crossing patterns. In their work, they linked pedestrian crossing speed and crosswalk characteristics (the classification of road, length, and width of the crosswalk and the width of the pedestrian island). In his research, Tarawneh [7] showed that group size, age, and gander significantly affect pedestrian speed. Some researchers have concluded that age and body height are the factors that have the greatest impact on pedestrian movement [8–10]. It is necessary to know the speed of pedestrians when designing traffic lights, designing pedestrian facilities, for traffic accidents expertise, and the like. Risks related to transportation activities include not only driver-based accidents in a transportation process but also error-based accidents in goods traffic [11]. Pedestrians are the most vulnerable participants in traffic, and pedestrian traffic is affected by a number of factors [12]. The research conducted in Beijing included measuring pedestrian crossing speed [13]. Zhuang and Wu used previously obtained speeds to analyze crossing speed at crosswalks with countdown timers [14]. Stollof et al. also investigated pedestrian crossing speed at crosswalks with countdown timers, but they also investigated pedestrian crossing speed at ordinary signalized crosswalks [15]. In their work, Iryo-Asano and Alhajyaseen [16] modelled changes in pedestrian speeds when crossing signalized crosswalks. The speed of pedestrians is a direct consequence of the regime, i.e., the way pedestrians move. It is common to use the speed of a normal pedestrian in the analysis of pedestrian movement; however, when examining traffic accidents, it is necessary to know the speed of pedestrian movement for different regimes. It is usually not possible to determine the speed of pedestrians technically, based on the available physical traces. It is common for the speed of pedestrians to be adopted according to the recommendations from the literature, depending on the movement regime [17]. Some researchers have developed models to calculate the pedestrians speed at the time of contact with the vehicle [18]. Otković et al. [19] have developed models that predict children crossing speed, covering children aged 5 to 15 years. Earlier researches in the United Kingdom show that average crossing speed for younger pedestrians is between 1.32 and 1.72 m/s [20–23]. The pedestrian crossing speed for younger pedestrian in the Netherlands is 1.5 m/s [24]. To date, in some research, it has been found that the results of measuring pedestrian speeds have a normal distribution regardless of gender and age [25], that pedestrian speeds are affected by various factors, including street width, weather conditions, number of pedestrians crossing in a group, curbs, road markings, etc. [26], and that the speed of pedestrians is a direct consequence of the pedestrian age and the density of pedestrian flow at pedestrian crossings [1, 27]. Recommendations regarding the speed of pedestrians are different depending on the purpose for which the speeds are used. Thus, the recommendations on changing the speed of pedestrians at signaled pedestrian crossings state that it is necessary to reduce the speed from 1.2 m/s to 0.9 m/s [28].

Table values of pedestrian speeds are usually given within certain limits for the same regime. It is common in the literature to give the upper and lower speed limits for a particular regime. The speed ranges for the same moving regime are often too large to reliably determine the speed of pedestrians. In the same traffic situation, by adopting the lower or upper speed limit in a certain mode, different conclusions can be reached.

Statistical analyses of pedestrian speeds shown in the tables usually do not exist, so the reliability of the obtained data is unknown. In addition to the above, it is not known in which conditions and in what manner the measurements were performed and by which measuring devices. In addition to not knowing the technical parameters that could have influenced the obtained results, the characteristics of the respondents themselves are not known, i.e., their weight, height, etc. are not known. Most of the experiments were conducted during the 70s and 80s of the last century, so it is necessary to analyze the compliance of known data with the measured ones [17]. A special problem is the changes in growing up, on which the key influence chronologically has television, computers, and in the last decade, smartphones. The consequences on psychophysical and psychomotor development have long been known: primarily obesity [29, 30], cardiac, muscular, and skeletal changes [31–33] that, so far, have not been placed in the context of traffic safety, primarily pedestrian's safety. This influence is especially pronounced in highly developed countries. In the case of Serbia, numerous studies show intensive application and perspectives of IT sector development [34–36]. The context of the COVID-19 pandemic superimposes the use of television, computers, and smartphones, and the negative consequences of the physical development of children and adolescents will certainly be investigated in the context of the impact of the pandemic.

3. Research Method

It is not possible to clearly define certain movement regimes of pedestrians or school age children with technical parameters. For that reason, in order to determine the speed of movement of school age children, measurements of movement speeds were performed in precisely defined conditions and for certain regimes of movement. The defined movement regimes are identical to the tables in the existing literature, as follows:

(1) Slow walk—Slow
(2) Normal walk—Normal
(3) Fast walk—Fast
(4) Run
(5) Rush

Bearing in mind that the research covered school children, the measurements were performed on the grounds of primary and secondary schools, for each age group of school children, on a sample of at least 100 respondents. In this way, categories of respondents were formed and are shown in Table 1.

The conducted research was performed on a preformed test area. The test included measurements of children's movement speeds according to predefined regimes. The statistical data obtained by the performed measurement were processed and systematized according to the data given in the literature.

Table 1: Overview of categories of respondents depending on gender and age.

Age	Number of respondents		
	Male	Female	Σ
From 7 to 8 years	50	53	103
From 8 to 10 years	59	50	109
From 10 to 12 years	55	51	106
From 12 to 15 years	57	51	108
From 15 to 20 years	117	100	217
Total	**338**	**305**	**643**

Figure 1: The newtest powertimer 300-series testing system.

3.1. Measuring Devices Used in the Experiment. The Newtest Powertimer 300-series testing system device was used to determine the speed of school children. The device is designed for the accurate assessment of biomechanical and physiological explosive power, speed, reaction time, and quickness. The Newtest Powertimer 300-series is used to test athletic performance in about 20 different athletic disciplines.

This device enables precise measurements and tests that can be easily translated into numerical values. One of the most important features of this device is that the measurements are performed with an accuracy of 0.001 s.

A PC is used to control the Newtest Powertimer 300-series (Figure 1.), and it is recommended to use a laptop due to the portability of the device itself. Newtest Powertimer Analyzer (version 1.00.137) application allows easy protocol selection and testing control. The measured results obtained in this way are automatically saved and can be downloaded from the Newtest Powertimer database at any time.

The Newtest Powertimer 300-series consists of a main console with five inputs for sensors, an audible alarm, a USB output, and a power connector. The Newtest Powertimer 300-series sensors are photocells and a weight-sensitive pad that can also detect some other parameters. Depending on the discipline being measured, a combination of sensors or the use of only one sensor type is possible.

Photocells belong to the IP 67 class, and as such, they enable measurements with an accuracy of ±0.001 seconds when measuring time and ±1 mm when measuring jump height. The sensor range can be adjusted in the range of 0.2-3 m. Photocells can be used in the temperature range from −20°C to +40°C. Experimental measurement of pedestrian movement parameters can also be performed via video surveillance.

One of the abilities of the Newtest Powertimer 300-series device is to measure the speed of the subjects. To determine the speed of school children, for the purpose of research, the so-called "Speed test" was used.

3.2. Measurement Procedure. Due to the specific categories examined in this research, data collection during the research was performed on the grounds of a primary and secondary schools. In the primary school, the test area (Figure 2.) was formed on a sports field with a concrete base, and during the research, it was flat, dry, and clean. In high school, the research was conducted in a sports gymnasium with parquet flooring. Measurements were performed in May 2019 in daylight conditions. The outside temperature ranged from 15°C to 20°C; the weather was sunny.

The procedure for measuring the speed of movement of school-aged pedestrians consisted of three phases:

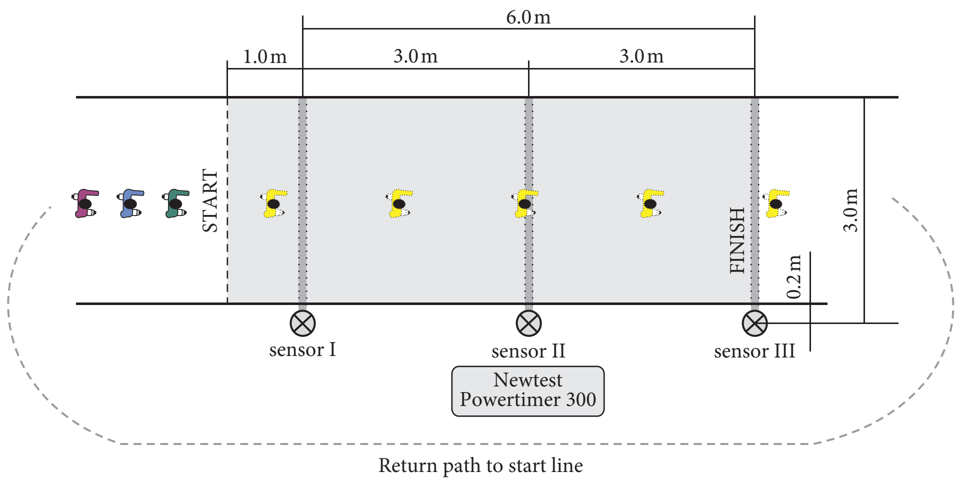

Figure 2: Schematic representation of the test area.

(1) Forming the test area

(2) Training of respondents

(3) Measurement of speed depending on the mode

The test area is organized into three spatial units. In the first part of the test area, the respondents formed a line in accordance with the list and the ordinal number of the respondents. For each respondent, the following is known: gender, age, height, and weight. In the second part of the test area, the speed of movement was measured and sensors were placed there; three photocells with the range set at 3 m were used for this research. The test area was formed in such a way as to more accurately reflect the usual width of the road with two traffic lanes. The start of the test is marked by the starting line, which is located 1 m in front of the first sensor. The sensors are placed in a line at a distance of 3 m from each other. The last sensor also represents the finish line. The third part of the test area is parallel to the second part, and it was used to return the respondents to the back of the line.

Before the start of the measurements, a short training was performed, and the respondents were informed about the research that is being performed, as well as the regimes of moving through the test zone. The regimes of movement were demonstratively shown by the researchers, and then after the roll call, a line of respondents was formed.

The passage of the subjects through the test zone was controlled by the researchers, while technical characteristics of the Newtest Powertimer 300-series device limit the number of persons in the test zone to one. Hence, the next respondent needs to wait for the previous respondent to leave the test zone in order for the next measurement to start.

The controlled passage of the subjects next to the sensor provides data in the Newtest Powertimer Analyzer (version 1.00.137) software package. Each passage is defined by the time needed to pass between the first and second sensors and the total time of passage between the sensors. In addition to the time needed to pass the course, the Newtest Powertimer Analyzer provides the ability to calculate the passage speed for the previously specified times. Data obtained by the measurement were transferred to the Microsoft Office Excel software package, in which a database was formed for additional analysis, such as categorization of participants, expansion of the database on age, height, weight, respondents, etc.

4. Results of the Measurements and Statistical Analysis

The obtained results of the measurement are presented by movement regimes, defined by age groups and gender. A comparative analysis of the results led to the conclusion that the distance covered did not affect the measured speed values. The time for which the subjects crossed the first three and the second three meters on the measuring range was very similar, and the oscillations were insignificant and were represented as positive and negative, for the same regime of movement (Table 2).

Due to the absence of significant differences in times it took the respondents to cross the first and second part of the testing area, all the presented results are expressed for crossing across the entire test area. Based on the conducted research, it can be concluded that the length of the covered distance does not affect the speed of pedestrians within the same regime of the same age and gender.

The mean value, standard deviation, and the minimum and maximum speed values were determined by measuring individual pedestrian speeds. Table 2 shows results of measuring the pedestrian speeds by gender, age, and movement regimes.

Tables 3–7 show the values of parametric characteristics (mathematical expectation and standard deviation), the type of speed distribution for all regimes for both genders, and the verification of the hypothesis of the established distribution. All hypotheses on the nonparametric distribution characteristic were verified by the χ^2 test with a significance threshold greater than $p = 0.05$ (from Tables 3–7). The verification parameters are given in the graphs (in Appendix, Figures 3–8).

Table 2: Display of measured results.

7-8	Male				Female			
	Average	Stdev	Max	Min	Average	Stdev	Max	Min
Slow	0.984	0.194	1.400	0.620	0.981	0.241	1.500	0.574
Normal	1.364	0.243	1.800	0.900	1.406	0.203	1.827	1.016
Fast	2.079	0.298	2.518	1.541	2.067	0.216	2.570	1.600
Run	2.415	0.299	2.756	1.920	2.390	0.262	3.057	1.921
Rush	3.649	0.225	4.000	3.100	3.485	0.282	3.976	2.923
8–10	Male				Female			
	Average	Stdev	Max	Min	Average	Stdev	Max	Min
Slow	1.090	0.218	1.590	0.704	1.072	0.179	1.472	0.717
Normal	1.388	0.238	1.900	0.900	1.379	0.222	1.903	0.982
Fast	2.073	0.284	2.715	1.641	1.968	0.236	2.509	1.552
Run	2.678	0.291	3.272	2.221	2.724	0.285	2.756	2.335
Rush	3.929	0.295	4.556	3.409	3.588	0.292	4.084	3.109
10–12	Male				Female			
	Average	Stdev	Max	Min	Average	Stdev	Max	Min
Slow	1.158	0.196	1.653	0.678	1.189	0.170	1.537	0.835
Normal	1.458	0.189	1.844	1.091	1.516	0.177	1.985	1.203
Fast	2.294	0.249	2.864	1.775	2.170	0.211	2.680	1.850
Run	2.798	0.296	3.464	2.311	2.781	0.286	3.297	2.350
Rush	4.061	0.297	4.598	3.466	3.905	0.288	4.468	3.333
12–15	Male				Female			
	Average	Stdev	Max	Min	Average	Stdev	Max	Min
Slow	1.183	0.182	1.542	0.797	1.213	0.174	1.499	0.750
Normal	1.561	0.158	1.909	1.249	1.621	0.173	2.077	1.338
Fast	2.247	0.300	2.841	1.800	2.132	0.175	2.504	1.806
Run	2.984	0.295	3.600	2.500	2.787	0.247	3.300	2.404
Rush	4.223	0.334	4.773	3.484	3.865	0.269	4.448	3.263
15–20	Male				Female			
	Average	Stdev	Max	Min	Average	Stdev	Max	Min
Slow	1.231	0.151	1.664	0.789	1.211	0.169	1.602	0.805
Normal	1.530	0.146	1.912	1.233	1.519	0.116	1.856	1.231
Fast	2.342	0.243	3.085	1.774	2.189	0.220	2.784	1.669
Run	3.018	0.292	3.601	2.443	2.854	0.246	3.472	2.105
Rush	4.516	0.248	4.990	3.947	3.932	0.276	4.570	3.394

Table 3: Parametric characteristics, distributions, and significance threshold for the age group of 7-8 years.

Gender	Regime	Mean	Stan. deviation	Distribution	Significance
Male sample = 50	Slow	0.9835	0.1935	Normal	0.2192
	Normal	1.3635	0.2429	Normal	0.7177
	Fast	2.0790	0.2977	Normal	0.4473
	Run	2.4146	0.2992	Normal	0.5919
	Rush	3.6487	0.2250	Normal	0.5713
Female sample = 53	Slow	0.9812	0.2409	Normal	0.2895
	Normal	1.4064	0.2026	Normal	0.8673
	Fast	2.0671	0.2156	Normal	0.8636
	Run	2.3895	0.2616	Normal	0.2678
	Rush	3.4853	0.2817	Normal	0.1806

4.1. Influence of Movement Regime for Same Gender and Ages of Respondents. Using the t test for dependent samples in the group of male children aged 7 to 8 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Using the t test for dependent samples in the group of female children aged 7 to 8 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Distributions and verifications of distributions in the comparable vertical of the movement regime (abscissas and ordinates of the histogram are identical) for male (blue) and female (red) children aged 7 to 8 years are given in Appendix in Figure 3.

Using the t test for dependent samples in the group of male children aged 8 to 10 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Using the t test for dependent

Table 4: Parametric characteristics, distributions, and significance threshold for the age group of 8–10 years.

Gender	Regime	Mean	Stan. deviation	Distribution	Significance
Male sample = 59	Slow	1.0897	0.2183	Normal	0.8099
	Normal	1.3877	0.2383	Normal	0.2276
	Fast	2.0725	0.2838	Normal	0.1912
	Run	2.6779	0.2912	Normal	0.8366
	Rush	3.9289	0.2953	Normal	0.0802
Female sample = 50	Slow	1.0717	0.1786	Normal	0.1799
	Normal	1.3790	0.2220	Normal	0.2195
	Fast	1.9676	0.2359	Normal	0.2543
	Run	2.7242	0.2850	Normal	0.1902
	Rush	3.5880	0.2920	Normal	0.2550

Table 5: Parametric characteristics, distributions, and significance threshold for the age group of 10–12 years.

Gender	Regime	Mean	Stan. deviation	Distribution	Significance
Male sample = 55	Slow	1.1585	0.1964	Normal	0.8586
	Normal	1.4581	0.1888	Normal	0.8148
	Fast	2.2939	0.2489	Normal	0.6867
	Run	2.7978	0.2959	Normal	0.6028
	Rush	4.0609	0.2969	Normal	0.3843
Female sample = 51	Slow	1.1889	0.1698	Normal	0.3442
	Normal	1.5161	0.1766	Normal	0.4916
	Fast	2.1699	0.2111	Normal	0.6314
	Run	2.7813	0.2855	Normal	0.0555
	Rush	3.9054	0.2879	Normal	0.1865

Table 6: Parametric characteristics, distributions, and significance threshold for the age group of 12–15 years.

Gender	Regime	Mean	Stan. deviation	Distribution	Significance
Male sample = 57	Slow	1.1833	0.1823	Normal	0.4283
	Normal	1.5607	0.1577	Normal	0.4541
	Fast	2.2465	0.2998	Normal	0.1542
	Run	2.9840	0.2945	Normal	0.2770
	Rush	4.2232	0.3337	Normal	0.1215
Female sample = 51	Slow	1.2128	0.1739	Normal	0.1419
	Normal	1.6206	0.1729	Normal	0.3115
	Fast	2.1323	0.1754	Normal	0.8915
	Run	2.7873	0.2465	Normal	0.6908
	Rush	3.8651	0.2691	Normal	0.3798

Table 7: Parametric characteristics, distributions, and significance threshold for the age group of 15–20 years.

Gender	Regime	Mean	Stan. deviation	Distribution	Significance
Male sample = 117	Slow	1.2311	0.1514	Normal	0.9292
	Normal	1.5300	0.1461	Normal	0.3924
	Fast	2.3417	0.2432	Normal	0.2429
	Run	3.0179	0.2916	Normal	0.3176
	Rush	4.5158	0.2479	Normal	0.7273
Female sample = 100	Slow	1.2106	0.1693	Normal	0.7449
	Normal	1.5189	0.1158	Normal	0.2643
	Fast	2.1887	0.2204	Normal	0.0776
	Run	2.8545	0.2462	Normal	0.8022
	Rush	3.9318	0.2755	Normal	0.8083

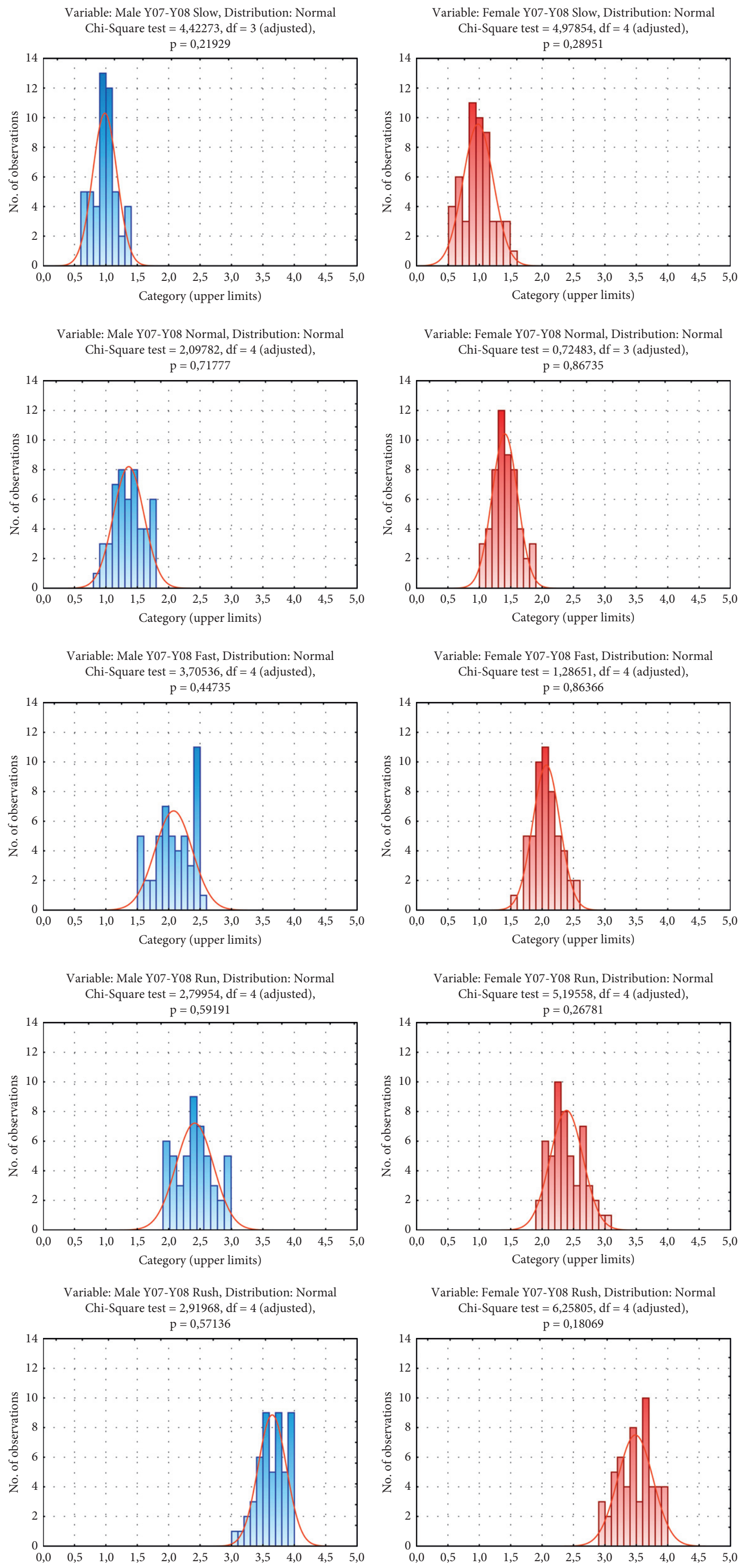

Figure 3: Distributions and verifications of distributions of speed in different regimes for male and female children aged 7 to 8 years.

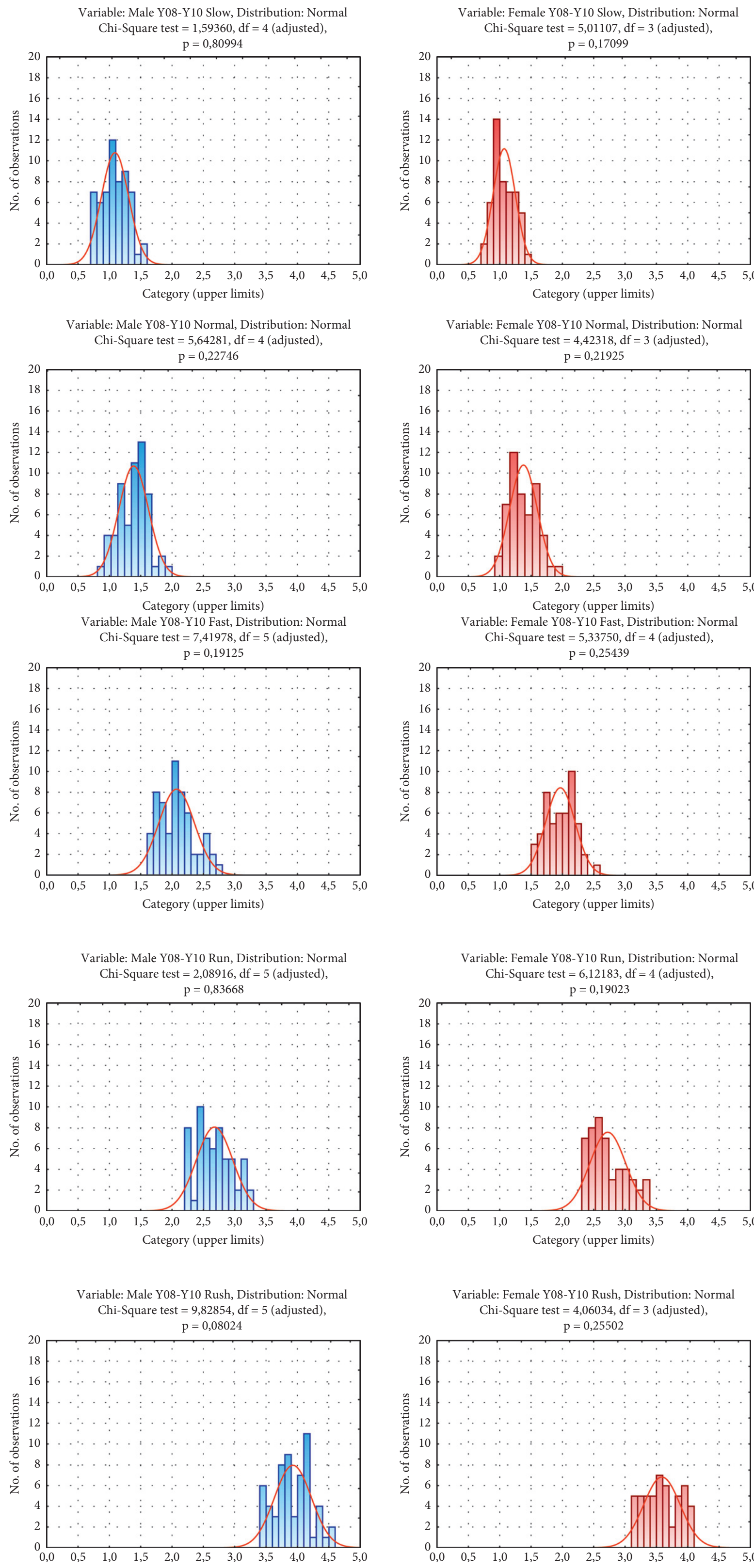

Figure 4: Distributions and verifications of distributions of speed in different regimes for male and female children aged 8 to 10 years.

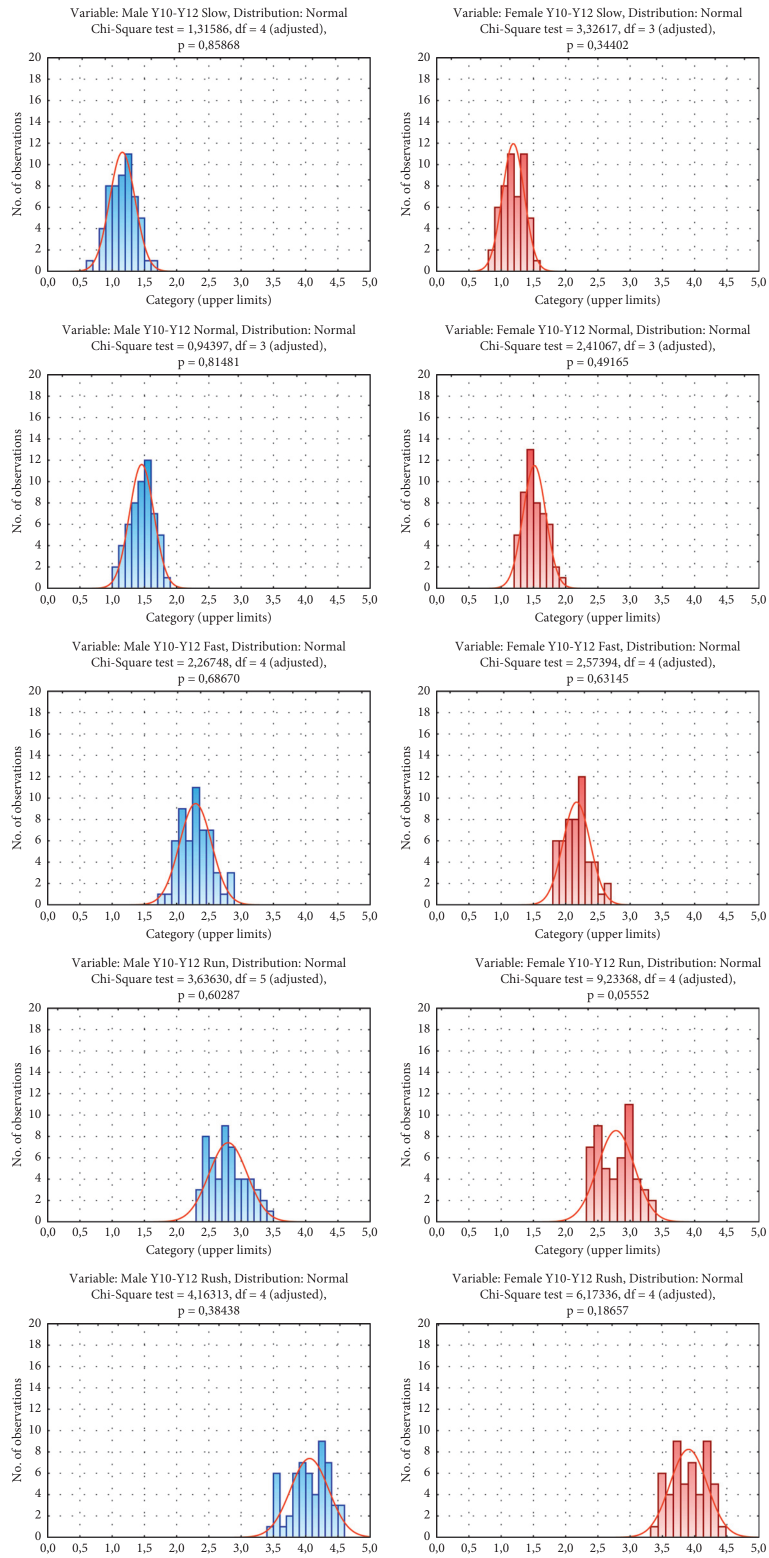

Figure 5: Distributions and verifications of distributions of speed in different regimes for male and female children aged 10 to 12 years.

samples in the group of female children aged 8 to 10 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Distributions and verifications of distributions in the comparable vertical of the movement regime (abscissas and ordinates of the histogram are identical) for male (blue) and female (red) children aged 8 to 10 years are given in Appendix in Figure 4.

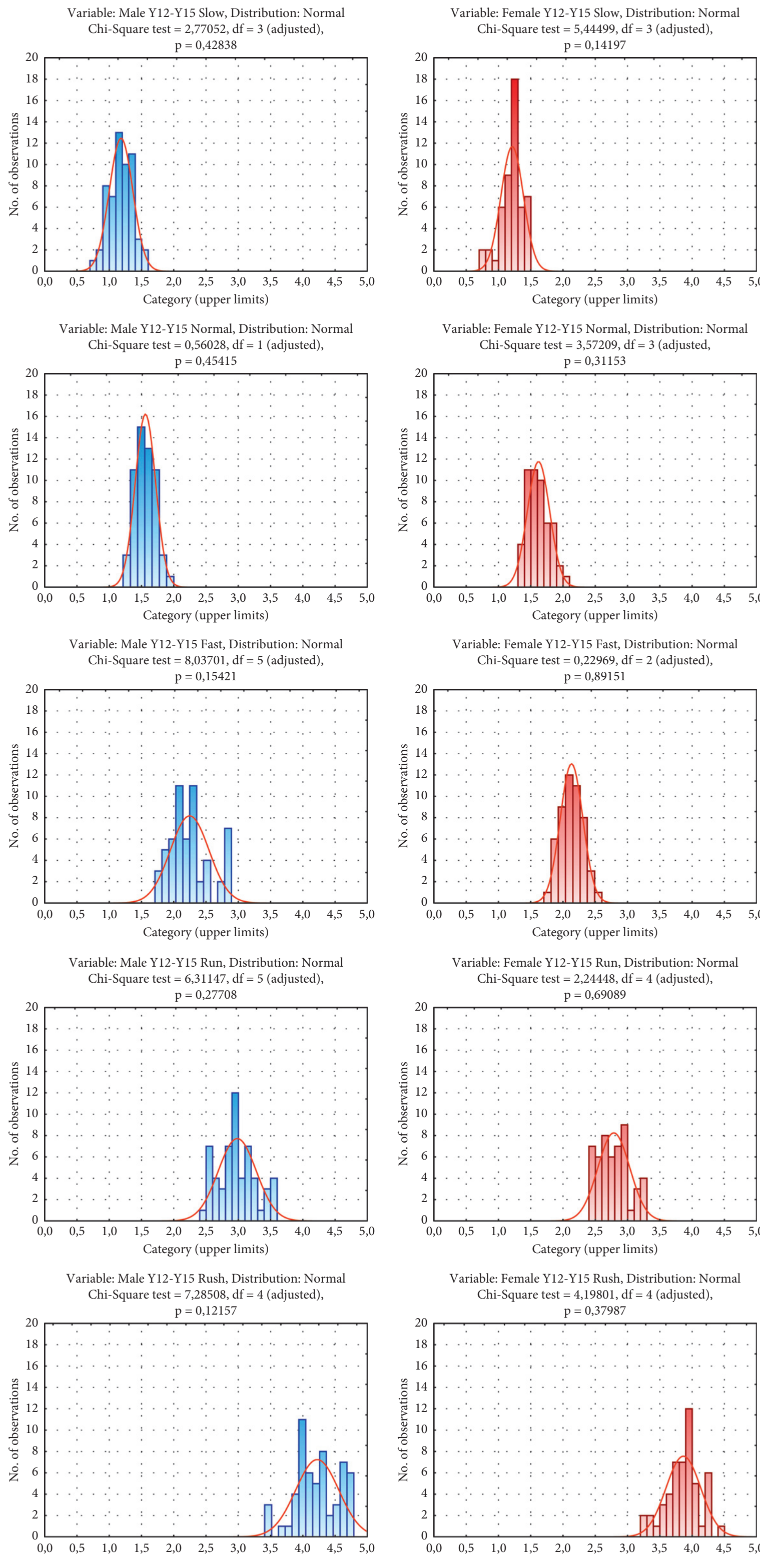

Figure 6: Distributions and verifications of distributions of speed in different regimes for male and female children aged 12 to 15 years.

Using the t test for dependent samples in the group of male children aged 10 to 12 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Using the t test for dependent samples in the group of female children aged 10 to 12 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Distributions and verifications of distributions in the comparable

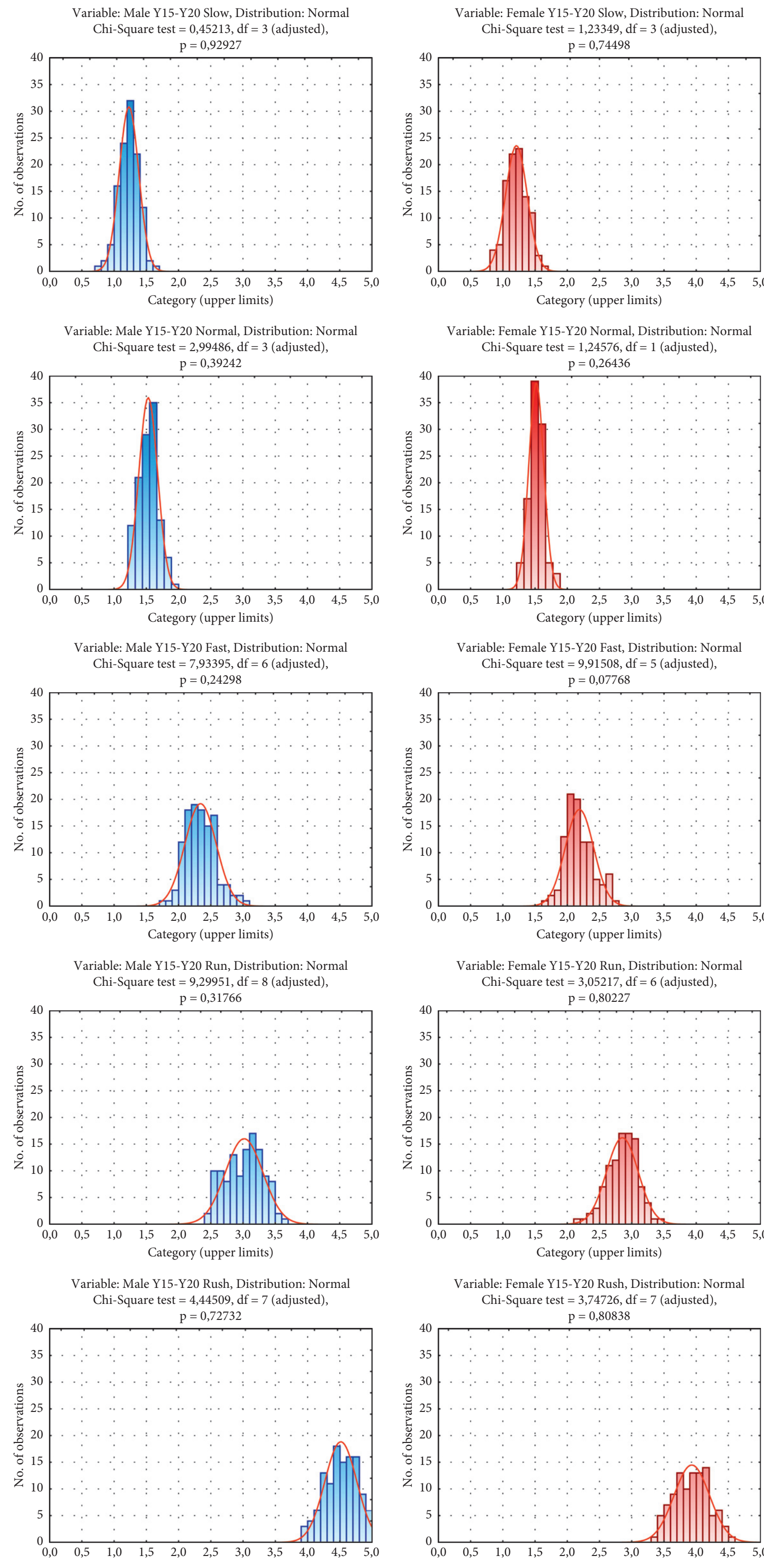

Figure 7: Distributions and verifications of distributions of speed in different regimes for male and female children aged 15 to 20 years.

vertical of the movement regime (abscissas and ordinates of the histogram are identical) for male (blue) and female (red) children aged 10 to 12 years are given in Appendix in Figure 5.

Using the t test for dependent samples in the group of male children aged 12 to 15 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Using the t test for dependent

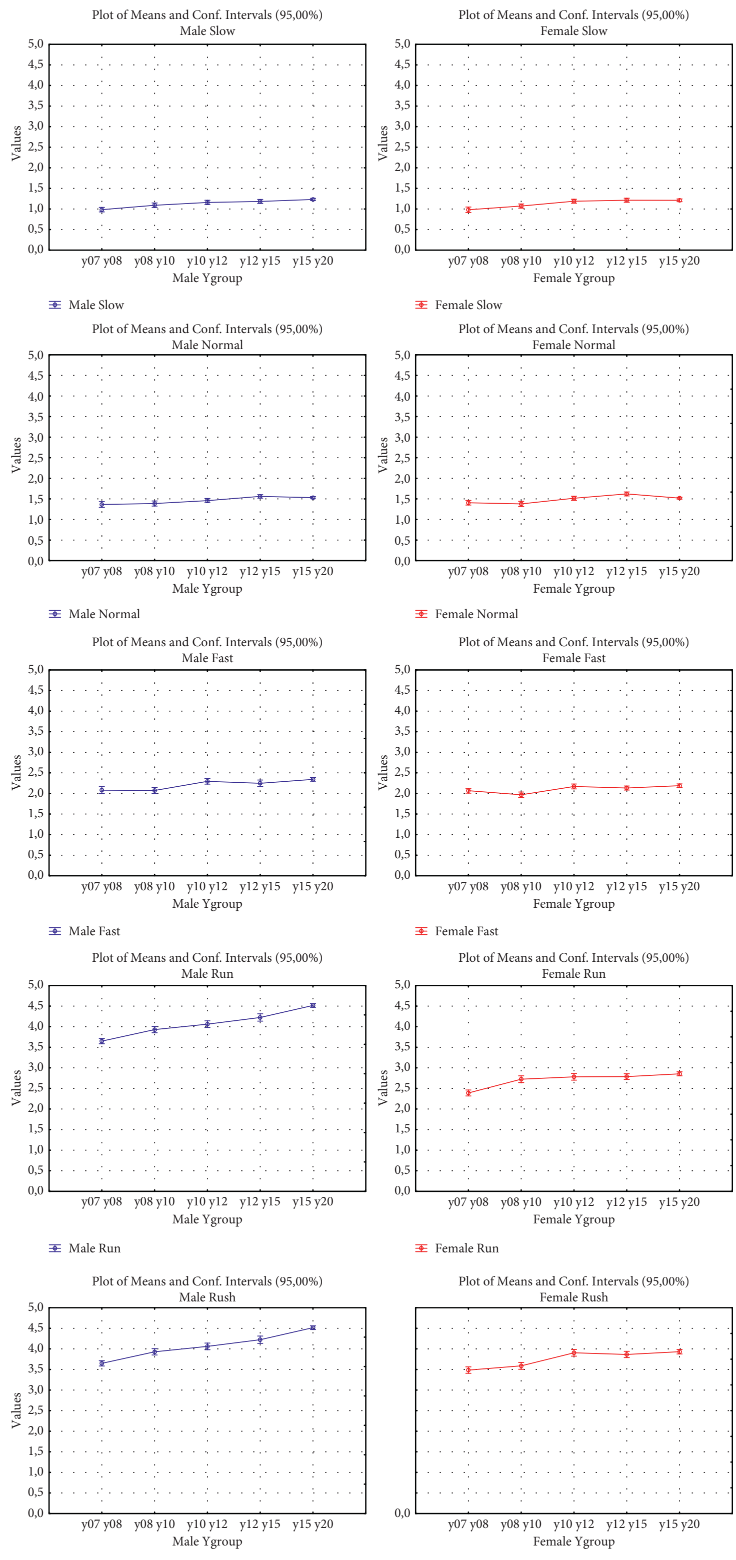

Figure 8: Variance analysis of the influence of age groups in different movement regimes for male and female children.

samples in the group of female children aged 12 to 15 years, there are significant differences between the average values of speeds in all regimes ($p \leq 0.0001$). Distributions and verifications of distributions in the comparable vertical of the movement regime (abscissas and ordinates of the histogram are identical) for male (blue) and female (red) children aged 12 to 15 years are given in Appendix in Figure 6.

Table 8: Comparisons of the mean values of speeds of different genders at the same ages by regimes.

Year	Regime				
	Slow	Normal	Fast	Run	Rush
7-8	$0.9835 \approx 0.9812$ $p = 0.4788$	$1.3635 \approx 1.4064$ $p = 0.1658$	$2.0790 \approx 2.0671$ $p = 0.4080$	$2.4146 \approx 2.3895$ $p = 0.3254$	$3.6487 > 3.4853$ $p = 0.0008$
8–10	$1.0897 \approx 1.0717$ $p = 0.6131$	$1.3877 \approx 1.3790$ $p = 0.8455$	$2.0725 \approx 1.9676$ $p = 0.4054$	$2.6779 < 2.7242$ $p = 0.0404$	$3.9289 > 3.5880$ $p \le 0.0001$
10–12	$1.1585 \approx 1.1889$ $p = 0.3967$	$1.4581 \approx 1.5161$ $p = 0.1062$	$2.2939 > 2.1699$ $p = 0.0069$	$2.7978 \approx 2.7813$ $p = 0.7717$	$4.0609 > 3.9054$ $p = 0.0073$
12–15	$1.1833 \approx 1.2128$ $p = 0.3940$	$1.5607 \approx 1.6206$ $p = 0.0624$	$2.2465 > 2.1323$ $p = 0.0190$	$2.9840 > 2.7873$ $p = 0.0003$	$4.2232 > 3.8651$ $p \le 0.0001$
15–18	$1.2311 \approx 1.2106$ $p = 0.3465$	$1.5300 \approx 1.5189$ $p = 0.5409$	$2.3417 \approx 2.1887$ $p \le 0.0001$	$3.0179 \approx 2.8545$ $p \le 0.0001$	$4.5158 \approx 3.9318$ $p \le 0.0001$

Using the t test for dependent samples in the group of male children aged 15 to 20 years, there are significant differences between the average values of speeds in all regimes ($p \le 0.0001$). Using the t test for dependent samples in the group of female children aged 15 to 20 years, there are significant differences between the average values of speeds in all regimes ($p \le 0.0001$). Distributions and verifications of distributions in the comparable vertical of the movement regime (abscissas and ordinates of the histogram are identical) for male (blue) and female (red) children aged 15 to 20 years are given in Appendix in Figure 7.

For all ages and for both genders, movement regimes are clearly differentiated by absolute statistical differences in movement speeds. With this outcome, a reliable statistical basis for examining the influence of gender and age on the average speed of movement was set.

4.2. Influence of Gender on Movement Speeds for Identical Movement Regimes and Ages. Based on all normal distributions, the mean values from Tables 3–7 by gender, age, and movement regimes were compared using the t test. Results with significance thresholds are given in Table 8.

For the whole interval of age groups, there are no significant differences between male and female children in two movement regimes: “slow” and “normal.” By age, differences in faster regimes were found, as follows:

(i) For ages 7 to 8, male children are faster only in “rush” regime.

(ii) For ages 8 to 10, female children are faster in “fast” regime and male children are faster in “rush” regime.

(iii) For ages 10 to 12, male children are faster in two regimes: “fast” and “rush.”

(iv) For ages 12 to 15, male children are faster in three regimes: “fast.” “run,” and “rush.”

(v) For ages 15 to 20, male children are faster in three regimes: “fast,” “run,” and “rush.”

In conclusion, the influence of gender exists to a lesser extent at younger ages and becomes moderately significant at older ages, for all faster regimes of walking or running, there are significant differences in average speeds in favor of male subjects.

4.3. Influence of Age on Pedestrian Speeds within the Same Regime and Same Genders. The variance analysis of the influence of age groups by regimes and gender was done by the Dunckan test. The presentation of obtained results is shown in Tables 9 and 10.

The influence of age on the average speed of movement within the same regime was statistically moderate in younger subjects and pronounced in older subjects. Differentiation is more pronounced in male respondents, and for them, it becomes absolute with age. As for the age of the female respondents, their differentiation ends at the age of 12 years, after which, the average speeds in the “fast,” “run,” and “rush” modes do not differ significantly.

5. Discussion

The obtained results, primarily the verified nonparametric characteristics of the normal distributions of speed, are consistent with some of the previous studies. Together with these researches, the presented results make the basis for more reliable application of the existing tabularly presented standards where the type of distributions of pedestrian speeds is not emphasized. These results can significantly increase the accuracy of spatiotemporal analyses in traffic accidents involving pedestrians. With the reconstruction of the movement regime, the known age, and gender, the expertise can be conducted with credible speeds of pedestrians. As with the design of security systems in order to reduce risk, the following results must be taken into account.

(i) At all ages for both genders, movement regimes are clearly differentiated by absolute statistical differences in movement speeds.

(ii) The influence of gender exists to a lesser extent at a younger age and becomes moderately significant at an older age.

(iii) Significant differences in average speeds of the pedestrian movement by regimes were found in male subjects. In female subjects, the preadolescent limit (10 to 12 years) was expressed as meritorious.

Table 9: Dunckan test of variance analysis on influence of different age groups on speed by movement regimes for male children.

Slow	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	0,9835	1,0897	1,1585	1,1833	1,2311
Y07 Y08		0,0013	0,0000	0,0000	0,0000
Y08 Y10	0,0013		0,0377	0,0064	0,0000
Y10 Y12	0,0000	0,0377		0,4509	0,0365
Y12 Y15	0,0000	0,0064	0,4509		0,1490
Y15 Y20	0,0000	0,0000	0,0365	0,1490	
Normal	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	1,3635	1,3877	1,4581	1,5607	1,5300
Y07 Y08		0,4796	0,0079	0,0000	0,0000
Y08 Y10	0,4796		0,0395	0,0000	0,0001
Y10 Y12	0,0079	0,0395		0,0038	0,0356
Y12 Y15	0,0000	0,0000	0,0038		0,3684
Y15 Y20	0,0000	0,0001	0,0356	0,3684	
Fast	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	2,0790	2,0725	2,2939	2,2465	2,3417
Y07 Y08		0,8944	0,0000	0,0006	0,0000
Y08 Y10	0,8944		0,0000	0,0005	0,0000
Y10 Y12	0,0000	0,0000		0,3308	0,3255
Y12 Y15	0,0006	0,0005	0,3308		0,0637
Y15 Y20	0,0000	0,0000	0,3255	0,0637	
Run	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	2,4146	2,6779	2,7978	2,9840	3,0179
Y07 Y08		0,0000	0,0000	0,0000	0,0000
Y08 Y10	0,0000		0,0237	0,0000	0,0000
Y10 Y12	0,0000	0,0237		0,0004	0,0001
Y12 Y15	0,0000	0,0000	0,0004		0,5231
Y15 Y20	0,0000	0,0000	0,0001	0,5231	
Rush	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	3,6487	3,9289	4,0609	4,2232	4,5158
Y07 Y08		0,0000	0,0000	0,0000	0,0000
Y08 Y10	0,0000		0,0084	0,0000	0,0000
Y10 Y12	0,0000	0,0084		0,0012	0,0000
Y12 Y15	0,0000	0,0000	0,0012		0,0000
Y15 Y20	0,0000	0,0000	0,0000	0,0000	

Table 10: Dunckan test of variance analysis on influence of different age groups on speed by movement regimes for female children.

Slow	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	0,9812	1,0717	1,1889	1,2128	1,2106
Y07 Y08		0,0095	0,0000	0,0000	0,0000
Y08 Y10	0,0095		0,0008	0,0001	0,0001
Y10 Y12	0,0000	0,0008		0,5229	0,5353
Y12 Y15	0,0000	0,0001	0,5229		0,9483
Y15 Y20	0,0000	0,0001	0,5353	0,9483	
Normal	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	1,4064	1,3790	1,5161	1,6206	1,5189
Y07 Y08		0,3980	0,0007	0,0000	0,0008
Y08 Y10	0,3980		0,0000	0,0000	0,0000
Y10 Y12	0,0007	0,0000		0,0018	0,9313
Y12 Y15	0,0000	0,0000	0,0018		0,0017
Y15 Y20	0,0008	0,0000	0,9313	0,0017	
Fast	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	2,0671	1,9676	2,1699	2,1323	2,1887
Y07 Y08		0,0132	0,0143	0,1048	0,0044
Y08 Y10	0,0132		0,0000	0,0001	0,0000
Y10 Y12	0,0143	0,0000		0,3497	0,6382
Y12 Y15	0,1048	0,0001	0,3497		0,1864

Table 10: Continued.

Y15 Y20	0,0044	0,0000	0,6382	0,1864	
Run	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	2,3895	2,7242	2,7813	2,7873	2,8545
Y07 Y08		0,0000	0,0000	0,0000	0,0000
Y08 Y10	0,0000		0,2464	0,2288	0,0138
Y10 Y12	0,0000	0,2464		0,9021	0,1622
Y12 Y15	0,0000	0,2288	0,9021		0,1731
Y15 Y20	0,0000	0,0138	0,1622	0,1731	
Rush	Y07 Y08	Y08 Y10	Y10 Y12	Y12 Y15	Y15 Y20
	3,4853	3,5880	3,9054	3,8651	3,9318
Y07 Y08		0,0511	0,0000	0,0000	0,0000
Y08 Y10	0,0511		0,0000	0,0000	0,0000
Y10 Y12	0,0000	0,0000		0,4446	0,6154
Y12 Y15	0,0000	0,0000	0,4446		0,2345
Y15 Y20	0,0000	0,0000	0,6154	0,2345	

(iv) Speeds of movement do not depend on the length of the distance covered for the conditions of the set test area.

(v) The weight and height of the respondents did not show statistical significance that can be related to the speed of movement according to defined regimes and age limits.

(vi) Period of the research is an important basis for a long-term study and the basis for future pedestrian speed standards, primarily due to the expected negative impact of the COVID-19 pandemic on the psychophysical development of children and adolescents.

6. Conclusions

In this article, the speed of movement of school age children in experimental conditions was measured. The measurement was performed both for male and female children by age groups in defined movement regimes. Movement regimes are defined as slow, normal, fast, run, and rush. The age groups are divided into classes of 7-8, 8–10, 10–12, 12–15, and 15–20 years. Based on the measurement of movement speeds of school age children, it was determined that the movement regime has the greatest influence on speed. For the same movement regime, age shows a significant effect on speed especially in younger age groups. The standard deviation of the measured speeds has a lower value in the slow and normal modes compared with fast, run, and rush. A comparative analysis of the measured mean values of the speed of movement of school age children with the values from the literature showed certain similarities, along with the difference between the minimum and maximum values. It is possible that this difference was due to the sample size used in the measurement or the conditions under which the experiment was performed.

Analyzes have shown that measured pedestrian speeds have the normal distribution regardless of the movement regime, age, and gender, which is in accordance with the conclusions of previous aticle [25]. Comparative analysis of measured speeds in the normal regime for all age categories, regardless of gender coincided with the results given in [20–24].

Measurement of pedestrian speeds in children aged 7 to 20 years show good agreement with the recommendations given for pedestrian speeds on pedestrian traffic lights crossings in previous study [28].

Further research should focus on measuring speeds in real conditions, intersections, pedestrian crossings, etc., which would make it possible to perform a comparative analysis with the results obtained in this article. The obtained mean values of speeds, taking into account the standard deviation, can be used as reliable input data in various analyzes.

Data Availability

The numerical data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Energy-Aware Flexible Job Shop Scheduling Using Mixed Integer Programming and Constraint Programming

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Compromising productivity in exchange for energy saving does not appeal to highly capitalized manufacturing industries. However, we might be able to maintain the same productivity while significantly reducing energy consumption. This paper addresses a flexible job shop scheduling problem with a shutdown (on/off) strategy aiming to minimize makespan and total energy consumption. First, an alternative mixed integer linear programming model is proposed. Second, a novel constraint programming is proposed. Third, practical operational scenarios are compared. Finally, we provide benchmarking instances, CPLEX codes, and genetic algorithm codes, in order to promote related research, thus expediting the adoption of energy-efficient scheduling in manufacturing facilities. The computational study demonstrates that (1) the proposed models significantly outperform other benchmark models and (2) we can maintain maximum productivity while significantly reducing energy consumption by 14.85% (w/o shutdown) and 15.23% (w/shutdown) on average.

1. Introduction

Energy consumption is a very important issue for our society in terms of both environment and economy. U.S. Energy Information Administration [1] recently reported international energy outlook 2019 with projections to 2050. In the report, the world energy consumption is expected to increase by approximately 50%, accounting for more than half of the non-OECD Asian countries, including China and India. Industrial sectors, such as manufacturing, agriculture, and construction, are the largest consumer among end users, and their energy consumption will increase by more than 30% from 2018 to 2050. The share of energy consumed by energy-intensive manufacturing holds steady at 50% from 2018 to 2050. These predictions and phenomena were analyzed in several studies [2–4].

Manufacturing has enormous potential for energy saving because 80% of the energy consumed by machines occurs in the idle state [5]. For this reason, several methods to increase energy efficiency in manufacturing have been attempted. The common method is to optimize a production schedule by considering green metrics along with traditional performance indicators. This approach called energy-aware scheduling or energy-efficient scheduling has the advantage of achieving significant performance at no extra cost [6].

In this paper, we deal with energy-efficient scheduling in the flexible job shop scheduling problem (FJSP). Mouzon et al. [5] observed that if an idle period is long enough, the energy could be saved by using shutdown (on/off) strategy to turn the machine off and on. Che et al. [7] first developed a mixed integer linear programming (MILP) model for a single machine scheduling with a shutdown strategy, and the model was effectively validated with CPLEX solver. Subsequently, the shutdown strategy was applied to various production systems, and the first MILP model for FJSP with a shutdown strategy was proposed by Zhang et al. [8]. However, the proposed model was complex and computationally inefficient, so Meng et al. [9] improved it. However, both studies used only one type of MILP formulations for FJSP. This paper proposes the most efficient MILP formulation.

The contributions of this paper are threefold. First, we propose an alternative MILP model for FJSP with a shutdown strategy. Second, we devise a constraint programming (CP). Third, the experimental study demonstrates that we can reduce energy consumption by 14.85% (w/o shutdown) and 15.23% (w/shutdown) on average, while not compromising productivity. In addition, we provide benchmarking instances, CPLEX MIP and CP source codes, and GA code, in order to promote related-research, thus expediting the adoption of energy-efficient scheduling in manufacturing facilities.

The remainder of the paper is organized as follows: Section 2 shows the literature review of FJSP, energy-efficient scheduling, and constraint programming. In Section 3, the problem description and solution methods are described. In Section 4, we compare the performance of proposed models and existing model through computational experiments. Finally, the conclusion and some directions for future research are given in Section 5.

2. Literature Review

2.1. Flexible Job Shop Scheduling Problem. The FJSP has been extensively studied over the past 30 years. A variety of techniques from exact methods to heuristics have been used in this research. Exact methods include branch-and-bound algorithm, MILP, and Lagrangian relaxation method among others, while heuristics include ant colony optimization, artificial bee colony, artificial immune system, evolutionary algorithms, greedy randomized adaptive search procedure, neighborhood search, particle swarm optimization, simulated annealing, Tabu search, hybrid techniques, and so on. See Chaudhry and Khan [10] for the survey about FJSP. We focus on the MILP method.

MILP models for FJSP are classified into four different types by the main binary decision variable. The first is the machine-position formulation (MPF) that determines the position of the machine, where each operation is processed [8, 9, 11, 12]. The second is the general precedence formulation (GPF) that determines whether one operation precedes the other operation on the same machine [13, 14]. Note that one operation is not necessarily positioned immediately before the other operation. The third is the immediate precedence formulation (IPF) that determines whether one operation immediately precedes the other operation on the same machine [15]. The fourth is the time indexed formulation (TIF) that determines the time of the machine when each operation is started [16]. Demir and Kürşat Isleyen [17] classified mathematical models by this criterion and compared the computational results of MILP models.

2.2. Energy-Efficient Scheduling. The studies for energy-efficient scheduling are classified into four groups based on saving methods. The first is to reduce unnecessary idle time. This is a model that extends the existing model to save energy by reducing unnecessary idle time. The second is to shut down the idle machines. Turning off machines during the idle can save energy when idle time is long enough. The decision when to shut down a machine is added into the traditional scheduling model. The third is to slow down a machine speed. Energy consumption depends on a speed of a machine. We can save energy by adjusting a speed of a machine without impacting the makespan. The fourth is off-peak production. In the peak time, electricity costs are high. Therefore, a production at nonpeak time can save a significant amount of electricity costs. Table 1 categorizes studies on energy-efficient scheduling by this criterion. See Gahm et al. [37] and Gao et al. [38] for reviews of energy-efficient scheduling.

Our study belongs to the energy-efficient FJSP using the shutdown option. Among the studies, Dai et al. [25] and Wu and Sun [26] developed a genetic simulated annealing algorithm. Zhang et al. [8] developed MILP model and discovered energy-efficient rules that could be implemented in real practice. Meng et al. [9, 27] proposed several effective MILP models and evaluated the performance of these models. Zhang et al. [8] and Meng et al. [9, 27] used MPF, while our paper uses IPF. Moreover, we develop constraint programming and genetic algorithm models.

2.3. Constraint Programming. Hiller and Lieberman [39] noted that no presentation of the basic ideas of MILP is complete these days without introducing CP––that is promising to greatly expand our ability to formulate and solve various scheduling problems. CP has been applied to various scheduling problems, demonstrating a rapid computational speed. The search within IBM CPLEX CP Optimizer is equipped with the presolve functionality, some constraint propagation algorithms, temporal linear relaxation used to guide the search, and two search space exploration strategies that are used concurrently: the large neighborhood search for producing good quality solutions and failure-directed search for proving infeasibility or optimality [40].

3. Problem Description and Solutions

Consider a flexible job shop environment that consists of a set of heterogeneous machines ($k \in K$) and a set of jobs ($i \in I$). Each job i consists of a set of operations ($J_i = \{1, \ldots, n_i\}$). Each operation needs to be processed in a specific order (known as precedence constraints) for a given job. A machine can perform at most one operation at a time. Each operation must be processed by one of qualified machines. In addition to the standard FJSP problem, an amount of energy consumption is considered in this energy-aware scheduling approach. The energy is consumed during production, idle, and shutdown. The production requires the highest amount of energy, while the idle does the medium and the shutdown requires the lowest. In particular, the shutdown can be enforced when a continuous idle period of a machine is expected to be long enough to compensate the shutdown penalty. When idle times are inevitable, the key is to adjust small-size idle intervals and locate them in a single large-size interval to turn on a long-size shutdown.

Table 1: Articles including energy-efficient scheduling models.

Saving method	Environment		References
Reduce idle time	Single machine		Jiang et al. [18]
	Hybrid flow shop		Li et al. [19]; Zhang et al. [20]
	JSP		Jiang et al. [21]
	FJSP		Yin et al. [22]; Jiang et al. [23]
Shutdown idle machines	Single machine		Mouzon et al. [5]; Che et al. [7]
	Hybrid flow shop		Meng et al. [24]
	FJSP	Meta Heuristic	Dai et al. [25]; Wu and Sun [26]
		MILP-MPF	Zhang et al. [8]; Meng et al. [9]; Meng et al. [27]
		MILP-IPF	This study
Exploit variable machine speed	Single machine		Che et al. [28]
	Flow shop		Fang et al. [29]; Mansouri et al. [30]
	JSP		Zhang and Chiong [31]
	FJSP		Zhang et al. [32]
Shift production soft-enter to off-peak	Single/parallel machine		Rager et al. [33]
	Hybrid flow shop		Schulz et al. [34]
	FJSP		Moon and Park [35]; Gong et al. [36]

3.1. Mixed Integer Linear Programing Models. Meng et al. [9] presented six MILP models for our problem and showed that the second model outperforms all the other models through the numerical experiments. We term this efficient model MILP-2. Despite the superiority of MILP-2, we found that it can be further improved during the implementation by employing tuples instead of arrays, thus dramatically reducing the number of binary decision variables. For instance, the MILP-2 uses a binary variable $Y_{i,j,k,t}$ that represents whether the j-th operation of job i is processed at the t-th position of machine k. This variable is a sparse array, in which most of the elements are zero. Moreover, Meng et al. [9] set the maximum number of the positions of machine k (denoted by m_k) to the total number of operations ($\sum_{i\in I} n_i$), which is excessively large. We set m_k to the number of operations that machine k can process in the instance. By taking those measures, we were able to reduce the number of binary variables by 50–60% in the same instances. We term this efficient model MILP-2A.

MILP-2 is an extension of MPF for FJSP so that energy consumption can be considered. However, Demir and Kürşat Isleyen [17] showed that MPF is the slowest model among alternative models. Choi and Choi [15] proposed a new immediate precedence formulation (IPF) that decides whether one operation immediately precedes the other as shown in Figure 1.

Now, we will propose a new model that improves IPF and extends it to account for energy consumption. We mostly use the same notations as Meng et al. [9]. The details are as follows.

Parameters:

I: set of jobs.

n_i: number of operations of job $i \in I$.

J_i: set of operations of job $i \in I$, that is, $J_i = \{1, \ldots, n_i\}$.

O: set of job and operation pairs, that is, $O = \{(i, j) | i \in I,\ j \in J_i\}$.

K: set of all machines.

K_o: set of machines which can process operation $o \in O$.

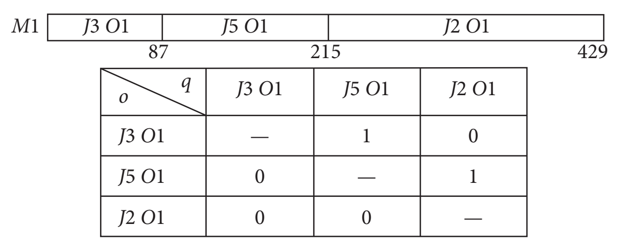

Figure 1: An illustration of immediate precedence formulation using a decision variable $W_{o,q}$.

$p_{o,k}$: processing time of $o \in O$ by machine $k \in K_o$.

D_k: the unit energy consumed at the idle time for machine k when the shutdown strategy is not used

P_0: the unit energy consumed by a facility for lighting, heating, and cooling during the makespan.

$E_{o,k}$: the energy consumed when operation o is processed by machine k.

N_k: the maximum times of shutdown strategy for machine k.

G_k: the energy consumption of machine k when the shutdown strategy is used.

TB_k: the breakeven period of machine k in which the same amount of energy is consumed during the idle time whether the shutdown strategy is used or not. Hence, $TB_k = G_k / D_k$.

O_q: the set of operations which can be processed by the same machine with operation $q \in O$.

PO: the set of precedence operation pairs in the same job operations, that is, $PO = \{(o, q) | o = (i,\ j), q = (i, j + 1),\ i \in I,\ j = 1, \ldots, n_i - 1\}$.

$M_1 = \sum_{o\in O} \max\{p_{o,k} | k \in K_o\}$.

$M_2 = \max\{D_k \cdot TB_k | k \in K\}$.

Decision variables:

$X_{o,k}$: 1 if $o \in O$ is processed by machine $k \in K_o$ and 0 otherwise.

S_o: start time of $o \in O$.

C_o: completion time of $o \in O$.

$C_{\max}$: makespan, that is, $C_{\max} = \max\{c_o | o = (i, n_i) \in O\}$.

V_o: idle time after operation $o \in O$.

R_o: energy consumption during V_o.

$W_{o,q}$: 1 if $o \in O$ immediately precedes $q \in O$ on the same machine and 0 otherwise.

$Z_{o,k}$: 1 if turning shutdown strategy is implemented during V_o on machine $k \in K_o$ and 0 otherwise.

$Q_{o,k}$: 1 if $o \in O$ is processed last on machine $k \in K_o$ and 0 otherwise.

3.1.1. MILP-3 for Energy-Aware Flexible Job Shop Scheduling.

$$\text{Min} \sum_{o \in O} \sum_{k \in K_o} E_{o,k} X_{o,k} + \sum_{o \in O} R_o + P_0 C_{\max}, \tag{1}$$

$$\sum_{k \in K_o} X_{o,k} = 1, \quad \forall o \in O, \tag{2}$$

$$C_o = S_o + \sum_{k \in K_o} p_{o,k} X_{o,k}, \quad \forall o \in O, \tag{3}$$

$$S_q \geq C_o, \quad \forall (o,q) \in PO, \tag{4}$$

$$C_{\max} \geq C_o, \quad \forall o = (i, n_i) \in O, \tag{5}$$

$$\sum_{o \in O} Q_{o,k} \leq 1, \quad \forall k \in K, \tag{6}$$

$$\sum_{o \in O_q} W_{o,q} \leq 1, \quad \forall q \in O, \tag{7}$$

$$\sum_{q \in O_o} W_{o,q} + \sum_{k \in K_o} Q_{o,k} = 1, \quad \forall o \in O, \tag{8}$$

$$W_{o,q} - 1 \leq X_{o,k} - X_{q,k}, \quad \forall o \in O,\ q \in O_o,\ k \in K_o \cap K_q, \tag{9}$$

$$X_{o,k} - X_{q,k} \leq 1 - W_{o,q}, \quad \forall o \in O,\ q \in O_o,\ k \in K_o \cap K_q, \tag{10}$$

$$\sum_{k \in K_o \cap K_q} X_{o,k} \geq W_{o,q}, \quad \forall o \in O,\ q \in O_o, \tag{11}$$

$$\sum_{k \in K_o \cap K_q} X_{q,k} \geq W_{o,q}, \quad \forall o \in O,\ q \in O_o, \tag{12}$$

$$Q_{o,k} \leq X_{o,k}, \quad \forall o \in O,\ k \in K_o, \tag{13}$$

$$S_q \geq C_o + M_1 \left(W_{o,q} - 1 \right), \quad \forall o \in O,\ q \in O_o, \tag{14}$$

$$V_o \leq M_1 \left(1 - \sum_{k \in K_o} Q_{o,k} \right), \quad \forall o \in O, \tag{15}$$

$$V_o \leq S_q - C_o + M_1 \left(1 - W_{o,q} \right), \quad \forall o \in O,\ q \in O_o, \tag{16}$$

$$V_o \geq S_q - C_o - M_1 \left(1 - W_{o,q} \right), \quad \forall o \in O,\ q \in O_o, \tag{17}$$

$$\sum_{o \in O} Z_{o,k} \leq N_k, \quad \forall k \in K, \tag{18}$$

$$V_o \geq TB_k Z_{o,k}, \quad \forall o \in O,\ k \in K_o, \tag{19}$$

$$R_o \geq G_k Z_{o,k}, \quad \forall o \in O,\ k \in K_o, \tag{20}$$

$$R_o \geq D_k V_o + M_2 \left(X_{o,k} - Z_{o,k} - 1 \right), \quad \forall o \in O,\ k \in K_o, \tag{21}$$

$$Z_{o,k} \leq X_{o,k}, \quad \forall o \in O,\ k \in K_o, \tag{22}$$

$$Z_{o,k} \leq 1 - Q_{o,k}, \quad \forall o \in O,\ k \in K_o. \tag{23}$$

Objective (1) is to minimize the total energy, which is consumed for production, idle (including shutdown), and common. Constraint (2) ensures that each operation is processed by exactly one machine. Constraint (3) links the completion time of an operation with its starting time. Constraint (4) enforces that each operation starts after its precedent operation is finished. Constraint (5) indicates the makespan. Constraint (6) imposes that each machine has at most one last job. Constraint (7) imposes that each operation has at most one immediate precedence operation. Constraint (8) imposes that each operation has an immediate next operation or it is the last operation on some machine. Constraints (9)–(12) encode that if o immediately precedes q, then they should be processed by the same machine. Constraint (13) imposes that o can be the last job of machine k only when machine k processes o. Constraint (14) enforces that operation q starts after the completion of operation o if it is processed immediately after operation o on the same machine. Constraint (15) imposes that idle time of the last job is zero. Constraints (16)–(17) compute the idle time V_o of o. Constraint (18) restricts the number of times of shutdown strategy in machine k. Constraint (19) restricts the minimum length of V_o when shutdown strategy is used during V_o. Constraints (20)–(21) compute the idle energy consumption during V_o. Constraints (22)–(23) enforce that shutdown strategy can be turned during V_o on machine k only when o is processed by machine k and it is not the last operation of machine k. We term this newly proposed model MILP-3.

3.2. Constraint Programming. All time durations, such as makespan, shutdowns, and productions, are explicitly modeled as the interval variables as shown in Figure 2.

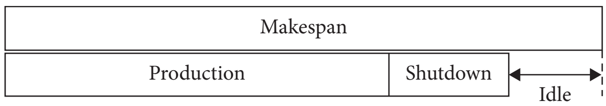

Figure 2: Modeling overview.

As Ham [41] pointed out, there is no standard in CP formulation, unlike a similar MILP formulation. Therefore, this paper formulates the model using generic keywords and syntaxes as we refer to the CP formulations by Laborie et al. [40] and IBM ILOG CP Optimizer [42].

The proposed CP model is built upon the following decision variables:

$Z_{k,s}$: interval representing s-th shutdown on machine $k \in K$

C_k : interval representing makespan of $k \in K$

T_o : interval representing operation $o \in O$

$X_{o,k}$: interval representing operation $o \in O$ on machine $k \in K_o$

$\text{Seq}_k \leftarrow [X_{o,k}]$: collection of variables assigned to machine k

eS: total energy consumption during shutdowns

eP: total energy consumption during productions

eI: total energy consumption during idles

eC: total common energy consumption

3.2.1. CP-1.

$$\text{Min}\, eP + eS + eI + eC, \tag{24}$$

$$\text{alternative}\left(T_o, \left[X_{o,k:\, k\in K_o}\right]\right), \quad \forall o \in O, \tag{25}$$

$$\text{endBeforeStart}\left(T_o, T_q\right), \quad \forall (o,q) \in PO, \tag{26}$$

$$\text{noOverlap}\left(\text{Seq}_k\right), \quad \forall k \in K, \tag{27}$$

$$\text{span}\left(C_k, \left[X_{o,k:\, o\in O, k\in K}\right]\right), \quad \forall k \in K, \tag{28}$$

$$\text{startOf}\left(Z_{k,s}\right) > \text{startOf}\left(C_k\right), \quad \forall k \in K,\ s \le N_k, \tag{29}$$

$$\text{endOf}\left(Z_{k,s}\right) < \text{endOf}\left(C_k\right), \quad \forall k \in K,\ s \le N_k, \tag{30}$$

$$\text{sizeOf}\left(Z_{k,s}\right) \ge TB_k, \quad \forall k \in K,\ s \le N_k, \tag{31}$$

$$eP = \sum_{o\in O}\sum_{k\in K_o} E_{o,k}\,\text{sizeOf}\left(T_o\right), \tag{32}$$

$$eS = G_k \sum_{k\in K_o}\sum_{s\le N_k} \text{presenceOf}\left(Z_{k,s}\right), \tag{33}$$

$$eI = D_k \sum_{k\in K}\left(\text{sizeOf}\left(C_k\right) - \sum_{s\le N_k}\text{sizeOf}\left(Z_{k,s}\right) - \sum_{o\in O}\text{sizeOf}\left(X_{o,k}\right)\right), \tag{34}$$

$$eC = P_0 \underset{\forall o\in O}{\text{Max}}\left\{\text{endOf}\left(T_o\right)\right\}. \tag{35}$$

Objective (24) is to minimize the total energy consumption, which is comprised of production, shutdown, idle, and common. Constraint (25) ensures that each operation is processed by exactly one machine. Constraint (26) enforces each operation starts after its precedent operation is finished. Constraint (27) prevents intervals in a sequence from overlapping. Constraint (28) determines the makespan of each machine. Constraints (29)–(30) ensure that a shutdown can occur during a makespan. Constraint (31) ensures the minimum length of each shutdown. Constraints (32)–(35) compute the total energy consumption for production, shutdown, idle, and common, respectively. We term this model CP-1.

During the preliminary study, the CP-1 could not outperform the MILP-2A model. Here, we explored an alternative CP model. In the CP-1, the idle time was computed based on other interval variables in Constraint (34). We here present an alternative CP model, which explicitly captures the idle intervals.

$\mathbf{I}_{k,t}$: interval representing t-th idle on machine $k \in K$.

$$eI = D_k \sum_{k\in K} \sum_{t \le m_k} \text{sizeOf}\left(I_{k,t}\right), \tag{36}$$

$$\text{sizeOf}\left(C_k\right) = \sum_{o\in O} \text{sizeOf}\left(X_{o,k}\right) + \sum_{s \le N_k} \text{sizeOf}\left(Z_{k,s}\right) + \sum_{t \le m_k} \text{sizeOf}\left(I_{k,t}\right). \tag{37}$$

Constraint (36) replaces Constraint (34). Then, Constraint (37) is introduced to ensure that a makespan of the machine must be packed by productions, shutdowns, and idles. All other constraints stay in place. We term this revised model CP-2.

Figure 3 represents an optimal schedule for a small benchmark instance (mfjs07). Figure 3(a) shows the detailed production schedule per machine with an objective of makespan minimization, and Figure 3(b) depicts the schedule with an objective of energy minimization, while maintaining the same productivity. The proposed model merges the small-size idles enough to turn on shutdown strategy. For instance, the two idles that occurred in machine 4 are replaced by a single shutdown in the same machine. The energy-aware scheduling saved the energy consumption by 1.35% without hurting productivity in the mfjs07 instance.

4. Computational Experiments

In this section, the effectiveness of the proposed models is examined. The MILP, CP, and flow control models are all coded in IBM OPL 12.8.0 on a personal computer with an Intel® Core i7-4770 CPU with 16 GB of RAM. All the test instances, MILP codes, CP codes in IBM OPL, and GA code can be found online at https://github.com/hamcruise/FJSP-Shutdown.

4.1. Problem Instances. Meng et al. [9] proposed a set of test instances derived from the known benchmark instances SFJS01-10 and MFJS01-10 [12] by considering energy consumption. We adopted the same test instances. SFJS01-10 are small-sized, and MFJS01-10 are medium-sized. We also adopted another FJSP benchmark test instance suggested by Behnke and Geiger [43]. Among their extensive 60 instances, we adopted the first 10 instances and added energy parameters in the same way Meng et al. [9] did. Finally, we also used another FJSP benchmark test instance suggested by Kacem et al. [44], which has been adopted by Singh and Mahapatra [45]. The detailed size of the instance ($a/b/c$) is recorded in Table 2, where index a denotes the number of jobs, b denotes the maximum number of operations for a job, and c denotes the number of machines.

For all instances, the common power (P_0) and maximum times of shutdown (N_k) are set to be 5 and 3, respectively. The processing powers are drawn from the uniform distribution [3, 5]. The idle power (D_k) is randomly generated from the set {1, 2, 3}, and the energy consumption during shutdown (G_k) is generated from the set {10, 30, 60}.

4.2. Experimental Results. Figure 4 shows the ratio of the number of binary variables of MILP models to MILP-2. As the size of MILP-2 increases, the binary variables of MILP-2A and MILP-3 decrease. In particular, it is observed that the reduction ratio of the binary variable of MILP-3 sharply decreases as the size increases.

In this subsection, we implemented a genetic algorithm to compare the performance between proposed methods and metaheuristic. Genetic algorithm (GA) is known as an effective metaheuristic to solve flexible job shop scheduling problems [46–49]. The overall GA framework in Zhang et al. [50] was adopted. We had conducted a preliminary test for tuning hyperparameters with respect to the quadruple (*popSize, numGen, crRate*, *mutRate*), where *popSize* is the population size (*popSize* ∈ {100, 200, 400}), *numGen* is the maximum number of generations (*numGen* ∈ {50, 100, 200}), *crRate* is the crossover rate (*crRate* ∈ {0.6, 0.7, 0.8, 0.9, 1.0}), and *mutRate* is the mutation rate (*mutRate* ∈ {0.0, 0.1, 0.2, 0.3}). The best GA hyperparameters that were obtained from the preliminary test were as follows: *popSize* = 100, *numGen* = 50, *crRate* = 0.7, and *mutRate* = 0.1. The increasing population size and number of generations did not ensure obtaining better solutions. The value of the fitness function converged fast in practice.

Tables 3 and 4 compare the proposed MILP and GA with CP models in terms of the objective function value (total energy consumption) and computation times within 600 seconds for Fattahi and Behnke's instances, respectively. Column 1 identifies the name of the instance, columns 2–7 include the total energy consumption, and columns 8–13 report the computation times. The bold font indicates the optimality.

Table 3 reports the results based on Fattahi's instances. For small-sized instances (SFJS01-10), all approaches found the optimal solutions, except GA. In computation times, all approaches, except CP-1, terminated in one second. For medium-sized instances (MFJS01-10), CP-2 yielded the best results on average. In computation times, GA significantly outperforms all other approaches seconds. However, MILP-2, MILP-2A, and MILP-3 terminated at a similar time.

Table 4 reports the results based on Behnke's instances. The proposed MILP-2A performed the best in average. GA is significantly faster than the MILP and CP approaches. However, the total energy consumption is increased up to 8.1% on average.

In order to determine if the means of two sets of data are significantly different from each other, we conducted the t-test: Paired Two-Sample for Means at an alpha level of 0.05. Table 5 indicates that, for medium-sized Fattahi's instances, there is a statistically significant difference between CP-2 vs. CP-1 and GA, while there is no statistically significant difference between CP-2 vs. MILP-2, MILP-2A, and MILP-3. For Behnke's instances, there is a statistically significant difference between MILP-2A vs. CP-1, MILP-2, MILP-2A,

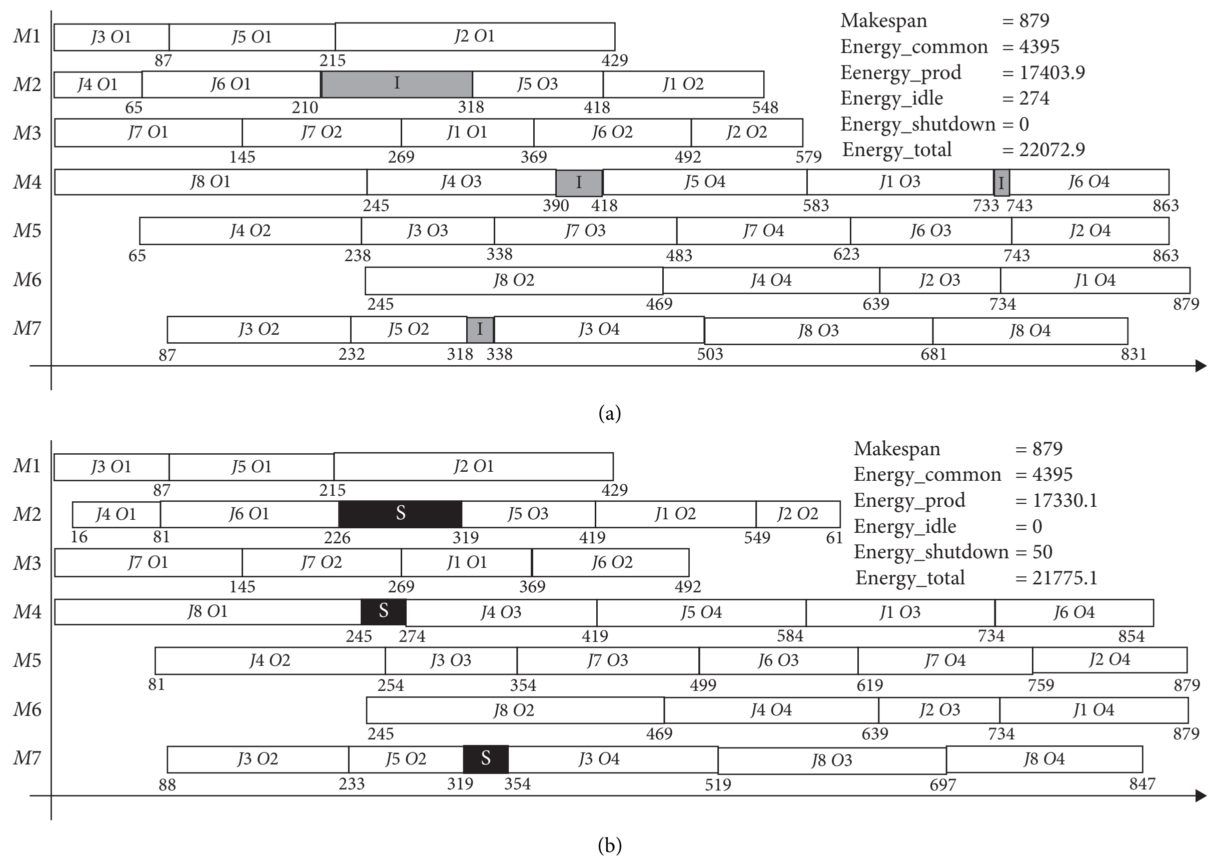

FIGURE 3: Schedules for the mfjs07 instance. (a) Traditional scheduling to minimize $C_{\max}$. (b) Energy-aware scheduling to minimize energy consumption while keeping the same productivity.

TABLE 2: Characteristics of the test instances.

Fattahi instances				Behnke instances	
Name	Size	Name	Size	Name	Size
sfjs01	2/2/2	mfjs01	5/3/6	Behnke1	10/3/20
sfjs02	2/2/2	mfjs02	5/3/7	Behnke2	10/3/20
sfjs03	3/2/2	mfjs03	6/3/7	Behnke3	10/3/20
sfjs04	3/2/2	mfjs04	7/3/7	Behnke4	10/3/20
sfjs05	3/2/2	mfjs05	7/3/7	Behnke5	10/3/20
sfjs06	3/3/2	mfjs06	8/3/7	Behnke6	20/3/20
sfjs07	3/3/5	mfjs07	8/4/7	Behnke7	20/3/20
sfjs08	3/3/4	mfjs08	9/4/8	Behnke8	20/3/20
sfjs09	3/3/3	mfjs09	11/4/8	Behnke9	20/3/20
sfjs10	4/3/5	mfjs10	12/4/8	Behnke10	20/3/20
Kacem instances					
Name	Size	Name	Size	Name	Size
Kacem1	8/4/8	Kacem2	10/3/10	Kacem3	15/4/10

MILP-3, and GA methods, while there is no statistically significant difference between MILP-2A and CP-2.

The previous tables compared the performance of models with a fixed computation time. It is necessary to check how the performance changes according to different computation times. Table 6 summarizes the total energy consumption in terms of computational run time for the Kacem's instances. Both CP and MILP models proved the optimality of Kacem1 instance within 60 s. CP managed to prove the optimality of Kacem2 instance within 60 s, while MILP spent 150 s. In the Kacem3 instance, the CP-2 found an optimal solution within 60 s, while MILP-2A could not find an optimal solution within 600 s. In addition, the CP-2 found a much better solution, in just 10 seconds, than the one MILP-2A found in 600 seconds. This experiment demonstrates that CP is quick to generate efficient (or optimal) solutions.

The energy saving does not appeal to highly capitalized manufacturing industries, such as automobiles and

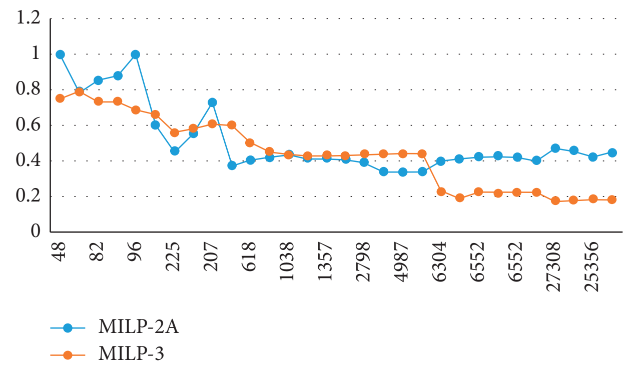

Figure 4: Comparison of the number of binary variables of MILP models.

Table 3: Comparison of models in terms of total cost and computation times on Fattahi instances.

Instance	Total energy consumption						Computation time (second)					
	CP-1	CP-2	MILP-2	MILP-2A	MILP-3	GA	CP-1	CP-2	MILP-2	MILP-2A	MILP-3	GA
sfjs01	815.2	815.2	815.2	815.2	815.2	815.2	54.6	0.3	0.0	0.0	0.0	0.2
sfjs02	1362.2	1362.2	1362.2	1362.2	1362.2	1362.2	65.4	0.3	0.0	0.0	0.0	0.2
sfjs03	2806.2	2806.2	2806.2	2806.2	2806.2	2806.2	507.3	0.3	0.0	0.0	0.0	0.2
sfjs04	4560.3	4560.3	4560.3	4560.3	4560.3	4560.3	600.1	0.3	0.0	0.0	0.0	0.2
sfjs05	1405.4	1405.4	1405.4	1405.4	1405.4	1405.4	547.7	0.3	0.0	0.0	0.0	0.2
sfjs06	4304.6	4304.6	4304.6	4304.6	4304.6	4420.6	600.1	0.3	0.1	0.0	0.0	0.3
sfjs07	5256.0	5256.0	5256.0	5256.0	5256.0	5345.2	600.0	0.3	0.1	0.0	0.0	0.3
sfjs08	3429.7	3429.7	3429.7	3429.7	3429.7	3477.7	600.0	0.3	0.3	0.1	0.0	0.3
sfjs09	2848.0	2848.0	2848.0	2848.0	2848.0	3023.2	600.2	0.4	0.1	0.1	0.1	0.3
sfjs10	8877.0	8877.0	8877.0	8877.0	8877.0	8877	600.0	0.4	0.1	0.0	0.0	0.4
mfjs01	9380.7	9380.7	9380.7	9380.7	9380.7	9981.2	600.0	600.1	2.9	0.8	1.6	0.5
mfjs02	8642.0	8642.0	8642.0	8642.0	8642.0	9082	600.0	600.0	2.8	1.1	1.9	0.5
mfjs03	10799.4	10762.8	10757.8	10757.8	10757.8	11700	600.0	600.0	35.3	4.7	10.8	0.6
mfjs04	13075.9	13038.6	13038.6	13038.6	13038.6	13696	600.0	600.1	117.5	27.3	82.3	0.6
mfjs05	12744.4	12600.1	12600.1	12600.1	12600.1	13579.1	600.0	600.1	93.3	23.7	426.8	0.6
mfjs06	15169.7	14960.1	14960.1	14960.1	14960.1	16257.5	600.0	600.1	49.6	16.7	52.0	0.7
mfjs07	20842.1	20542.1	21098.3	20990.3	21179.6	21884.9	600.0	600.0	607.5	600.2	600.3	1.0
mfjs08	24295.0	23763.8	24289.6	23999.0	23993.4	25812.3	600.0	600.1	601.8	600.3	600.3	1.0
mfjs09	30999.4	29788.1	31386.7	30882.5	30846.4	32237.1	600.1	600.0	601.1	600.5	600.1	1.2
mfjs10	34946.8	34410.7	36794.5	35168.6	37136.6	37293.6	600.0	600.1	600.4	601.6	600.8	1.5
Average	10828.0	10677.7	10930.7	10804.2	10910.0	11380.8	538.8	300.2	135.7	123.9	148.9	0.5

Table 4: Comparison of models in terms of total cost and computation times on Behnke instances.

Instance	Total energy consumption						Computation time (second)					
	CP-1	CP-2	MILP-2	MILP-2A	MILP-3	GA	CP-1	CP-2	MILP-2	MILP-2A	MILP-3	GA
Behnke1	1839.2	1795.8	1795.8	1795.8	1795.8	1889.3	600.0	600.1	600.1	104.6	600.1	1.1
Behnke2	1787.8	1768.0	1763.9	1763.9	1763.9	1884.6	600.0	600.1	318.3	167.3	180.8	1.1
Behnke3	1752.4	1749.9	1749.9	1749.9	1749.9	1902.6	600.0	600.2	332.6	55.3	309.2	1.1
Behnke4	2012.4	1964.2	1961.4	1945.9	1950.4	2082.9	600.0	600.1	600.2	379.7	600.1	1.1
Behnke5	1928.2	1865.7	1867.3	1865.7	1872.6	2101.1	600.0	600.1	600.3	124.4	600.1	1.0
Behnke6	3565.1	3354.1	3385.8	3361.3	3381.6	3637.7	600.1	600.2	600.4	600.2	600.1	2.2
Behnke7	3875.4	3483.1	3475.3	3454.6	3455.2	3734.9	600.0	600.2	602.7	600.3	600.3	2.2
Behnke8	3701.7	3445.2	3509.6	3474.4	3521.3	3774.9	600.0	600.3	604.4	600.4	600.3	1.9
Behnke9	3526.5	3326.6	3324.4	3294.4	3340.0	3579.2	600.0	600.3	600.4	600.3	600.2	2.1
Behnke10	4150.0	3703.4	3742.8	3705.7	3784.6	3916.8	600.0	600.3	603.3	600.4	600.3	2.1
Average	2813.9	2645.6	2657.6	2641.2	2661.5	2850.4	600.0	600.2	546.3	383.3	529.1	1.6

semiconductors, because the total energy cost is not even comparable to the revenue the manufacturers yield, so their sole goal is to maximize productivity. However, if we can maintain the same productivity, while significantly reducing energy consumption, the energy-aware production scheduling will be embraced by the industries. This type of

Table 5: Comparison of models in terms of t-test: paired two-sample for means.

CP-2 vs.	Medium-sized Fattahi instances (MFJS01-10)					MILP-2A vs.	Behnke instances				
	CP-1	MILP-2	MILP-2A	MILP-3	GA		CP-1	CP-2	MILP-2	MILP-3	GA
t-value t (9)	−2.511	−1.918	−2.038	−1.684	−5.185	t-value t (9)	−3.387	−0.780	−3.426	−2.337	−8.547
p-value	0.0333	0.0874	0.0720	0.1265	0.0006	p-value	0.0080	0.4552	0.0076	0.0442	0.0000

Table 6: Comparison of models in terms of total energy consumption according to different CPU times.

Instance	Model	CPU (sec)								
		10	30	60	90	120	150	180	300	600
Kacem1	CP-2	407.5	401.4	393.4	—	—	—	—	—	—
	MILP-2A	443.0	408.6	393.4	—	—	—	—	—	—
	GA	422.6								
Kacem2	CP-2	205.8	202.2	200.8	—	—	—	—	—	—
	MILP-2A	238.6	220.8	215.5	210.0	201.5	200.8	—	—	—
	GA	227.5								
Kacem3	CP-2	520.2	435.8	435.8	435.8	435.8	435.8	435.8	435.8	435.8
	MILP-2A	1909.2	1908.1	1908.1	1908.1	1908.1	1908.1	1908.1	1908.1	1908.1
	GA	501.8								

Table 7: Potential energy saving based on Fattahi instances.

Instance	Total energy consumption			Energy saving	
	Tradition	Energy-aware scheduling		Energy-aware scheduling	
		w/o shutdown	w/ shutdown	w/o shutdown (%)	w/ shutdown (%)
sfjs01	815.2	815.2	815.2	0.00	0.00
sfjs02	1362.2	1362.2	1362.2	0.00	0.00
sfjs03	2806.2	2806.2	2806.2	0.00	0.00
sfjs04	4560.3	4560.3	4560.3	0.00	0.00
sfjs05	1405.4	1405.4	1405.4	0.00	0.00
sfjs06	4630.6	4360.6	4360.6	5.83	5.83
sfjs07	5530.2	5304.2	5304.2	4.09	4.09
sfjs08	3599.2	3599.2	3599.2	0.00	0.00
sfjs09	3121.0	2951.0	2951.0	5.45	5.45
sfjs10	9217.8	8893.0	8877.0	3.52	3.70
mfjs01	9498.6	9468.6	9468.6	0.32	0.32
mfjs02	9036.2	8918.2	8918.2	1.31	1.31
mfjs03	11410.0	11356.0	11278.0	0.47	1.16
mfjs04	13233.9	13163.9	13075.9	0.53	1.19
mfjs05	13333.6	13293.6	13293.6	0.30	0.30
mfjs06	16443.1	16086.7	16086.7	2.17	2.17
mfjs07	22072.9	21973.1	21775.1	0.45	1.35
mfjs08	24884.4	24509.6	24503.8	1.51	1.53
mfjs09	32144.4	31262.2	31262.2	2.74	2.74
mfjs10	35857.7	34874.9	34874.9	2.74	2.74
Average				1.57	1.69

mathematical approach is known as epsilon-constraint method, where one of the objectives is taken as a single objective function and the others are included into a model as constraint [51].

Tables 7 and 8 attempt to meet this demand by comparing the traditional scheduling and energy-aware scheduling. The traditional scheduling minimizes the makespan (cycle time reduction), whereas the energy-aware scheduling minimizes the total energy consumption as it maintains the same makespan. Column 1 identifies the name of the instance. Column 2 reports the total energy consumption when the model solves each test instance with the makespan minimization. Columns 3-4 report the total energy consumption when the model runs with the energy consumption minimization with the same makespan. This experimentation identifies potential energy-saving without compromising productivity. For Fattahi's instances, Table 7 shows 1.57% and 1.69% saving without and with shutdown

Table 8: Potential energy saving based on Behnke instances.

Instance	Total energy consumption			Energy saving	
	Tradition	Energy-aware scheduling		Instance	
		w/o shutdown	w/ shutdown	w/o shutdown (%)	w/ shutdown (%)
Behnke1	2156.2	1809.9	1809.9	16.06	16.06
Behnke2	1955.2	1789.3	1789.3	8.49	8.49
Behnke3	2106.1	1840.9	1796.3	12.59	14.71
Behnke4	2237.8	1945.9	1945.9	13.04	13.04
Behnke5	2125.1	1953.2	1953.2	8.09	8.09
Behnke6	4356.7	3358.3	3358.3	22.92	22.92
Behnke7	4210.8	3543.7	3543.7	15.84	15.84
Behnke8	4200.7	3502.8	3502.8	16.61	16.61
Behnke9	4022.5	3341.8	3297.9	16.92	18.01
Behnke10	4558.5	3740.1	3714.5	17.95	18.51
Average				14.85	15.23

Table 9: Energy saving according to different energy consumption.

Instance	$E_{o,k}$ (%)	$2E_{o,k}$ (%)	$3E_{o,k}$ (%)	$4E_{o,k}$ (%)
Kacem1	10.5	9.5	9.2	8.9
Kacem2	2.8	1.7	1.3	1.1
Kacem3	11.4	9.7	8.9	8.6
Average	8.2	7.0	6.5	6.2

strategy, respectively. The mild saving can be explained by the test instance itself.

Table 8 reports the results of Behnke's instances. This experimentation identified the potential energy-saving without compromising productivity by 14.85% (w/o shutdown) and 15.23% (w/shutdown). The increased savings compared with the ones with Fattahi's instance are due to the size of this Behnke's instance, allowing the solver the flexibility to find better solutions. In order to determine if the means of two sets of data are significantly different from each other, we conducted the t-test: Paired Two-Sample for Means at an alpha level of 0.05. The test indicates that there is a statistically significant difference between traditional and energy-aware methods with $t\ (19) = 3.5$ and $p < 0.01$ in Fattahi's instance and $t\ (9) = 5.53$ and $p < 0.001$ in Behnke's instance.

Table 9 records the amount of energy saving by applying the proposed energy-aware method according to different multipliers on $E_{o,k}$. This experimentation identified the potential energy-saving without compromising productivity by 6–8%. The improvement was slightly decreased as the multiplier was increased.

5. Conclusion

We have investigated the energy-efficient FJSP with a shutdown (on/off) strategy to save idle energy consumption. The shutdown can be enforced when a continuous idle period of a machine is expected to be long enough to compensate for the shutdown penalty. An alternative MILP model is proposed. Then, a novel constraint programming is proposed. Finally, practical operational scenarios are examined.

The computational study demonstrated that (1) the proposed models significantly outperform the best benchmark model (MILP-2) and (2) we can maintain the maximum productivity while significantly reducing the energy-consumption by 14.85% (w/o shutdown) and 15.23% (w/ shutdown) on average, thus promoting energy-aware production scheduling to highly capitalized manufacturing industries. We offer benchmarking instances, CPLEX MIP, CP, and GA source codes, which have been used in this research, in order to promote related research, thus expediting the adoption of energy-efficient scheduling in manufacturing facilities.

In future research, we will extend the proposed models to consider time-of-use (TOU) electricity and peak power load since the energy cost can be further saved. Utility companies across the U.S. are offering TOU-based electricity demand response programs. The key is to shift productions to off-peak periods.

Data Availability

The data used to support the findings of this study have been deposited in the GitHub repository (https://github.com/hamcruise/FJSP-Shutdown)

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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Research Article

A Hybrid Neutrosophic-Grey Analytic Hierarchy Process Method: Decision-Making Modelling in Uncertain Environments

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The analytic hierarchy process (AHP) is recognised as one of the most commonly applied methods in the multiple attribute decision-making (MADM) literature. In the AHP, encompassing uncertainty feature necessitates using suitable uncertainty theories, since dealing efficiently with uncertainty in subjective judgements is of great importance in real-world decision-making problems. The neutrosophic set (NS) theory and grey systems are two reliable uncertainty theories which can bring considerable benefits to uncertain decision-making. The aim of this study is to improve uncertain decision-making by incorporating advantages of the NS and grey systems theories with the AHP in investigating sustainability through agility readiness evaluation in large manufacturing plants. This study pioneers a combined neutrosophic-grey AHP (NG-AHP) method for uncertain decision-making modelling. The applicability of the hybrid NG-AHP method is shown in an illustrative real-case study for agility evaluations in the Iranian steel industry. The computational results indicate the effectiveness of the proposed method in adequately capturing uncertainty in the subjective judgements of decision makers. In addition, the results verify the significance of the research in group decision-making under uncertainty. The practical outcome reveals that, to become a more sustainable agile steel producer in the case country, they should first focus on the "organisation management agility" as the most significant criterion in the assessment followed by "manufacturing process agility," "product design agility," "integration of information system," and "partnership formation capability," respectively.

1. Introduction

In recent years, corporations have moved to the centre of focus in the sustainability debate. The reason for this is that they are considered to be responsible for enormous negative impacts on the environment and society [1]. Sustainability aims to produce a dynamic balance between the three sustainability dimensions: environmental, economic, and social over time [2]. In the contexts of sustainable operations and agility, agile manufacturing (AM) should first be defined. AM has the property of robustness, which means that AM systems must be able to tolerate changes and interruptions within the given demand requirements. Therefore, AM operations can be seen as inherently sustainable. In other words, agility and sustainability are interconnected in this sense, and an agile system can have the potential capability to work as a sustainable system. This link has not been adequately researched in the literature. In this study, we have considered the general definition of sustainability taking into account all three pillars of sustainability in the steel industry.

In addition to the predicted increase in the global population up to 9.7 billion people by 2050 [3], the steel requirement per capita is also expected to increase by 2050 to 11.8 tons. Steel production is responsible for around 7% of global greenhouse gas (GHG) emissions. Bearing in mind the increasing production volume per capita and the necessity to decrease our global greenhouse gas emissions to tackle climate change, it is evident that the steel industry has to shift to more sustainable processes [4]. Steel manufacturing needs more attention from the sustainable development perspective particularly in developing countries. Iskanius et al. [5] investigated the leading forces and abilities for agility in Finnish steel product manufacturing and concluded that the need for agility is clearly recognised in the traditional steel industry and it has to be considered in the long-term strategy planning of steel manufacturing enterprises. Thus, the research question to be addressed is as follows:

RQ: how can agility readiness impact sustainable engineering decisions under uncertain decision-making environment in steel manufacturing?

Decision support tools such as multiple attribute decision-making (MADM) can now be identified as invaluable business analytic methods for helping large organisations to move forward towards providing sustainable operations by developing agility in their manufacturing processes. In the MADM literature, there are methods that have simple implementation and flexibility such as analytic hierarchy process (AHP), best-worst method (BWM) [6], level-based weight assessment (LBWA) [7], and full consistency method (FUCOM) [8]. The AHP is one of the most commonly practised MADM methods [9] mainly because of its ease of application and its flexibility for integration with various methods. An abundance of studies in the literature is focused specifically on applications of AHP such as traffic accessibility [10], advertising media selection [11], selecting e-purse smart card technology [12], and topic popularity selection [13], to name a few. AHP has been utilised to assess complicated multiattribute alternatives by collecting opinions of a group of decision makers (DMs). The feature of inclusion of subjective factors has been considered as one of the AHP's advancements compared to other MADM methods [14]. Many studies have focused on the fuzzy set (FS)-based extension of AHP, namely, fuzzy AHP (F-AHP), so as to capture uncertainty [15–18]. However, few studies have considered the extension of AHP simultaneously with other uncertainty theories such as grey systems and neutrosophic set (NS) theories, which are able to enhance decision-making process under uncertain environment. There are only a few recent developments and applications of AHP and NS theory in the literature [19–25]. Furthermore, only limited research, which is directly related to grey AHP method, has been carried out [26–33]. This gap has motivated the current research to develop AHP under hybrid grey and NS decision-making environments to deal with uncertainty embedded in human subjective judgements which can incorporate the advantage of both in one decision-making model. The NS theory is able to independently quantify the indeterminacy membership function values. Unlike the FS theory, the NS theory has the capability to express the information about rejection. There are growing applications of the NS theory in the decision-making literature [6, 24, 34–40]. Smarandache [41] introduced the NS theory and in [42] thoroughly elaborated on the distinctions between NS and intuitionistic fuzzy set (IFS) theories by providing explanatory examples. It has improved the IFS theory which was initially introduced by Atanassov [43] as an extension of Zadeh's FS theory [44]. Besides the NS theory, Pythagorean fuzzy set (PFS) theory was introduced by Yager [45] and has been a recent extension of IFS theory which is drawing the attention of researchers in the realm of decision-making under uncertainty [46–48]. D-numbers are also introduced to deal with uncertainty in decision-making [49, 50]. In addition to NS theory, grey system theory compared to many mainstream uncertainty theories, such as FS theory, has appreciable features, particularly when it is necessary to deal with uncertain data, and lack of information such as (1) generating satisfactory results utilising a relatively small data volume; (2) producing robust results regarding the noise, and lack of modelling information; and (3) yielding fairly flexible, nonparametric assumptions, and a general way to integrate fuzziness into a problem [16]. Smarandache [51] discussed the NS theory and grey systems all together. In most grey AHP studies, the utilised whitenisation functions cause information loss by converting grey information into crisp values. Moreover, calculating the consistency ratio (CR) to check the consistency among evaluations of DMs in pairwise comparison matrices is another cause of concern. Additionally, in several studies, the integration method is utilised as a combination of grey relational analysis (GRA), and AHP or grey incidence analysis (GIA) and AHP [52–56]. The GRA and GIA are characterised under the grey system theory concept as two distinct MADM methods. The main common feature of these studies is that AHP is applied for calculating criteria weights, and then either GRA or GIA is used for evaluation of alternatives. This category of studies should not be mixed up with the grey-based AHP method, because GRA/GIA-AHP methods do not apply AHP in combination with grey systems theory.

In this paper, we take advantage of operational research (OR) tools from the realm of MADM to evaluate agility readiness of Iranian steel manufacturing corporations with the aim of developing sustainable operations. Two methods, namely, G-AHP (i.e., grey AHP) and N-AHP (i.e., neutrosophic AHP), are combined, and the application of the model is demonstrated as a hybrid method NG-AHP (i.e., neutrosophic-grey AHP) in an agility evaluation case in the Iranian steel industry. It is believed that based on the provided method, the uncertainty of DMs can be best handled via hybrid neutrosophic-grey uncertainty theories. The N-AHP approach is an integration of the NS theory with the AHP, in which the single-valued trapezoidal neutrosophic numbers (SVTNNs) are utilised in the AHP calculations [19]. The proposed G-AHP method has furthered the existing grey AHP methods in two major ways. Firstly, it preserves the grey characteristics of grey numbers during calculation steps by reducing information loss, specifically by omitting the need for whitenisation function deployment. Secondly, it ensures assessment consistency in pairwise comparisons by introducing two importance rating scales and constructing the pairwise comparisons based on the suggested procedure. It also obtains the aggregated opinions of DMs efficiently, while also handling the inherent ambiguity in the subjective judgements of DMs through preserving grey values.

To the best of our knowledge, OR tools such as MADM methods have not been applied extensively for sustainable development and there is a gap in the literature in this matter [57]. Moreover, only a few studies have explored sustainability through the agility perspective in manufacturing settings. In other words, achieving sustainable operations in engineering through AM or sustainable agility has not been a well-researched topic in the literature. It is explained that agility and sustainability are closely connected, meaning that studying agility in manufacturing enterprises can thus lead to better understanding of sustainable development. To bridge this gap, we are exploring agility readiness in the steel manufacturing business by applying a novel combined MADM method. The current research features the following three specific contributions:

(1) Investigating sustainable engineering by agility readiness evaluation in an Iranian steel manufacturing setting.

(2) Extending group AHP to a grey environment (G-AHP) while preserving the grey characteristics of the judgements with fully consistent evaluations in the pairwise comparison matrices. The first characteristic of the proposed G-AHP is that no whitenisation function is needed unlike most other grey AHP methods which would utilise whitenisation functions to get crisp values. The second feature is that no CR calculation is required in pairwise comparison matrices due to the way they are established, which also helps save time and cost. To the best of our knowledge, no grey AHP method in the literature has these two traits simultaneously and with a straightforward procedure.

(3) Integrating N-AHP [19] with G-AHP (i.e., NG-AHP) in a real-world agility evaluation case in the Iranian steel industry to illustrate its capability and versatility in one hybrid methodological application. The application of the hybrid methodology (i.e., NG-AHP) was shown to reveal the benefits of both methods in one single framework, while also emphasising the synergistic effects of the two in one single framework and also overcoming their drawbacks at the same time.

In Figure 1, a generic hierarchical structure is shown in which the applied levels of proposed methods are presented. The calculation steps of each method are shown in Figure 2.

The proposed hybrid NG-AHP is comprised of two separate methods including integration of the N-AHP (Section 4), and G-AHP (Section 5). The criteria weights are calculated by the N-AHP, and the importance weights of alternatives are obtained by G-AHP. Ultimately, the weights are integrated, and alternatives are ranked to calculate the total weights of alternatives in the final decision matrix (Section 6). In Section 7, findings are discussed, and the paper is concluded in Section 8.

2. Sustainability and Agility

Agility is characterised as the ability to react to and handle unpredictable changes and encompasses cost reduction, quality improvement, delivery, and service improvement. Agility lies in the domain of AM which is the ability to meet volatile business requirements with adaptability and has been developed in response to lean manufacturing (LM) systems [58, 59]. Leanness aims at maximising profit through cost reduction, while agility tries to maximise profit by providing precisely what a customer needs [60]. Agility is also considered as the interface between the company and the market [61].

Sustainability generally concentrates on protecting natural resources against exploitation via productivity and competitiveness by manufacturing and service organisations. However, the concept of sustainability includes two key aspects other than the environmental aspect, which are economic and social [62, 63]. Thereby, the three dimensions of sustainability (i.e., environmental, economic, and social) have to be considered and treated equally. Gunasekaran and Spalanzani [62] investigated sustainable business development (SBD) in manufacturing and services, which has been regarded as a critical issue due to many causes such as climate change and natural disasters. Sustainability efforts can be included in all stages of a supply chain from product design and manufacturing to the product end-of-life stage such as remanufacturing [64]. Rostamzadeh et al. [65] investigated sustainability issues in the supply chain risk management domain by applying an integrated fuzzy MCDM based on TOPSIS and criteria importance through intercriteria correlation (CRITIC). Ivory and Brooks [66] offered a conceptual framework illuminating the strategic agility metacapabilities (resource fluidity, collective commitment, and strategic sensitivity) and related practices/processes that firms use to effectively deal with corporate sustainability with a paradoxical lens.

There would be an intuitive possible connection between agility and sustainability because more efficient and improved quality production by being quick and flexible in agile manufacturing potentially would lead to less production waste and carbon emissions and ultimately to more sustainable production. Carvalho et al. [60] recognised the trade-offs between lean, agile, resilient, and green (LARG) management systems as a probable pathway towards a more sustainable system. It is also indicated that agility and sustainability are regarded as performance measures for contemporary enterprises. In the current manufacturing scenario, agility needs to be matched with sustainability [67]. Pham and Thomas [68] suggested that for firms to be competitive, they should achieve an effective level of leanness, agility, and sustainability that associates with change and uncertainty in an operational system and the individual business environment. Flumerfelt et al. [59] investigated theories and practices of agile and lean manufacturing systems to gain an understanding of whether these employ

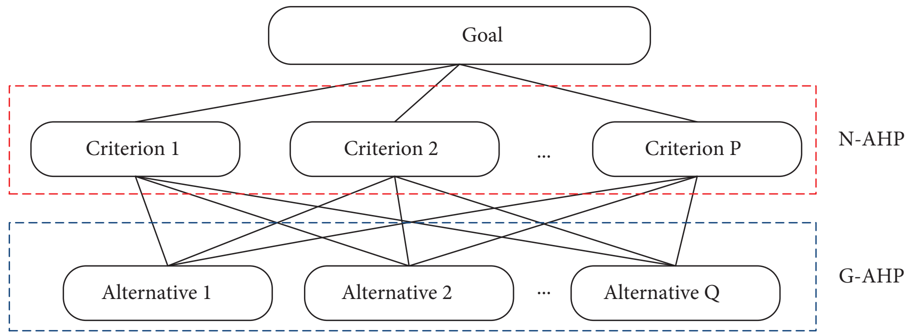

Figure 1: The NG-AHP decision-modelling hierarchy.

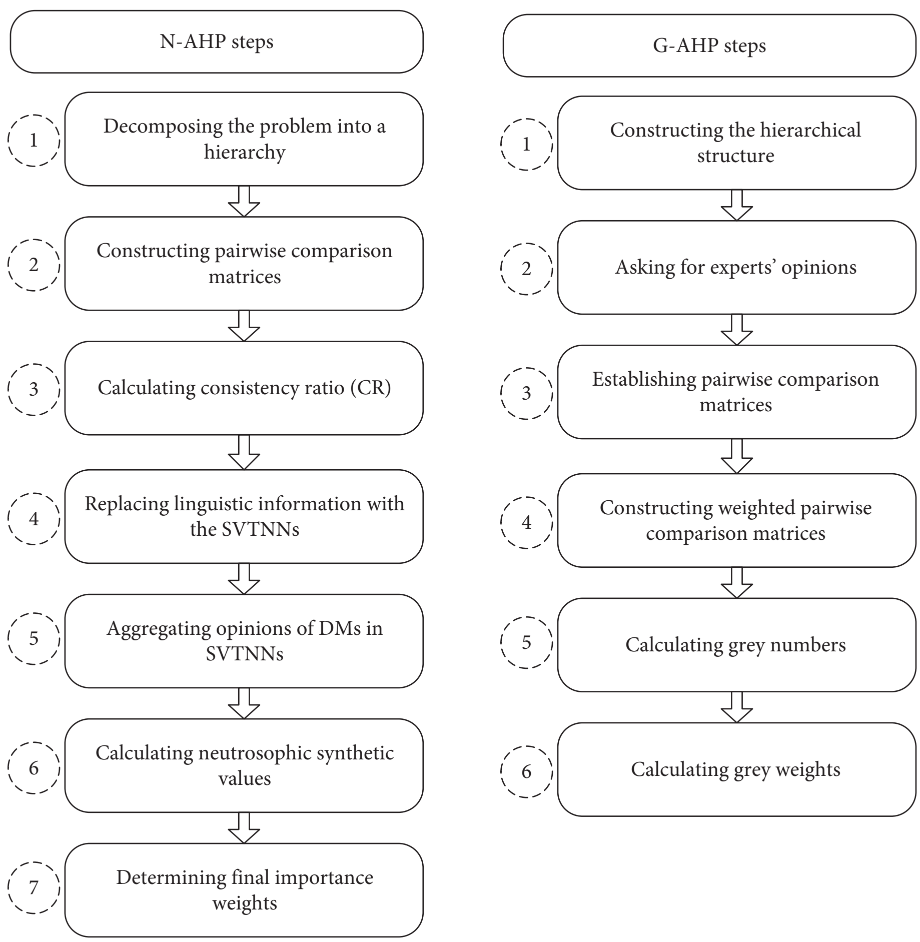

Figure 2: The calculation steps of the N-AHP [19] and the G-AHP.

sustainability or not. They recognised AM operations are sustainable because sustainability means ability to endure, and AM systems must be robust which means they are capable to endure alterations under various demand circumstances.

3. Preliminaries

3.1. Neutrosophic Set Theory. Some basic definitions of NS theory are provided in this section [69].

Definition 1 (see [41]). Let U be a finite set of objects and let x signify a generic element in U. The NS A in U is characterised by a truth-membership function $T_A(x)$, an indeterminacy-membership function $I_A(x)$, and a falsity-membership function $F_A(x)$. $T_A(x)$, $I_A(x)$, and $F_A(x)$ are the elements of $]0^-, 1^+[$. It can be shown as

$$A = \{ < x, \ (T_A(x), I_A(x), F_A(x)) > : x \in U, T_A(x), I_A(x), F_A(x) \in \ ]0^-, 1^+[\ \}. \quad (1)$$

Note that $0^- \leq T_A(x) + I_A(x) + F_A(x) \leq 3^+$.

Definition 2 (see [70]). Let U be a finite set of elements, and let x signify a generic element in U. A single-valued neutrosophic set (SVNS) A in U is defined by a truth-membership function $T_A(x)$, an indeterminacy-membership function $I_A(x)$, and a falsity-membership function $F_A(x)$. $T_A(x)$, $I_A(x)$, and $F_A(x)$ are the elements of $[0,1]$. It can be shown as

$$A = \{< x, \ (T_A(x), I_A(x), F_A(x)) >: x \in U, T_A(x), I_A(x), F_A(x) \in [0,1]\}. \quad (2)$$

Note that $0 \le T_A(x) + I_A(x) + F_A(x) \le 3$.

For convenience, an SVNS $A = \{< x, (T_A(x), I_A(x), F_A(x)) >: x \in U\}$ is sometimes shown as a $A = \{< T_A(x), I_A(x), F_A(x) >: x \in U\}$ called simplified form.

Definition 3 (see [71]). An SVTNN $\tilde{a} = < (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} >$, $a_1, b_1, c_1, d_1 \in R$, $a_1 \le b_1 \le c_1 \le d_1$, and $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \in [0,1]$ is a particular single-valued neutrosophic number (SVNN) whose $T_{\tilde{a}}(x)$, $I_{\tilde{a}}(x)$, and $F_{\tilde{a}}(x)$ are presented as the following equations, respectively:

$$T_{\tilde{a}}(x) = \begin{cases} \dfrac{(x - a_1) w_{\tilde{a}}}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ w_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{(d_1 - x) w_{\tilde{a}}}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 0, & \text{otherwise}, \end{cases} \quad (3)$$

$$I_{\tilde{a}}(x) = \begin{cases} \dfrac{(b_1 - x + u_{\tilde{a}}(x - a_1))}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ u_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{(x - c_1 + u_{\tilde{a}}(d_1 - x))}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 1, & \text{otherwise}, \end{cases} \quad (4)$$

$$F_{\tilde{a}}(x) = \begin{cases} \dfrac{(b_1 - x + y_{\tilde{a}}(x - a_1))}{(b_1 - a_1)}, & a_1 \le x < b_1, \\ y_{\tilde{a}}, & b_1 \le x \le c_1, \\ \dfrac{(x - c_1 + y_{\tilde{a}}(d_1 - x))}{(d_1 - c_1)}, & c_1 < x \le d_1, \\ 1, & \text{otherwise}. \end{cases} \quad (5)$$

Definition 4 (see [72]). Given $\tilde{a} = < (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} >$, and $\tilde{b} = < (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} >$, and $\lambda > 0$, $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}, w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \in [0,1]$, $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 \in \mathbb{R}$, $a_1 \le b_1 \le c_1 \le d_1$, and $a_2 \le b_2 \le c_2 \le d_2$, and then equations (6) and (7) are true:

$$\tilde{a} + \tilde{b} = < (a_1 + a_2, \ b_1 + b_2, \ c_1 + c_2, \ d_1 + d_2); w_{\tilde{a}} + w_{\tilde{b}} - w_{\tilde{a}} w_{\tilde{b}}, \ u_{\tilde{a}} u_{\tilde{b}}, \ y_{\tilde{a}} y_{\tilde{b}} >, \quad (6)$$

$$\lambda \tilde{a} = < (\lambda a_1, \lambda b_1, \lambda c_1, \lambda d_1); 1 - (1 - w_{\tilde{a}})^{\lambda}, u_{\tilde{a}}^{\lambda}, y_{\tilde{a}}^{\lambda} >. \quad (7)$$

When $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 > 0$, then equations (8) and (9) are true:

$$\tilde{a}\tilde{b} = < (a_1 a_2, \ b_1 b_2, \ c_1 c_2, \ d_1 d_2); w_{\tilde{a}} w_{\tilde{b}}, \ u_{\tilde{a}} + u_{\tilde{b}} - u_{\tilde{a}} u_{\tilde{b}}, \ y_{\tilde{a}} + y_{\tilde{b}} - y_{\tilde{a}} y_{\tilde{b}} >, \quad (8)$$

$$\tilde{a}^{\lambda} = < \left(a_1^{\lambda}, b_1^{\lambda}, c_1^{\lambda}, d_1^{\lambda}\right); w_{\tilde{a}}^{\lambda}, 1 - (1 - u_{\tilde{a}})^{\lambda}, 1 - (1 - y_{\tilde{a}})^{\lambda} >. \quad (9)$$

Definition 5 (see [72]). Given $\tilde{a} = < (a, b, c, d); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} >$ and $a, b, c, d > 0$. Then, the score function of $\tilde{a}$ can be calculated in accordance with the following equation:

$$S(\tilde{a}) = \frac{1}{12}(a + b + c + d)(2 + w_{\tilde{a}} - u_{\tilde{a}} - y_{\tilde{a}}), \quad S(\tilde{a}) \in [0,1]. \quad (10)$$

Definition 6 (see [72]). In order to compare two SVTNNs $\tilde{a} = < (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} >$, and $\tilde{b} = < (a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} >$ where $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 > 0$, then according to equation (10), the score functions will be computed, and if $S(\tilde{a}) > S(\tilde{b})$, then $\tilde{a} > \tilde{b}$; if $S(\tilde{a}) = S(\tilde{b})$, then $\tilde{a} = \tilde{b}$.

Definition 7. Let $\tilde{a}_j = < (a_j, b_j, c_j, d_j); w_{\tilde{a}_j}, u_{\tilde{a}_j}, y_{\tilde{a}_j} >$ $(j = 1, 2, \ldots, n)$ be a set of SVTNNs, then a trapezoidal neutrosophic weighted arithmetic averaging (TNWAA) operator is computed on the basis of [72]

$$\begin{aligned} \text{TNWAA}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) &= \sum_{j=1}^{n} p_j \tilde{a}_j \\ &= < \left(\sum_{j=1}^{n} p_j a_j, \sum_{j=1}^{n} p_j b_j, \sum_{j=1}^{n} p_j c_j, \sum_{j=1}^{n} p_j d_j \right); 1 \\ &\quad - \prod_{j=1}^{n} \left(1 - w_{\tilde{a}_j}\right)^{p_j}, \prod_{j=1}^{n} u_{\tilde{a}_j}^{p_j}, \prod_{j=1}^{n} y_{\tilde{a}_j}^{p_j} >, \end{aligned} \quad (11)$$

where p_j is the weight of $\tilde{a}_j$ $(j = 1, 2, \ldots, n)$ while $p_j > 0$, and $\sum_{j=1}^{n} p_j = 1$.

3.2. Subtraction, Division, and Inverse of SVTNNs.

3.2. Subtraction, Division, and Inverse of SVTNNs. The subtraction and division of simplified SVNNs (or single-valued neutrosophic values) and SVNSs are introduced by Smarandache [73] and Ye [74], respectively. Rani and Garg [75] also studied subtraction and division operations on interval neutrosophic sets. In this section, subtraction, division, and inverse of SVTNNs in general nonsimplified form are defined.

3.2.1. Subtraction of SVTNNs. Let $\tilde{a} = <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}>$, and $\tilde{b} = <(a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}>$ be two SVTNNs, and $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}, w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \in [0,1]$ with the restrictions that $w_{\tilde{b}} \neq 1$, $u_{\tilde{b}} \neq 0$, $y_{\tilde{b}} \neq 0$, and $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 \in \mathbb{R}$, $a_1 \leq b_1 \leq c_1 \leq d_1$, and $a_2 \leq b_2 \leq c_2 \leq d_2$, then the subtraction of the two SVTNNs is shown in

$$\tilde{a} - \tilde{b} = <(a_1 - d_2, b_1 - c_2, c_1 - b_2, d_1 - a_2); \frac{w_{\tilde{a}} - w_{\tilde{b}}}{1 - w_{\tilde{b}}}, \frac{u_{\tilde{a}}}{u_{\tilde{b}}}, \frac{y_{\tilde{a}}}{y_{\tilde{b}}}>. \quad (12)$$

Note: for a negative value, replace it with zero. For a value of over one, replace it with one.

Proof. Let us consider equation (13) where

$$\begin{aligned} \tilde{a} &= <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}> \\ \tilde{b} &= <(a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}> \\ \tilde{c} &= <(x, r, z, s); w_{\tilde{c}}, u_{\tilde{c}}, y_{\tilde{c}}> \\ \tilde{a} - \tilde{b} &= \tilde{c}. \end{aligned} \quad (13)$$

By adding neutrosophically, $\tilde{b}$ to the sides of equation (13)–(16) results,

$$\begin{aligned} \tilde{a} = \tilde{c} + \tilde{b} = &<(x + a_2, r + b_2, z + c_2, s + d_2); w_{\tilde{c}} \\ &+ w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}}, u_{\tilde{c}} u_{\tilde{b}}, y_{\tilde{c}} y_{\tilde{b}}>. \end{aligned} \quad (14)$$

Then,

$$\begin{aligned} \tilde{a} &= <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}> = \\ &= <(x + a_2, r + b_2, z + c_2, s + d_2); w_{\tilde{c}} \\ &\quad + w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}}, u_{\tilde{c}} u_{\tilde{b}}, y_{\tilde{c}} y_{\tilde{b}}>, \end{aligned} \quad (15)$$

and

$$\begin{cases} w_{\tilde{a}} = w_{\tilde{c}} + w_{\tilde{b}} - w_{\tilde{c}} w_{\tilde{b}} \Rightarrow w_{\tilde{a}} - w_{\tilde{b}} = w_{\tilde{c}}\left(1 - w_{\tilde{b}}\right) \Rightarrow w_{\tilde{c}} = \dfrac{w_{\tilde{a}} - w_{\tilde{b}}}{1 - w_{\tilde{b}}}, \\ u_{\tilde{a}} = u_{\tilde{c}} u_{\tilde{b}} \Rightarrow u_{\tilde{c}} = \dfrac{u_{\tilde{a}}}{u_{\tilde{b}}}, \\ y_{\tilde{a}} = y_{\tilde{c}} y_{\tilde{b}} \Rightarrow y_{\tilde{c}} = \dfrac{y_{\tilde{a}}}{y_{\tilde{b}}}. \end{cases} \quad (16)$$

It is concluded that $-\tilde{b} = <(-d_2, -c_2, -b_2, -a_2); (w_{\tilde{b}}/w_{\tilde{b}} - 1), (1/u_{\tilde{b}}), (1/y_{\tilde{b}})>$, noting the remark above. □

3.2.2. Division of SVTNNs. Let $\tilde{a} = <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}>$ and $\tilde{b} = <(a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}>$ be two SVTNNs where $a_1, b_1, c_1, d_1, a_2, b_2, c_2, d_2 > 0$, $a_1 \leq b_1 \leq c_1 \leq d_1$, $a_2 \leq b_2 \leq c_2 \leq d_2$, and $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}, w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}} \in [0,1]$ with the restrictions that $w_{\tilde{b}} \neq 1$, $u_{\tilde{b}} \neq 0$, and $y_{\tilde{b}} \neq 0$, then the division of the two SVTNNs is shown in

$$\tilde{a} \div \tilde{b} = <\left(\frac{a_1}{d_2}, \frac{b_1}{c_2}, \frac{c_1}{b_2}, \frac{d_1}{a_2}\right); \frac{w_{\tilde{a}}}{w_{\tilde{b}}}, \frac{u_{\tilde{a}} - u_{\tilde{b}}}{1 - u_{\tilde{b}}}, \frac{y_{\tilde{a}} - y_{\tilde{b}}}{1 - y_{\tilde{b}}}>. \quad (17)$$

Note: for a negative value, replace it with zero. For a value of over one, replace it with one.

Proof. Let us consider equation (18) where

$$\begin{aligned} \tilde{a} &= <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}> \\ \tilde{b} &= <(a_2, b_2, c_2, d_2); w_{\tilde{b}}, u_{\tilde{b}}, y_{\tilde{b}}> \\ \tilde{c} &= <(x, r, z, s); w_{\tilde{c}}, u_{\tilde{c}}, y_{\tilde{c}}> \\ \tilde{a} \div \tilde{b} &= \tilde{c}. \end{aligned} \quad (18)$$

By multiplying neutrosophically, $\tilde{b}$ to the sides of equation (18)–(21) is obtained:

$$\begin{aligned} \tilde{a} &= \tilde{c} \times \tilde{b} = \\ &= <(x a_2, r b_2, z c_2, s d_2); w_{\tilde{c}} w_{\tilde{b}}, u_{\tilde{c}} + u_{\tilde{b}} - u_{\tilde{c}} u_{\tilde{b}}, y_{\tilde{c}} \\ &\quad + y_{\tilde{b}} - y_{\tilde{c}} y_{\tilde{b}}>. \end{aligned} \quad (19)$$

Then,

$$\begin{aligned} \tilde{a} &= <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}> = \\ &= <(x a_2, r b_2, z c_2, s d_2); w_{\tilde{c}} w_{\tilde{b}}, u_{\tilde{c}} + u_{\tilde{b}} - u_{\tilde{c}} u_{\tilde{b}}, y_{\tilde{c}} \\ &\quad + y_{\tilde{b}} - y_{\tilde{c}} y_{\tilde{b}}>. \end{aligned} \quad (20)$$

and

$$\begin{cases} w_{\tilde{a}} = w_{\tilde{c}} w_{\tilde{b}} \Rightarrow w_{\tilde{c}} = \dfrac{w_{\tilde{a}}}{w_{\tilde{b}}}, \\ u_{\tilde{a}} = u_{\tilde{c}} + u_{\tilde{b}} - u_{\tilde{c}} u_{\tilde{b}} \Rightarrow u_{\tilde{a}} - u_{\tilde{b}} = u_{\tilde{c}}\left(1 - u_{\tilde{b}}\right) \Rightarrow u_{\tilde{c}} = \dfrac{u_{\tilde{a}} - u_{\tilde{b}}}{1 - u_{\tilde{b}}}, \\ y_{\tilde{a}} = y_{\tilde{c}} + y_{\tilde{b}} - y_{\tilde{c}} y_{\tilde{b}} \Rightarrow y_{\tilde{a}} - y_{\tilde{b}} = y_{\tilde{c}}\left(1 - y_{\tilde{b}}\right) \Rightarrow y_{\tilde{c}} = \dfrac{y_{\tilde{a}} - y_{\tilde{b}}}{1 - y_{\tilde{b}}}. \end{cases} \quad (21)$$

□

3.2.3. Inverse of an SVTNN. Let $\tilde{a} = <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}>$ be an SVTNN where $a_1, b_1, c_1, d_1 > 0$, $a_1 \leq b_1 \leq c_1 \leq d_1$, and $w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}, \in [0,1]$, then the inverse of $\tilde{a}$ is represented in

$$\tilde{a}^{-1} = \frac{1}{\tilde{a}} = <\left(\frac{1}{d_1}, \frac{1}{c_1}, \frac{1}{b_1}, \frac{1}{a_1}\right); \frac{1}{w_{\tilde{a}}}, \frac{u_{\tilde{a}}}{u_{\tilde{a}} - 1}, \frac{y_{\tilde{a}}}{y_{\tilde{a}} - 1}>. \quad (22)$$

Note: for a negative value, replace it with zero. For a value of over one, replace it with one.

Proof. Let us consider equation (23), where $\tilde{a} = <(a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}}>$, and $\tilde{a}^{-1} = <(x, r, z, s); w_{\tilde{c}}, u_{\tilde{c}}, y_{\tilde{c}}>$,

$$\tilde{a}^{-1} = \frac{1}{\tilde{a}} = \frac{\langle (1,1,1,1); 1,0,0 \rangle}{\langle (a_1, b_1, c_1, d_1); w_{\tilde{a}}, u_{\tilde{a}}, y_{\tilde{a}} \rangle}. \quad (23)$$

Then, based on the division rule of two SVTNNs referring to equation (17), the proof is provided. □

3.3. Grey System Theory. In this section, some basic definitions of grey systems theory are provided [69].

Definition 8. A grey number $\otimes X$ is defined as an interval with known upper, and lower bounds which are shown by $\overline{X}$ and $\underline{X}$, respectively, but there is no known distribution information for X [76, 77], as represented in

$$\otimes X = [\underline{X}, \overline{X}] = \left[X' \in \otimes X \mid \underline{X} \le X' \le \overline{X}\right]. \quad (24)$$

Definition 9. Given $\otimes X_1 = [\underline{X}_1, \overline{X}_1]$ and $\otimes X_2 = [\underline{X}_2, \overline{X}_2]$ are two grey numbers, then the basic operations of grey numbers can be defined as follows [78, 79]:

$$\otimes X_1 + \otimes X_2 = [\underline{X}_1 + \underline{X}_2, \overline{X}_1 + \overline{X}_2], \quad (25)$$

$$\otimes X_1 - \otimes X_2 = [\underline{X}_1 - \overline{X}_2, \overline{X}_1 - \underline{X}_2], \quad (26)$$

$$\otimes X_1 \times \otimes X_2 = \begin{bmatrix} \min(\underline{X}_1\underline{X}_2, \underline{X}_1\overline{X}_2, \overline{X}_1\underline{X}_2, \overline{X}_1\overline{X}_2) \\ \max(\underline{X}_1\underline{X}_2, \underline{X}_1\overline{X}_2, \overline{X}_1\underline{X}_2, \overline{X}_1\overline{X}_2) \end{bmatrix}, \quad (27)$$

$$\otimes X_1 \div \otimes X_2 = [\underline{X}_1, \overline{X}_1] \times \left[\frac{1}{\overline{X}_2}, \frac{1}{\underline{X}_2}\right]. \quad (28)$$

Definition 10. The length of a grey number $\otimes X$ is defined as

$$L(\otimes X) = [\overline{X} - \underline{X}]. \quad (29)$$

Definition 11. Comparison of grey numbers [80].

Given $\otimes X_1 = [\underline{X}_1, \overline{X}_1]$ and $\otimes X_2 = [\underline{X}_2, \overline{X}_2]$ are two grey numbers, the possibility degree of $\otimes X_1 \le \otimes X_2$ can be defined as follows:

$$P\{\otimes X_1 \le \otimes X_2\} = \frac{\max(0, L^* - \max(0, \overline{X}_1 - \underline{X}_2))}{L^*}, \quad (30)$$

where $L^* = L(\otimes X_1) + L(\otimes X_2)$.

There are four possible cases on the real number axis to determine the relationship between $\otimes X_1$ and $\otimes X_2$:

(1) If $\underline{X}_1 = \underline{X}_2$ and $\overline{X}_1 = \overline{X}_2$, then $\otimes X_1 = \otimes X_2$. Thus, $P\{\otimes X_1 \le \otimes X_2\} = 0.5$

(2) If $\underline{X}_2 > \overline{X}_1$, then $\otimes X_2 > \otimes X_1$. Thus, $P\{\otimes X_1 \le \otimes X_2\} = 1$

(3) If $\overline{X}_2 < \underline{X}_1$, then $\otimes X_2 < \otimes X_1$. Thus, $P\{\otimes X_1 \le \otimes X_2\} = 0$

(i) (4-a) If $\{\otimes X_1 \le \otimes X_2\} > 0.5$, then $\otimes X_2 > \otimes X_1$

(ii) (4-b) If $\{\otimes X_1 \le \otimes X_2\} < 0.5$, then $\otimes X_2 < \otimes X_1$

Definition 12 (see [81]). Whitenised (whitened or crisp value) of a grey number is a deterministic number with its value between the upper and lower bounds of a grey number $\otimes X$. The whitenised value $x_{(\lambda)}$ can be defined as equation (31) in which λ is whitening coefficient, and $\lambda \in [0,1]$:

$$x_{(\lambda)} = (1-\lambda)\,\underline{x} + \lambda\overline{x}. \quad (31)$$

For $\lambda = 0.5$, equation (32) will be resulted:

$$x_{(\lambda=0.5)} = \frac{1}{2}\left(\underline{x} + \overline{x}\right). \quad (32)$$

Definition 13 (see [81, 82]). Given $\otimes X_1 = [\underline{X}_1, \overline{X}_1]$ and $\otimes X_2 = [\underline{X}_2, \overline{X}_2]$ are two grey numbers, then the distance between $\otimes X_1$ and $\otimes X_2$ can be calculated as signed difference between their centres as shown in

$$d(\otimes X_1, \otimes X_2) = \frac{\underline{x}_1 + \overline{x}_1}{2} - \frac{\underline{x}_2 + \overline{x}_2}{2} = \frac{1}{2}\left[(\underline{x}_1 - \underline{x}_2) + (\overline{x}_1 - \overline{x}_2)\right]. \quad (33)$$

Definition 14 (see [79]). Given $\otimes X = [\underline{X}, \overline{X}]$ is a grey number, and >0; then, equation (34) is resulted:

$$k \times [\underline{X}, \overline{X}] = [k\,\underline{X}, k\overline{X}]. \quad (34)$$

4. The N-AHP Method

The N-AHP method follows the steps below as introduced in [19].

Step 1 (hierarchical structure): it is an essential step to establish a hierarchy, representing the goal, criteria, and alternatives because it makes the problem more comprehensible.

Step 2 (pairwise comparison matrix): the DMs evaluate elements (i.e., alternatives or criteria), using the Saaty rating scale Table 1. In the experts' judgements questionnaire, DMs choose a linguistic phrase representing the importance degree of each element in comparison to others.

Given $C_1, C_2, \ldots, C_n$ signify the elements, and a_{ijk} shows a quantified evaluation on a pair of elements, C_i and C_j by k^{th} DM ($k = 1, 2, \ldots, p$). This leads to a pairwise comparison matrix as represented in [84, 85]

$$A_k = \left[a_{ijk}\right] = \begin{bmatrix} 1 & a_{12k} & \cdots & a_{1nk} \\ 1/a_{12k} & 1 & \ldots & a_{2nk} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1nk} & 1/a_{2nk} & \cdots & 1 \end{bmatrix}. \quad (35)$$

Step 3 (calculating CR): referring to Saaty's suggestion [86], a consistency test has to be conducted to differentiate the consistent comparisons from the inconsistent comparisons. See equation (36)

Table 1: The importance rating scale [83].

Numerical Scale	Verbal Scale
1	Equal importance
2	Weak importance
3	Moderate importance
4	Moderate plus importance
5	Strong importance
6	Strong plus importance
7	Very strong importance
8	Very very strong importance
9	Extreme importance

and Table 2. If the value CR ≥ 0.1, then the DMs have to do a revision in their evaluations [88]:

$$\mathrm{CR} = \frac{((\lambda_{\max} - n)/(n-1))}{\mathrm{RI}}. \quad (36)$$

Step 4 (replacing the linguistic information with the SVTNNs): the elements of the pairwise comparison matrices are replaced with the corresponding SVTNNs using the scale shown in Table 3 (see Section 3.2.3 for calculating inverse of an SVTNN).

Step 5 (aggregating the opinions of DMs in SVTNNs): to aggregate the opinions of DMs, the TNWAA operator is used, as shown in equation (11).

Step 6 (neutrosophic synthetic values): the neutrosophic synthetic value of each element (S_i) is computed based on

$$S_i = \sum_{j=1}^{n} \eta_{ij} \times \left[\sum_{i=1}^{n}\sum_{j=1}^{n} \eta_{ij}\right]^{-1}, \quad i = 1, \ldots, n, \quad (37)$$

where n is the number of elements and η_{ij} is the $(i, j)^{\text{th}}$ element of the aggregated pairwise comparison matrix.

Step 7 (determining the final importance weights): this is calculated based on equation (38), and the final importance weights are shown by W_i which are in SVTNNs. In order to compare weights, equation (10) is used:

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i}, \quad i = 1, \ldots, n. \quad (38)$$

Table 2: RI values [87].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 3: The neutrosophic rating scale in the N-AHP [19].

Numerical scale	SVTNNs	Score function
1/9	$\langle(0.11, 0.11, 0.11, 0.11); 1, 0, 0\rangle$	0.11
1/8	$\langle(0.11, 0.11, 0.13, 0.14); 1, 0, 0\rangle$	0.12
1/7	$\langle(0.11, 0.13, 0.14, 0.17); 1, 0, 0\rangle$	0.14
1/6	$\langle(0.13, 0.14, 0.17, 0.2); 1, 0, 0\rangle$	0.16
1/5	$\langle(0.14, 0.17, 0.2, 0.25); 1, 0, 0\rangle$	0.19
1/4	$\langle(0.17, 0.20, 0.25, 0.33); 1, 0, 0\rangle$	0.24
1/3	$\langle(0.14, 0.17, 0.33, 0.50); 1, 0, 0\rangle$	0.29
1/2	$\langle(0.20, 0.25, 0.5, 1); 1, 0, 0\rangle$	0.49
1	$\langle(1, 1, 1, 1); 0.5, 0.5, 0.5\rangle$	0.5
2	$\langle(1, 2, 4, 5); 0.4, 0.65, 0.6\rangle$	1.15
3	$\langle(2, 3, 6, 7); 0.3, 0.75, 0.7\rangle$	1.28
4	$\langle(3, 4, 5, 6); 0.6, 0.35, 0.4\rangle$	2.78
5	$\langle(4, 5, 6, 7); 0.8, 0.15, 0.2\rangle$	4.49
6	$\langle(5, 6, 7, 8); 0.7, 0.25, 0.3\rangle$	4.66
7	$\langle(6, 7, 8, 9); 0.9, 0.1, 0.1\rangle$	6.75
8	$\langle(7, 8, 9, 9); 0.85, 0.1, 0.15\rangle$	7.15
9	$\langle(9, 9, 9, 9); 1, 0, 0\rangle$	9

5. The G-AHP Method

The proposed G-AHP is inspired by the fuzzy Delphi method in [84, 85]. The main characteristics of the proposed G-AHP method compared to other similar grey AHP methods in the literature are as follows: (1) no whitenisation function is used; all the calculations from the beginning to the end are in grey numbers, and in accordance with basic grey operations rules (Section 3.3). This preserves the grey characteristics of the values and judgements and helps reach a more valid outcome; (2) no consistency calculation is needed; the pairwise comparison matrices are constructed in a way that CR values of any pairwise comparison matrix are zero, and evaluations are fully consistent; (3) two judgement scales are introduced. Here, the 5-point judgement or importance scale (Table 4) is utilised by DMs to show the significance of each element individually. The 9-point relative importance scale (Table 5) is constructed for obtaining an importance comparison of each element compared to other elements in pairwise comparison matrices.

It is assumed that there are p DMs, and let $\rho = (\rho_1, \rho_2, \ldots, \rho_p)^T$ be the importance weight vector of the DMs where $\sum_{k=1}^{p} \rho_k = 1, \rho_k \geq 0, k = 1, \ldots, p$. It is also given that the decision-making model includes two finite sets of alternatives and criteria which are shown by $= \{x_1, x_2, \ldots, x_n\}$ and $C = \{c_1, c_2, \ldots, c_m\}$, respectively. The steps of the grey weights' calculation applied in the proposed G-AHP method are represented as follows:

(i) Step 1 (constructing the hierarchical structure): at this initial step, the hierarchical structure of the decision-making problem including goal, criteria, alternatives, or subalternatives will be constructed.

(ii) Step 2 (asking for experts' opinions): the DMs are asked to evaluate elements (criteria or alternatives) on the basis of their significance. The DMs determine the relative importance of each alternative x_i over x_j or each criterion c_i over c_j by using the importance scale (Table 4).

(iii) Step 3 (pairwise comparison matrices): according to each DM's opinion, the pairwise comparison matrices are constructed utilising the numerical

Table 4: The significance of elements.

Numerical scale	Linguistic term
2	Poor (P)
3	Fairly poor (FP)
4	Moderate (M)
5	Fairly good (FG)
6	Good (G)

Table 5: The relative importance scale.

Numerical value	Verbal term
0.33	Extremely less important
0.50	Very strongly less important
0.67	Strongly less important
0.83	Moderately less important
1.00	Equally important
1.20	Moderately more important
1.50	Strongly more important
2.00	Very strongly more important
3.00	Extremely more important

scale (Table 4). As shown in equation (39), in the case of comparing criteria, n should be replaced with m. The a_{ijk} represents the relative significance of element i over element j from the viewpoint of the k^{th} DM:

$$A_k = \left[a_{ijk}\right] = \begin{bmatrix} 1 & a_{12k} & \cdots & a_{1nk} \\ 1/a_{12k} & 1 & \cdots & a_{2nk} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1nk} & 1/a_{2nk} & \cdots & 1 \end{bmatrix}. \quad (39)$$

(iv) Step 4 (weighted pairwise comparison matrices): ρ_k is the importance weight of the k^{th} DM which belongs to the interval $[0, 1]$, and the greater the weight value, the more significant the DM's opinion is. According to each DM's importance weight ρ_k and elements of matrices of equation (39), the β_{ijk} values can be calculated based on

$$\beta_{ijk} = a_{ijk} \times \rho_k, \quad \forall\, k = 1, \ldots, p;\ \forall i, j = 1, \ldots, n \vee m, \quad (40)$$

$$\beta_k = \left[\beta_{ijk}\right] = \begin{bmatrix} \rho_k & \beta_{12k} & \cdots & \beta_{1nk} \\ 1/\beta_{12k} & \rho_k & \cdots & \beta_{2nk} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\beta_{1nk} & 1/\beta_{2nk} & \cdots & \rho_k \end{bmatrix}. \quad (41)$$

(v) In the case of equal importance weights of DMs, there is no need to calculate equations (40) and (41), and simply equation (39) can be used.

(vi) Step 5 (grey number calculation): in order to calculate grey numbers $\otimes a_{ij}$, all evaluations are taken into account, considering the importance weight of each DM as equations (42)–(44), where $\gamma_{ij} \geq \alpha_{ij}$:

$$\otimes a_{ij} = \left[\alpha_{ij}, \gamma_{ij}\right], \quad (42)$$

$$\alpha_{ij} = \min\left(\beta_{ijk}\right), \quad \forall k = 1, \ldots, p;\ \forall i, \; j = 1, \ldots, n \vee m, \quad (43)$$

$$\gamma_{ij} = \max\left(\beta_{ijk}\right), \quad \forall k = 1, \ldots, p; \forall\, i, \; j = 1, \ldots, n \vee m. \quad (44)$$

(vii) According to the aforementioned explanations, the weighted grey pairwise comparison matrix for alternatives is defined in equations (45) and (46). In the case of criteria, n should be replaced with m in equations (45) and (46), where $\mu = \min(\rho_k)$, $\forall k = 1, \ldots, p$, and $\pi = \max(\rho_k), \forall\, k = 1, \ldots, p$:

$$\otimes A = \left[\otimes a_{ij}\right]_{n \times n}, \forall i, j = 1, 2, \ldots, n, \quad (45)$$

$$\otimes A = \begin{bmatrix} [\mu, \pi] & \ldots & \left[\alpha_{1j}, \gamma_{1j}\right] & \ldots & \left[\alpha_{1n}, \gamma_{1n}\right] \\ \vdots & & \vdots & & \vdots \\ \left[\left(1/\gamma_{1j}\right), \left(1/\alpha_{1j}\right)\right] & \ldots & [\mu, \pi] & \ldots & \left[\alpha_{2n}, \gamma_{2n}\right] \\ \vdots & & \vdots & & \vdots \\ \left[\left(1/\gamma_{1n}\right), \left(1/\alpha_{1n}\right)\right] & \ldots & \left[\left(1/\gamma_{jn}\right), \left(1/\alpha_{jn}\right)\right] & \ldots & [\mu, \pi] \end{bmatrix}. \quad (46)$$

(vii) Step 6 (grey weight calculation): grey weight of each alternative (i.e., $\otimes W_i$) can be calculated using equations (47) and (48). For criteria, n should be replaced with m in the following equations:

$$\otimes Z_i = \frac{\sum_{j=1}^{n} \otimes a_{ij}}{n}, \quad \forall i = 1, 2, \ldots, n, \quad (47)$$

$$\otimes W_i = \frac{\otimes Z_i}{\left(\sum_{i=1}^{n} \otimes Z_i\right)}, \quad \forall i = 1, 2, \ldots, n. \quad (48)$$

6. The Case Application

The proposed NG-AHP method was applied to agility evaluations in the Iranian steel industry. Five agility evaluation criteria were observed as evaluation criteria and were applied to four steel companies [89]. The criteria were organisation management agility (C1), product design agility (C2), manufacturing process agility (C3), partnership formation capability (C4), and integration of information system (C5). Based on the data collected from the chosen experts, the aim was to identify the most relevant agility criteria. Subsequently, the steel enterprises were ranked according to the agility readiness criteria. Four steel manufacturing companies were investigated in the present research, and their names were anonymized as SC1, SC2, SC3, and SC4.

Here, the expert selection process and their importance weight assignment task were carried out based on the experts' knowledge and expertise in the related steel industry. Six DMs who were steel industry experts and were available to provide insights on agility readiness criteria evaluation, as well as being independent from the four steel companies, were selected. Brief profiles of the experts are represented in Table 6. The importance weight of each DM is provided as $\rho = (0.15,\ 0.30,\ 0.10,\ 0.25, 0.15, 0.05)^T$ regarding their knowledge and experience.

The experts were initially contacted to participate in the study by completing two types of questionnaires for N-AHP and G-AHP, based on the scales provided in Tables 3 and 4. The acquired data are presented in Tables 7 and 8. The hierarchical structure of this problem is depicted in Figure 3.

The proposed N-AHP was applied so as to obtain weights for five criteria. These weights were used later in the G-AHP method to acquire the final ranking of steel companies. In Table 7, the initial pairwise comparison matrices based on the opinions of six DMs using the NS rating scale (Table 3) are shown $(A_1, \ldots, A_6)$.

The calculated CRs for each pairwise comparison matrix were 2.23%, 7.66%, 2.36%, 3.99%, 6.56%, and 7.57%, respectively; they were all below 10% indicating cardinal output-based consistency. The aggregation neutrosophic matrix was calculated based on TNWAA operator, and then by applying equations (37) and (38), final weights were estimated (Table 9).

Through G-AHP, opinions of DMs were obtained for the evaluation of each steel company (SC1, SC2, SC3, and SC4) against criteria based on the scale provided in Table 4. The numerical values in Table 4 then were substituted for linguistic phrases (Table 8).

Here, only the weight computations of four steel companies based on C1 (organisation management agility) are presented to show how the G-AHP method works. The resulted weights then make up the first column of the final decision matrix as shown in Table 10. The pairwise comparison matrices of four steel companies based on C1 (organisation management agility) according to opinions of six DMs are denoted as A_1, A_2, A_3, A_4, A_5, and A_6 as presented in Table 11. All the CRs for comparative matrices will be equal to zero due to the applied method of acquiring opinions of DMs. The interpretation of the values in linguistic terms can be figured out based on the scale represented in Table 5. These values range from 0.33 with the corresponding verbal term *extremely less important* to 3 with the corresponding verbal term *extremely more important*.

In order to obtain weighted pairwise comparison matrices of four steel companies, equations (40) and (41) were utilised considering importance weights vector as$\rho = (0.15,\ 0.30,\ 0.10,\ 0.25, 0.15, 0.05)^T$, and β_1, β_2, β_3, β_4, β_5, and β_6 were obtained as shown in Table 12.

Table 6: The DMs' profile.

DMs	Expertise	Department	Importance weights
DM1	Industrial engineering (MSc)	Selling	0.15
DM2	Accounting (MA)	Finance	0.30
DM3	Industrial engineering (MSc)	Procurement	0.10
DM4	Metallurgy engineering (BSc)	Manufacturing	0.25
DM5	Scientific assistant (MBA)	R&D	0.15
DM6	Industrial engineering (BSc)	HR	0.05

Table 7: The initial pairwise comparison matrices of six DMs.

	C1	C2	C3	C4	C5
	1	2	0.50	4	3
	0.50	1	0.50	4	2
A_1	2	2	1	5	4
	0.25	0.25	0.20	1	0.50
	0.33	0.50	0.25	2	1
	1	3	2	3	2
	0.33	1	0.50	2	2
A_2	0.50	2	1	2	3
	0.33	0.50	0.50	1	0.33
	0.50	0.50	0.33	3	1
	1	2	4	8	5
	0.50	1	3	6	5
A_3	0 25	0.33	1	3	2
	0.13	0.17	0.33	1	0.50
	0.20	0.20	0.50	2	1
	1	5	2	8	4
	0.20	1	0.50	3	2
A_4	0.50	2	1	6	2
	0.13	0.33	0.17	1	0.25
	0.25	0.50	0.50	4	1
	1	0.17	0.25	3	0.50
	6	1	2	4	3
A_5	4	0.50	1	6	2
	0.33	0.25	0.17	1	0.50
	2	0.33	0.50	2	1
	1	6	2	2	3
	0.17	1	0.20	0.20	0.17
A_6	0.50	5	1	3	2
	0.50	5	0.33	1	2
	0.33	6	0.50	0.50	1

Table 8: Evaluation of SC1, SC2, SC3, and SC4 on criteria by DMs.

		DM1	DM2	DM3	DM4	DM5	DM6
C1		G (6)	G (6)	FP (3)	G (6)	G (6)	FG (5)
C2		M (4)	FP (3)	M (4)	M (4)	G (6)	FG (5)
C3	SC1	FG (5)	FP (3)	FG (5)	G (6)	G (6)	FG (5)
C4		M (4)	FG (5)	G (6)	FG (5)	FG (5)	G (6)
C5		G (6)	M (4)	FP (3)	G (6)	G (6)	G (6)
C1		M (4)	FG (5)	M (4)	FG (5)	G (6)	FP (3)
C2		FP (3)	M (4)	FP (3)	M (4)	M (4)	FP (3)
C3	SC2	FP (3)	FP (3)	M (4)	M (4)	M (4)	FP (3)
C4		FP (3)	M (4)	M (4)	FG (5)	M (4)	FG (5)
C5		M (4)	M (4)	M (4)	M (4)	M (4)	FP (3)
C1		FG (5)	G (6)	M (4)	FG (5)	FG (5)	FG (5)
C2		FG (5)	M (4)	FG (5)	M (4)	G (6)	FG (5)
C3	SC3	M (4)	M (4)	FG (5)	FG (5)	FG (5)	FG (5)
C4		M (4)	FG (5)	M (4)	FG (5)	M (4)	G (6)
C5		FG (5)	M (4)	FP (3)	M (4)	M (4)	G (6)
C1		FP (3)	FG (5)	M (4)	M (4)	M (4)	FG (5)
C2		P (2)	M (4)	M (4)	M (4)	FG (5)	FG (5)
C3	SC4	P (2)	M (4)	FP (3)	FG (5)	M (4)	FG (5)
C4		P (2)	FP (3)	M (4)	M (4)	FP (3)	G (6)
C5		FP (3)	M (4)	M (4)	FG (5)	M (4)	FG (5)

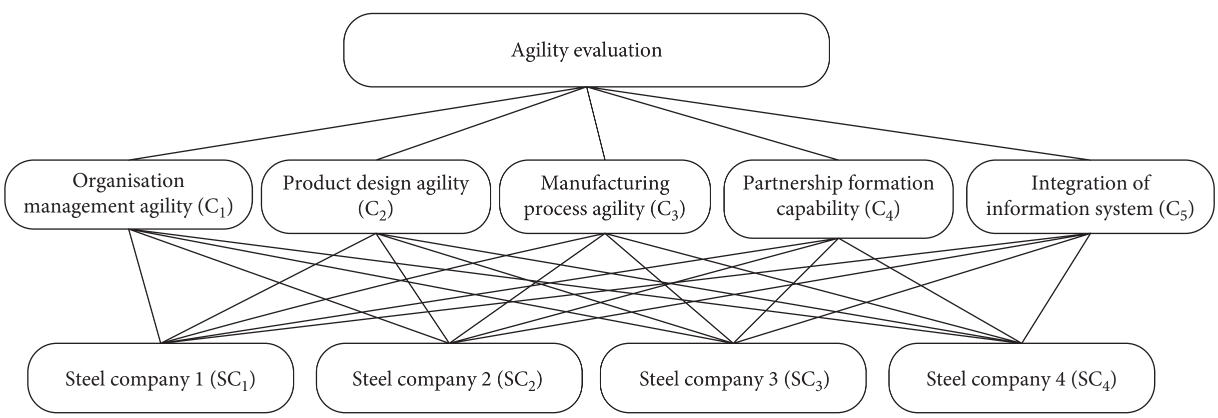

Figure 3: The hierarchical structure.

Table 9: Final weights of five evaluation criteria based on N-AHP.

Criteria	SVTNN weights	Crisp	Normalised	Rank
C1	$\langle(0.05, 0.14, 0.77, 2.01); 1, 0, 0\rangle$	0.7452	0.3227	1
C2	$\langle(0.03, 0.09, 0.51, 1.39); 1, 0, 0\rangle$	0.5071	0.2196	3
C3	$\langle(0.04, 0.12, 0.64, 1.73); 1, 0, 0\rangle$	0.6332	0.2742	2
C4	$\langle(0.01, 0.02, 0.11, 0.32); 1, 0, 0\rangle$	0.1145	0.0496	5
C5	$\langle(0.02, 0.05, 0.30, 0.86); 1, 0, 0\rangle$	0.3092	0.1339	4

Table 10: The final grey decision matrix.

	C1 **0.3227**	C2 **0.2196**	C3 **0.2742**	C4 **0.0496**	C5 **0.1339**
SC1	[0.0013, 0.0695]	[0.0013, 0.0521]	[0.0013, 0.0633]	[0.0013, 0.0870]	[0.0013, 0.0706]
SC2	[0.0202, 0.7395]	[0.0290, 0.6110]	[0.0196, 0.5976]	[0.0218, 1.0392]	[0.0194, 0.7444]
SC3	[0.0519, 2.8128]	[0.0525, 2.5580]	[0.0556, 2.5279]	[0.0580, 2.6429]	[0.0427, 3.1695]
SC4	[0.0607, 3.8360]	[0.0662, 3.4875]	[0.0741, 3.4512]	[0.0511, 3.7932]	[0.0702, 3.5025]

Table 11: The pairwise comparison matrices of SCs based on C1.

		SC1	SC2	SC3	SC4
A_1	SC1	1.00	1.50	1.20	2.00
	SC2	0.67	1.00	0.80	1.33
	SC3	0.83	1.25	1.00	1.67
	SC4	0.50	0.75	0.60	1.00
A_2	SC1	1.00	1.20	1.00	1.20
	SC2	0.83	1.00	0.83	1.00
	SC3	1.00	1.20	1.00	1.20
	SC4	0.83	1.00	0.83	1.00
A_3	SC1	1.00	0.75	0.75	0.75
	SC2	1.33	1.00	1.00	1.00
	SC3	1.33	1.00	1.00	1.00
	SC4	1.33	1.00	1.00	1.00
A_4	SC1	1.00	1.20	1.20	1.50
	SC2	0.83	1.00	1.00	1.25
	SC3	0.83	1.00	1.00	1.25
	SC4	0.67	0.80	0.80	1.00
A_5	SC1	1.00	1.00	1.20	1.50
	SC2	1.00	1.00	1.20	1.50
	SC3	0.83	0.83	1.00	1.25
	SC4	0.67	0.67	0.80	1.00
A_6	SC1	1.67	1.00	1.00	1.00
	SC2	0.60	1.00	0.60	0,60
	SC3	1.67	1.00	1.00	1.00
	SC4	1.67	1.00	1.00	1.00

Table 12: Weighted pairwise comparison matrices.

		SC1	SC2	SC3	SC4
β_1	SC1	0.150	0.225	0.180	0.300
	SC2	4.444	0.150	0.120	0.200
	SC3	5.556	8.333	0.150	0.250
	SC4	3.333	5.000	4.000	0.150
β_2	SC1	0.300	0.360	0.300	0.360
	SC2	2.778	0.300	0.250	0.300
	SC3	3.333	4.000	0.300	0.360
	SC4	2.778	3.333	2.778	0.300
β_3	SC1	0.100	0.075	0.075	0.075
	SC2	13.333	0.100	0.100	0.100
	SC3	13.333	10.000	0.100	0.100
	SC4	13.333	10.000	10.000	0.100
β_4	SC1	0.250	0300	0.300	0.375
	SC2	3.333	0.250	0.250	0.313
	SC3	3.333	4.000	0.250	0.313
	SC4	2.667	3.200	3.200	0.250
β_5	SC1	0.150	0.150	0.180	0.225
	SC2	6.667	0.150	0.180	0.225
	SC3	5.556	5.556	0.150	0.188
	SC4	4.444	4.444	5.33	0.150
β_6	SC1	0.050	0.083	0.050	0.050
	SC2	12.000	0.050	0.030	0.030
	SC3	20.000	33.333	0.050	0.050
	SC4	20.000	33.333	20.000	0.050

The weighted grey pairwise comparison matrix for steel companies was defined according to equations (45) and (46) as follows:

$$A = \begin{bmatrix} [0.0500,\ 0.3000] & [0.0750,\ 0.3600] & [0.0500,\ 0.3000] & [0.0500,\ 0.3750] \\ [2.7778,\ 13.3333] & [0.0500,\ 0.3000] & [0.0300,\ 0.2500] & [0.0300,\ 0.3125] \\ [3.3333,\ 20.0000] & [4.0000,\ 33.3333] & [0.0500,\ 0.3000] & [0.0500,\ 0.3600] \\ [2.6667,\ 20.0000] & [3.2000,\ 33.3333] & [2.7778,\ 20.0000] & [0.0500,\ 0.3000] \end{bmatrix}. \quad (49)$$

The $\otimes Z_i$ values were calculated according to equation (47) and grey weights of each steel company (i.e., $\otimes W_i$) were calculated using equation (48) as shown in Table 13.

The same steps as C1 for the other four criteria (C2, C3, C4, and C5) were carried out to obtain weights of the four alternatives, i.e., steel companies (SC1, SC2, SC3, and SC4).

7. Results and Discussion

The final grey decision matrix is shown in Table 10. Taking into account weights of each criterion obtained from N-AHP (Table 9) as shown in bold in Table 10, the final grey importance weights of each steel company can be calculated.

The final grey importance weights of each steel company can be achieved by multiplying the weights and adding them up (Table 14).

The four steel companies were ranked based on the obtained importance weights which are shown in Table 14. Comparisons were carried out with reference to Definition 11. The final ranking of steel companies is obtained as $\otimes W_4 > \otimes W_3 > \otimes W_2 > \otimes W_1$.

In respect of the crisp weights obtained from N-AHP (Table 9), it was revealed that $C1$ (organisation management agility) with the weight of 0.3262 is the most significant criterion in the assessment followed by $C3$ (manufacturing process agility), $C2$ (product design agility), $C5$ (integration of information system), and $C4$ (partnership formation capability) with weights of 0.2643, 0.2123, 0.1337, and 0.0635, respectively. The obtained weights of five criteria were utilised in the G-AHP method to reach the final ranking of steel companies. After applying G-AHP, regarding the final obtained weights in grey numbers (Table 14), it was concluded that steel company four (SC4) has the highest competence for agile strategies based on the five evaluation criteria. The SC3, SC2, and SC1 lay second, third, and fourth in the final prioritisation order, respectively.

It should be noted that either G-AHP or N-AHP has the capability to be used for the calculation of all the AHP steps in any similar decision-making problem separately. Noticing the difference that the final weights in the N-AHP will be in crisp values, the G-AHP will obtain grey values of weights. It has been demonstrated that G-AHP and N-AHP can operate together in one decision-making framework, namely, NG-AHP. Apart from separate merits of each of the two methods, this integration can provide a synergic effect and can be more beneficial by incorporating advantages of the NS and grey systems theories, simultaneously.

Organisation management agility (C1) is recognised as the most significant criterion leading a manufacturing firm towards agility and subsequent potential sustainability. Sharifi and Zhang [90] indicated that uncertainty in the business environment has been considered as the root of most failures in manufacturing industry and agility has two main factors for coping with unexpected, uncertain changes: (1) responding to change (anticipated or unexpected) in suitable ways and in due time and (2) taking advantage of changes as opportunities. Organisation management agility refers to the capability that enables a company to rapidly adapt in response to market changes by improving the organisational management procedures. Lozano et al. [91] mentioned that corporate sustainability (CS) has been recognised as one way of incorporating a sustainability agenda in the activities of an organisation in order to address the negative impacts of its operations on the environment and society. It is indicated that CS changes need to be integrated in soft organisational issues including values, visions, policies, and change management practices which are related to organisational systems of a company [91].

Manufacturing process agility (C3) is the second highly important factor. In prior research, some scholars suggested that internal business processes could be significant factors linking information technology (IT) capability and organisational performance [92], and a notable aspect of internal business processes is business process agility [93, 94]. Jayal et al. [95] indicated that achieving sustainability in manufacturing needs a holistic perspective spreading over both internal and external parts of an organisation. Thus, manufacturing process agility as an internal part can play a central role in attaining sustainability particularly in economic and environmental dimensions [96].

Findings revealed that product design agility (C2) is the third element that should be taken into consideration by practitioners to develop sustainable operations. It is in close connection with information systems (ISs) and computer technologies as they can play a considerable role in facilitating time reduction in product design and development [94, 97]. Vinodh [67] indicated that integration of agility and sustainability results in various advantages and that one of these is product design and development. Economic and environmental sustainability are significantly influenced by product design. Concentrating simultaneously on the green design of

Table 13: Grey weights of SCs based on C1.

$\otimes\mathbf{Z_i}$	$\otimes\mathbf{W_i}$
$\otimes\mathbf{Z}_1 = [0.0450, 0.3338]$	$\otimes\mathbf{W}_1 = [0.0013, 0.0695]$
$\otimes\mathbf{Z}_2 = [0.7219, 3.5490]$	$\otimes\mathbf{W}_2 = [0.0202, 0.7395]$
$\otimes\mathbf{Z}_3 = [1.8583, 13.4983]$	$\otimes\mathbf{W}_3 = [0.0519, 2.8128]$
$\otimes\mathbf{Z}_4 = [2.1736, 18.4083]$	$\otimes\mathbf{W}_4 = [0.0607, 3.8360]$

Table 14: Final grey importance weights.

Steel companies	$\otimes\mathbf{W_i}$
SC1	$\otimes W_1 = [0.0013, 0.0650]$
SC2	$\otimes W_2 = [0.0219, 0.6879]$
SC3	$\otimes W_3 = [0.0521, 2.7181]$
SC4	$\otimes W_4 = [0.0664, 3.6072]$

products during the premanufacturing stage and also on design agility in order to respond to customer needs can have positive impacts on environmental sustainability [98].

Integration of the information system (C5) which is connected to IT is regarded as the fourth agility criterion leading to sustainability. IT has been widely recognised as being a crucial factor for the survival and growth of an organisation [93, 99]. Aggoune et al. [100] in the evaluation of the relationship between the agility and sustainability of the information system indicated that there is no sustainability without agility. Frayret et al. [97] highlighted the significance of speed factor in agile manufacturing and declared that computer technologies are platforms for agility [101]. Information disclosure as one of the social sustainability indicators [52, 102] can be more applicable through integrated information systems. The reason is that more related information regarding materials being used during the production process and information about carbon emissions would become available. Additionally, application of blockchain technology by providing decentralised and immutable storage of verified transaction data can be significant in this matter [19].

Finally, partnership formation capability (C4) is another component building sustainable processes with notable importance in agile manufacturing. Yusuf et al. [103] named partnerships as one of the attributes agile organisations have, including trust-based relationship with customers/suppliers, close relation with suppliers, strategic link with customers, and rapid partnership formation. This criterion can relate to social sustainability for instance, by extending partnership with external stakeholders through green outsourcing which would lead to higher satisfaction of the community that has an interest in the outcomes from the actions of an organisation [52]. It can also result in economic sustainability as an outcome of joint ventures or green procurement contracts [104, 105].

8. Conclusions

In this article, we assess agility in the steel manufacturing industry with criteria which can help develop sustainable engineering operations in organisations. The trade-offs between lean, agile, resilient, and green (LARG) management systems as a probable pathway towards a more sustainable system is studied in the literature. It is also indicated that agility and sustainability are regarded as performance measures for contemporary enterprises. In this context, agility and sustainability are considered to be interconnected even though their link has not been adequately researched. In this study, a decision-modelling approach was introduced to show the application of the proposed hybrid method (i.e., NG-AHP) in an agility evaluation case in the Iranian steel industry. In the MADM field, a variety of uncertainty theories such as FS, IFS, PFS, and grey systems theories are applied to deal with the unsuitability of crisp values for the efficient modelling of real-life problems. Achieving sustainable operations via agile manufacturing is regarded as a vital management paradigm for making the production system more efficient and streamlined. Our proposed method is comprised of two MADM methods, namely, N-AHP and the G-AHP under uncertain decision environments. The importance weights of agility evaluation criteria in the Iranian steel industry were determined by applying the N-AHP, and then, the G-AHP was utilised to rank steel companies.

This study contributes to the literature in three main ways to answer the research question of how the agility readiness impacts sustainable engineering decisions under uncertain decision-making environment in steel manufacturing. First, it explored sustainable engineering by agility readiness evaluation in an Iranian steel manufacturing setting. Second, a new grey-based AHP method, namely, G-AHP, inspired by the fuzzy Delphi method was proposed. This provided a distinctive approach for the method compared to similar grey AHP methods in the literature in two main ways by introducing two judgement scales (Tables 4 and 5). The proposed G-AHP preserves the grey characteristics of the judgements in the AHP computing steps while preserving fully consistent evaluations in the pairwise comparison matrices. Third, a real-case example of agility evaluation in the steel industry was provided to demonstrate the joint applicability of the two methods as one decision-making methodology, namely, NG-AHP. Findings from the application revealed that in long-term strategy planning, steel manufacturing managers who are interested in agility, in the context of our study, should first deal with organisation management agility (C1) as the most significant criterion in the assessment followed by manufacturing process agility (C3), product design agility (C2), integration of information systems (C5), and partnership formation capability (C4), respectively. It was also concluded that steel company four (SC4) has the highest competence for agile strategies based on the five evaluation criteria followed by steel companies three (SC3), two (SC2), and one (SC1), respectively.

While this article offers contributions to the literature, it also has limitations which call for future research initiatives. Aspects of sustainability (i.e., economic, social, and environmental) to which our analysed criteria might have been more closely linked can be regarded as an interesting future research topic. In this study, however, we have considered the general definition of sustainability covering all three pillars and discussed more closely connected sustainability dimensions based on the literature. The relation between lean manufacturing, agile manufacturing, and sustainability can be further explored in other manufacturing contexts to provide more insights on their relationships. In addition, recent mathematical developments in the realm of the NS theory can be applied in the MADM field to effectively capture uncertainty in future research such as α-discounting method for multicriteria decision-making [106]. For instance, comparing SVTNNs in the final weights of the N-AHP with no need to get the crisp values to make comparisons can help reduce information loss and reach a better evaluation. It would also be interesting to compare Pythagorean fuzzy AHP with the NG-AHP in numerical examples via simulation. As another future research direction, triangulation can be utilised by applying methods such as BWM, LBWA, or FUCOM to increase the validity of the proposed method.

Data Availability

The data used to support the findings of the study are made available by Amin Vafadarnikjoo on Mendeley Data under the licence CC BY 4.0 (https://doi.org/10.17632/8d6s67bgcw.1).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

A Novel Multiphase Model for Traffic Safety Evaluation: A Case Study of South Africa

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Identification of key indicators that cause safety challenges and vulnerable roads is crucial for improving traffic safety. This paper, therefore, entails to the development of a novel multiphase multicriteria decision-making (MCDM) model to evaluate the vulnerability of urban roads for traffic safety. This was conducted by using data from 17 important roads of a South African city and combining several methods such as CRiteria Importance through Intercriteria Correlation (CRITIC), data envelopment analysis (DEA), and measurement of alternatives and ranking according to compromise solution (MARCOS). Taking the elements of the DEA method, two new approaches for calculating the weights of criteria, the DEA-1 and DEA-2 models, were formed and integrated with the CRITIC method to obtain the final values of criteria weights. The MARCOS method was applied to evaluate 17 alternatives, for each direction separately. The aim of developing such a model is to use the advantages of obtaining objectivity of criteria weights through linear programming and correlation of values of the collected data. Also, the MARCOS method, as one of the newer and applicable methods, provides additional significance. Extensive sensitivity analyses were conducted to validate the model. The findings suggest that there are a certain number of roads that have a high level of safety for both directions, as well as a group of risky roads, which need traffic improvement measures. Thus, the results indicate that the model is sensitive to various approaches and can prioritize vulnerable roads comprehensively based on which safety measures can be taken.

1. Introduction

The occurrence of road accidents is a recurring challenge across the world. The problem is more pervasive in the cities of developing countries such as South Africa. The majority of the people in the South African cities live in the sprawling suburbs and usually travel daily to various parts of the cities and towards the city centres to work and for other civic activities. The cities are characterized by the location of important public and commercial activities on the roadsides or close to road intersections and squares and having predominantly mixed land-use systems in and around the central areas. Due to the lack of a significant and efficient public transportation system, the majority of people travel by their individual cars or shared public taxis. Moreover, access roads linking suburban residential areas and arterial roads to provide higher accessibility also create more conflict points on these roads. The combined effect of various land-use, activity, road, and traffic-related challenges makes the urban roads susceptible to the incidence of traffic accidents. The occurrence of higher vehicular traffic accidents has been experienced not only on the principal thoroughfares of the cities but also on the arterial roads and intersections located in the suburban areas. For instance, according to the reports from the police stations of a city, more than 45% of the accidents that happen in the city are observed on the urban arterial roads that connect different suburbs of the city. However, it is also observed that some of the roads are more prone to accidents than others and need adequate interventions.

Improvement of road safety and the reduction of vehicular accidents have been considered as a prime focus in the cities. The road and traffic departments and municipalities are undertaking remedial measures such as improving road conditions, providing road pavement marking and signage, improving road traffic management systems such as signals, implementing traffic regulations, creating traffic safety awareness programs, and traffic safety audits. However, with limited resources, it becomes difficult to take up remedial measures on each road across the city, and therefore, prioritization of vulnerable roads and areas of accidents is necessary.

In the context of South African cities, most of the studies are aimed at either establishing the linkage between different road, traffic, environmental or human factors with the occurrence of the accidents on the roads or developing remedial measures to improve road safety. However, identification of vulnerable roads and prioritization of these roads based on road geometry, traffic-related parameters, and their linkage with the occurrence of accidents have been undermined. Moreover, most of the studies that have been conducted were based on the use of conventional statistical methods, and studies by using advanced methods are scarce. Since remedial measures to improve road safety demand prioritization or ranking of vulnerable roads in addition to exploring the causes of the occurrence of accidents, there is a need for robust, advanced, and flexible methods that could accommodate various parameters effectively and offer reliable predictions.

Therefore, the objective of the study is to develop an appropriate and robust method that can evaluate and rank vulnerable roads for the occurrence of vehicular traffic accidents effectively. For this purpose, a novel multiphase model consisting of several methods, CRiteria Importance through Intercriteria Correlation (CRITIC), data envelopment analysis (DEA), and measurement of alternatives and ranking according to compromise solution (MARCOS), was developed by using the data from 17 important arterial roads (U3-minor arterial roads) (COTO, TRH26, 2012) of Bloemfontein city in South Africa. The paper presents a study in the city of Bloemfontein related to traffic safety in 17 different streets. Data for both directions of movement (N and S) were collected, and a new integrated multiphase model was developed in order to obtain the most relevant indicators of traffic safety in the city. Six criteria were defined. Five of them represented input parameters in the DEA model, while the sixth criterion represented an output parameter, and the values of criteria weights were determined by developing two new approaches DEA-1 and DEA-2. After that, the values obtained with the CRITIC method were integrated, and the final values of criteria weights were calculated. They show that the number of traffic accidents per km is the most important factor, which is understandable. After that, implementation of the stated weights of criteria in the MARCOS method for ranking streets has been performed. Fulfilling the seated objective and the creation of an integrated model where the DEA method was used in one innovative way can be manifested as the main contribution of the study.

The rest of the paper is structured in the following manner. A succinct account of the literature concerning the traffic crash prediction models (CPMs), specifically the use of CRITIC, DEA, and MARCOS, and demands for hybrid models are given in the next section. This is followed by the methodology, which offers an account of the research flow for the development of the model and description of the CRITIC, DEA, and MARCOS methods. Case study, data collection, and determination of weights by using CRITIC, DEA-1, and DEA-2 models and final weights by the combination of these models as well as evaluation of alternatives by the use of the MARCOS model are presented in the following section. The next section includes the multiphase sensitivity analysis which was conducted by using a reverse rank matrix, changing criteria weights, and comparing with other MCDM models to validate the developed hybrid model. Finally, the implication of the model in terms of ranking of the streets concerning traffic safety is presented in the conclusion section.

2. Literature Review

Many traffic accident prediction models are available and used to estimate the occurrence of the accidents on a road section because of road and traffic-related parameters. These models enable establishing quantitative relations between road and traffic characteristics and traffic accidents, as well as the influence of the application of safety interventions on a road section [1]. These models include both traditional statistical or mathematical methods and advanced models based on artificial intelligence models such as multicriteria decision-making models. The conventional assessment methods include relative accident rate analysis, time series analysis, and regression analysis [2, 3]. These methods face a common challenge—the assessment results disagree due to the often different parameter choice [4]. Similarly, weight evaluation methods such as the analytic hierarchy process (AHP), expert scoring method (Delphi), principal component analysis method, eigenvalue method, and gray correlation method are used. The general problem of these methods is that they do not consider the internal correlation and inconsistency of indicators, and the outcomes obtained are often fairly different from the real ones [5]. Consequently, advanced MCDM models such as DEA, MARCOS, TOPSIS, and CRITIC methods that consider the uncertainties and relationship between qualitative concepts and quantitative concepts, which could assist in justifiable, explainable, and transparent decision-making, are increasingly used [3].

Furthermore, integrated model based on the q-ROULSs and EDAS method [6] and OHS risk assessment model by integrating picture fuzzy sets (PFSs) and alternative queuing method (AQM) [7] were used to evaluate and rank the risk of occupational hazards. In another recent study, association rule mining technique, as well as correlating various attributes to the severity of the accident, has been used to identify accident spots [8]. Apart from these models, although not directly linked to traffic safety or OHS, a new method based on double hierarchy hesitant linguistic term sets (DHHLTSs) and alternative queuing method (AQM) to evaluate the satisfaction of the rail transit network under a large group environment was developed recently [9].

Data envelopment analysis (DEA) was used by various scholars for analyzing traffic safety aspects. It has been used to prioritize traffic crash sites [10], examine operational efficiency related to the traffic safety [11], assess the urban safety on urban roads, Runde et al., prioritize road safety needs [12], develop road safety policies, and so on. DEA is able to consider multiple inputs and outputs and does not require a functional form, which relates to inputs and outputs. It can optimize each observation and can compare it against best practice observations. This method is also different from other ranking methods as it can add standard errors of crash modification factor and crash costs in the selecting process, as well as the average values (Sadeghi & Moghaddam, 2016). However, DEA has certain limitations that include the following: it can only calculate relative efficiency measures; and since it is a nonparametric technique, statistical hypothesis tests are difficult [13]. Also, when the number of inputs and outputs is more than the number of decision-making units, DEA models will not be able to separate DMUs [14]. Consequently, DEA, in recent years, is integrated with other methods such as artificial neural networks [15], analytical hierarchy process [16], analytic network process [17], TOPSIS [13, 18], and fuzzy logic [15, 16] to convert the qualitative variables into quantitative equivalences.

The MARCOS method has also been used to evaluate the road infrastructure on a road section to rank the accident risk on road sections. The ability to consider fuzzy reference points through the fuzzy ideal and fuzzy anti-ideal solution at the very beginning of model formation is a major advantage of this method. Also, the ability to determine the degree of utility concerning both set solutions more precisely, proposing new ways to determine utility functions and their aggregation, and the possibility to handle a large set of criteria and alternatives are the other advantages [19].

The CRITIC model determines the objective weights that are premised on the quantification of two fundamental notions of multicriteria decision-making (MCDM) such as the contrast intensity and the conflicting character of the evaluation criteria [20]. The extraction and exploitation of these two fundamental features which are stored as intrinsic information in the data defining the multicriteria problem benefit the decision-making process. In this method, the objective weights derived incorporate both the contrast intensity of each criterion and the conflict between the criteria. Also, the contrast intensity of the criteria is considered by the standard deviation. The conflict between them is assessed by the correlation coefficient [21]. This method comprehensively measures the objective weight by the contrast intensity and conflict between different indexes, which is argued to be more scientific and reasonable. However, studies on the application of the CRITIC method in traffic safety are scarce.

Each of the models discussed has limitations and advantages, and the performance of each model depends on the information available and parameter selection [3, 4]. As a result, often, the models are used in combination with other relevant models, or in other words, hybrid models are popular. Therefore, in this study, the integration of DEA, MARCOS, and CRITIC models has been made, which is a major contribution to the body of the knowledge in the analysis of road traffic safety.

3. Methodology

3.1. A Developed Model for Traffic Safety Evaluation. Figure 1 presents a whole diagram of the research flow which is divided into four main phases that are interdependent. The first and second phase have four steps each. The third phase has seven activities, while the last, fourth phase includes a sensitivity analysis that needs to be performed through seven steps, too.

The model presented in Figure 1 encompasses a complete research flow consisting of a total of 22 activities that are causally related. The first phase is the recognition of the need for research, and the area of traffic safety is always present and important for the study of key indicators that affect output parameters, which relate to the number of traffic accidents. After the need for research in the city of Bloemfontein has been determined, the next step is field exploration and then the formation of a database, sorting the data according to the needs of research. The second phase involves determining adequate criteria based on which the evaluation of alternatives will be performed. Six criteria are defined. Five of them refer to input parameters, and the sixth is the output parameter in DEA. After that, data are sorted for each of 17 streets in which the research was conducted. It is important to note that a double MCDM model has been formed, which includes separate data collection and evaluation of streets for both directions (north and south). The third phase is the creation of a new integrated multicriteria model consisting of several steps. CRITIC [22, 23] and DEA methods were used to determine the weight values of criteria. The DEA model was used to determine the values of the criteria in two ways, which is presented in more detail below. Based on their individual values, averaging was performed, the final values were obtained, and they were included in the MARCOS method [24–26] when evaluating alternatives. The last, fourth phase is the verification of previously obtained results through a multiphase sensitivity analysis. Validity tests refer to the (a) formation of reverse rank matrices in which the worst alternative is eliminated from further calculation, (b) change of criterion weight in a dynamic environment, (c) evaluation of alternatives based on individually obtained values of criteria weights using CRITIC, DEA-1, and DEA- 2 methods; in addition, a scenario in which all criteria have equal significance was created, (d) comparative analysis of the obtained results with five other MCDM methods, (e) calculation of SCC for all ranks obtained by applying different approaches, and (f) calculation of the standard deviation of ranks obtained by applying different approaches.

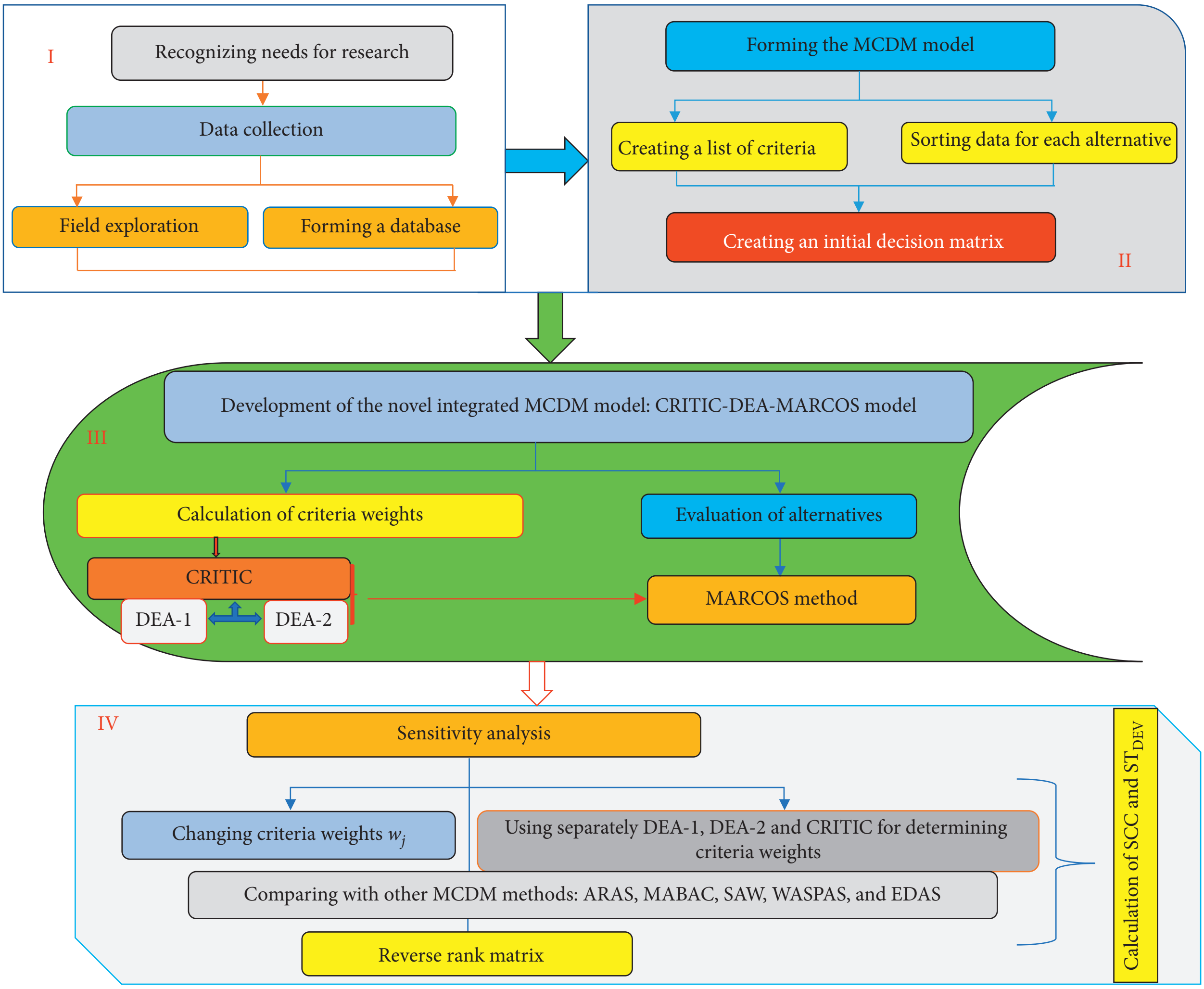


Figure 1: Research flow with a developed model for traffic safety evaluation.

3.2. CRITIC Method. Diakoulaki et al. [20] introduced the CRITIC method as a tool for determining the objective weights of criteria in MCDM problems. Steps of this method are presented as follows:

Step 1: formation of the decision matrix (X):

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}, \quad i = 1, 2, \dots, m; \; j = 1, 2, \dots, n. \tag{1}$$

Step 2: normalization of the initial decision matrix depending on the criterion type:

$$r_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad \text{if } j \in B \longrightarrow \max, \tag{2}$$

$$r_{ij} = \frac{x_{ij} - \max_i x_{ij}}{\min_i x_{ij} - \max_i x_{ij}} \quad \text{if } j \in C \longrightarrow \min. \tag{3}$$

Step 3: calculation of symmetric linear correlation matrix r_{ij}:

$$r_{ij} = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n \sum x_i^2 - \left(\sum x_i\right)^2} \cdot \sqrt{n \sum y_i^2 - \left(\sum y_i\right)^2}}. \tag{4}$$

Step 4: determination of objective weights:

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j}, C_j = \sigma \sum_{j'=1}^{n} 1 - r_{ij}, \sum_{j=1}^{n} \left(1 - r_{ij}\right), \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(x_i - \overline{x}\right)^2}. \tag{5}$$

3.3. DEA Method. The DEA-based road safety (DEARS) model proposed by Shen et al. [27] is as follows:

$$\begin{aligned} \theta_o^{\text{DEA-RS}} &= \max \sum_{i=1}^{m} w_i x_{io}, \\ \text{st}: &\sum_{i=1}^{m} w_i x_{ij} - \sum_{i=m+1}^{m+s} w_i y_{ij} \leq 0, \quad j = 1, \ldots, n, \\ &\sum_{i=m+1}^{m+s} w_i y_{io} = 1, \\ &w_i \geq 0, \quad i = 1, \ldots, m+s. \end{aligned} \tag{6}$$

The decision-making unit (DMU) consists of m input parameters, while s represents output parameters taking into account the weights of the parameters denoted by w_i.

In this paper, the DEA method is applied to calculate the weights of the criteria in one part of the model. In order to be able to accurately determine the weights after obtaining them by applying equation (6), the following two equations (7) and (8) are formed for the DEA-1 model and (9) and (10) for the DEA-2 model:

$$V_{j\text{DEA}-1} = \frac{\sum_{i=1}^{n} w_{ij}}{n}, \quad j = 1, \ldots, m+s, \tag{7}$$

where n represents the total number of DMUs. In essence, in this equation, all the weights of the criteria are averaged using the arithmetic mean.

After that, the final values according to the DEA-1 model are obtained as follows:

$$w_{j\text{DEA}-1} = \frac{V_j}{\sum_{j=1}^{m+s} v_j}, \tag{8}$$

where V_j represents the mean values of weights from the previous equation.

$$V_{i\text{DEA}-2} = \frac{w_j}{\sum_{j=1}^{m+s} w_j}, \tag{9}$$

where all individual weights are divided by their sum.

$$w_{j\text{DEA}-2} = \frac{\sum_{i=1}^{n} V_{ij}}{n}, \quad j = 1, \ldots, m+s. \tag{10}$$

Final values according to the DEA-2 model are obtained by applying equation (10). In essence, in this equation, all the weights of the criteria are averaged using the arithmetic mean. Also, n represents the total number of DMUs.

3.4. MARCOS Method. The MARCOS method developed by Stević et al. [24] consists of the following steps [28]:

Step 1: formation of an initial decision-making matrix.

Step 2: formation of an extended initial matrix. In this step, the extension of the initial matrix is performed by defining the ideal (AI) and anti-ideal (AAI) solution.

$$X = \begin{array}{c} \\ AAI \\ A_1 \\ A_2 \\ \cdots \\ A_m \\ AI \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{aa1} & x_{aa2} & \cdots & x_{aan} \\ x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{22} & \cdots & x_{mn} \\ x_{ai1} & x_{ai2} & \cdots & x_{ain} \end{bmatrix} \end{array}. \tag{11}$$

The anti-ideal solution (AAI) is the worst alternative, while the ideal solution (AI) is an alternative with the best characteristic defined by applying equations (12) and (13):

$$\text{AAI} = \min_i x_{ij} \quad \text{if } j \in B \text{ and } \max_i x_{ij} \text{ if } j \in C, \tag{12}$$

$$\text{AI} = \max_i x_{ij} \quad \text{if } j \in B \text{ and } \min_i x_{ij} \text{ if } j \in C, \tag{13}$$

where B represents a benefit group of criteria, while C represents a group of cost criteria.

Step 3: normalization of the extended initial matrix (X). The elements of the normalized matrix $N = [n_{ij}]_{m\times n}$ are obtained by applying equations (14) and (15):

$$n_{ij} = \frac{x_{ai}}{x_{ij}} \quad \text{if } j \in C, \tag{14}$$

$$n_{ij} = \frac{x_{ij}}{x_{ai}} \quad \text{if } j \in B, \tag{15}$$

where elements x_{ij} and x_{ai} represent the elements of matrix X.

Step 4: determination of the weighted matrix $V = [v_{ij}]_{m\times n}$:

$$v_{ij} = n_{ij} \times w_j. \tag{16}$$

Step 5: calculation of the utility degree of alternatives K_i by applying equations (17) and (18):

$$K_i^- = \frac{S_i}{S_{aai}}, \tag{17}$$

$$K_i^+ = \frac{S_i}{S_{ai}}, \tag{18}$$

where S_i $(i = 1, 2, \ldots, m)$ represents the sum of the elements of weighted matrix V:

$$S_i = \sum_{i=1}^{n} v_{ij}. \tag{19}$$

Step 6: determination of the utility function of alternatives $f(K_i)$ defined by the following equation:

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + 1 - f(K_i^+)/f(K_i^+) + 1 - f(K_i^-)/f(K_i^-)}, \tag{20}$$

where $f(K_i^-)$ represents the utility function in relation to the anti-ideal solution, while $f(K_i^+)$ represents the utility function in relation to the ideal solution.

Utility functions in relation to the ideal and anti-ideal solution are determined by applying equations (21) and (22):

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-}, \tag{21}$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-}. \tag{22}$$

Step 7: ranking the alternatives. Ranking of the alternatives is premised on the final values of utility functions. It is desirable that an alternative has the highest possible value of the utility function.

4. Case Study

The arterial roads of Bloemfontein city in South Africa (Figure 2) were chosen for collecting data for this research. Bloemfontein is a typical middle-sized sprawling city with a population of more than 500,000 and functions as the capital of the Free State province. The majority of the people live in suburban areas, thereby necessitating large-scale intracity vehicular travel.

The city has a hierarchical road system with principal arterials (U1 and U2), minor arterial (U3), collector roads (U4), local streets (U5), and cul-de-sacs (COTO, TRH26, 2012). The road network constitutes a general gridiron and loop pattern and the integration of the two. The U3 roads, which pass through the suburban areas, connect to the U1 and U2 roads of the city. Also, these U3 roads act as the major thoroughfares in the suburban areas offering linkage to the collector roads and the local streets to offer access to the people.

The road surfaces of most of the roads are paved and well maintained. The principal mode of travel in the city is personal/individual-driven motor cars. About 60% of people travel by their private vehicles for daily commute. However, according to police reports, a significant share (about 45%) of the total accidents, which occur in and around the city, is observed on these U3 arterial roads. Thus, the importance of the arterial roads (U3) and the high incidence of traffic accidents on these roads of the city warranted this investigation.

4.1. Survey and Data Collection.

4.1. Survey and Data Collection. A survey research method was used to collect data. Data were collected from both primary and secondary sources. Three different types of survey, household surveys, traffic surveys, and road geometrical parameter survey, were made. The household sample survey was conducted among 410 road users (from households located in six important suburbs of the city. The suburbs include Fichardt Park, Pellissier, Universitas, Gradenia Park, Wilgehof, and Langenhoven Park. The suburbs were chosen based on their functional importance, population, vehicle ownership, accessibility, the complexity of the road network, the location of arterial thoroughfares inside the residential area, and the occurrence of the number of accidents. The sample size is adequate (≥384) for a population 500,000 at a 95% confidence level and worst-case percentage of 50%). This household survey was conducted to understand the perceptions of road users on the factors that cause accidents on urban roads. A systematic stratified random sampling process was used to conduct the survey. Traffic and road surveys were conducted on important road sections. A traffic survey was conducted at important road sections of the selected 17 U3 roads passing through the selected suburban areas to observe the volume (ADT), speed, and traffic control and management scenarios. The roads selected for this investigation include Jan Spies Street, Totius Street, Wynand Mouton Drive, De Bruyn Street, Paul Kruger Drive North, Paul Kruger Drive South, Volkspele Drive, Pellissier Drive, Paul Kruger Drive (E), Gardenia Avenue, Van Schalkwyk Street, Haldon Drive, Edeling Street, Stals Road, Benade Drive (N), Benade Drive (S), and Eric Rosendorf Street. These U3 roads connect different suburbs and important activity centres of the city. Generally, these roads are flexible paved one-way roads having two or more lanes with or without medians. The junctions of the roads are controlled by automated signalling systems. The traffic survey was conducted uninterruptedly for sixteen hours a day (6.00 am to 22.00 hours) for a week that includes both weekdays and weekends. Similarly, physical road surveys were conducted at important road sections of these roads to assess the current status of the road geometry parameters (road width, shoulder width, lane width, number of lanes, curbs, curvature, median width, gradient, sight distance, and road surface condition) and their influence on the incidence of the accidents. The households' surveys and road and traffic surveys were conducted during the year 2017. The average accident data on different roads over the period 2010 to 2017 were collected from published and unpublished documents and the police station records of the city. The surveys and assessment of the incidence of accidents were conducted on both directions represented by N and S, indicating the two different ways of these roads.

4.2. Determining Criteria Weights Using the CRITIC Method.

Step 1: development of the decision matrix (X) that is shown in Table 1. The initial matrix is shown for both directions since, as already mentioned, the data are different by directions, which means that we practically have two initial matrices.

Step 2: normalization of the initial matrix is shown in Table 2.

Normalization for cost criteria is performed using equation (2), for example,

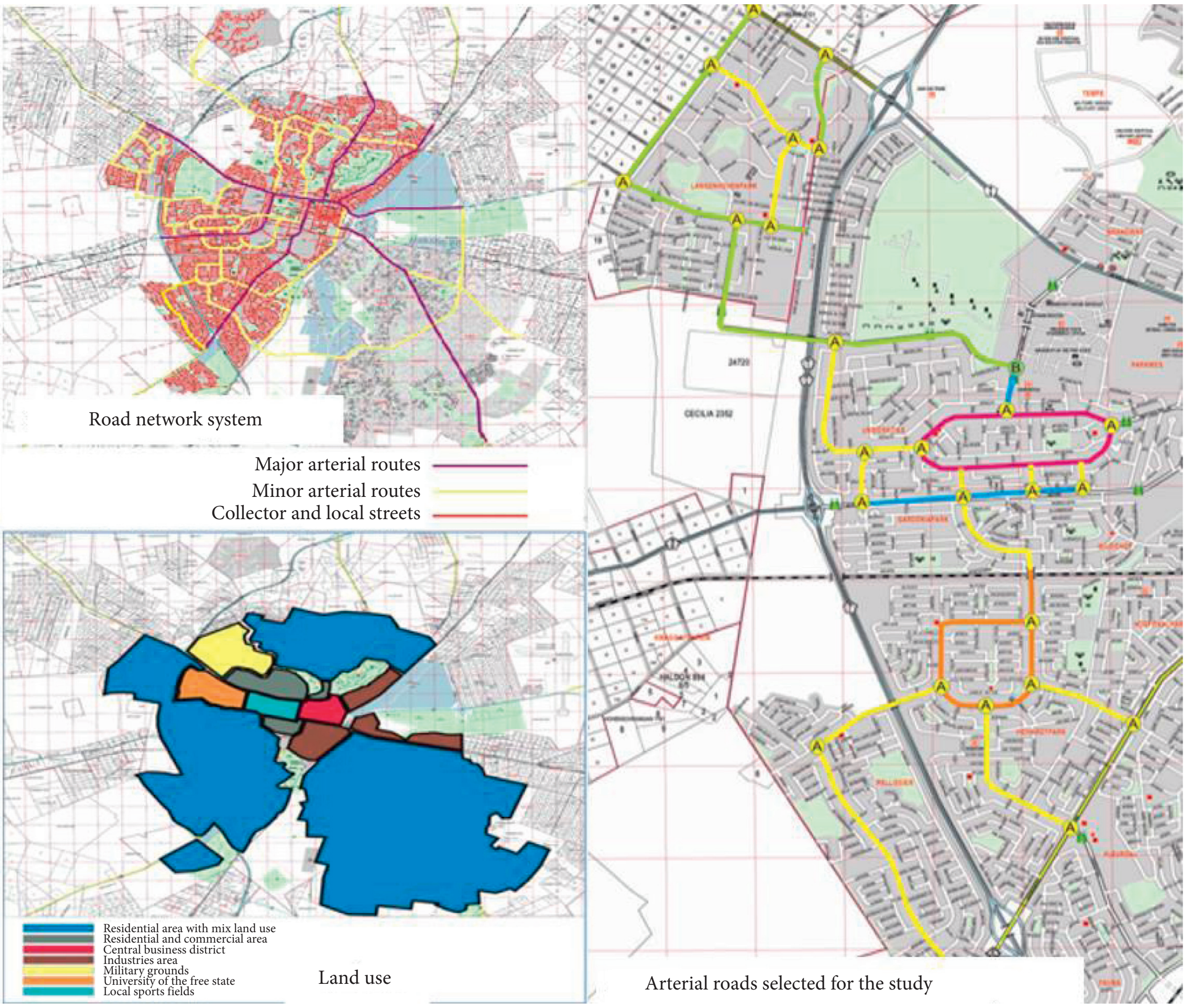


Figure 2: Map of the arterial roads selected for the study.

Table 1: Initial decision matrix for both directions (N and S).

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
ST_1	71	4611	6.2	2	8	16	ST_1	69	5082	6.2	2	7	17
ST_2	76	8908	6.5	2	8	25	ST_2	73	9359	6.7	2	7	23
ST_3	79	9938	6.1	1	9	32	ST_3	75	10133	6.2	1	11	26
ST_4	77	8888	6.0	2	8	13	ST_4	74	9009	6.4	2	7	11
ST_5	72	9285	7.5	2	15	32	ST_5	70	9133	7.5	2	12	30
ST_6	75	7409	7.0	2	11	21	ST_6	74	6171	7	2	5	15
ST_7	58	6040	6.0	2	4	8	ST_7	57	5929	6	2	3	7
ST_8	71	5888	7.5	2	4	12	ST_8	73	4696	7.5	2	4	13
ST_9	73	10055	6.7	2	7	22	ST_9	78	11669	6.8	2	9	30
ST_{10}	74	5444	6.0	2	4	9	ST_{10}	66	5962	6	2	4	9
ST_{11}	67	3227	4.3	2	4	7	ST_{11}	74	5257	4.3	2	4	14
ST_{12}	81	10016	12.0	3	8	33	ST_{12}	74	10636	12	3	5	31
ST_{13}	65	7434	6.0	2	4	9	ST_{13}	69	6980	6	2	5	15
ST_{14}	67	7267	6.0	2	4	11	ST_{14}	61	7879	6	2	3	7
ST_{15}	75	8693	9.0	2	11	28	ST_{15}	71	8500	8.5	2	9	22
ST_{16}	70	7047	7.5	2	7	16	ST_{16}	72	6654	7.5	2	7	19
ST_{17}	66	5029	6.0	2	4	9	ST_{17}	61	4330	6	2	3	5

Table 2: Normalization of initial decision matrices.

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
ST_1	0.435	0.797	0.247	0.500	0.636	0.654	ST_1	0.429	0.898	0.247	0.500	0.556	0.538
ST_2	0.217	0.168	0.286	0.500	0.636	0.308	ST_2	0.238	0.315	0.312	0.500	0.556	0.308
ST_3	0.087	0.017	0.234	0.000	0.545	0.038	ST_3	0.143	0.209	0.247	0.000	0.111	0.192
ST_4	0.174	0.171	0.221	0.500	0.636	0.769	ST_4	0.190	0.362	0.273	0.500	0.556	0.769
ST_5	0.391	0.113	0.416	0.500	0.000	0.038	ST_5	0.381	0.346	0.416	0.500	0.000	0.038
ST_6	0.261	0.388	0.351	0.500	0.364	0.462	ST_6	0.190	0.749	0.351	0.500	0.778	0.615
ST_7	1.000	0.588	0.221	0.500	1.000	0.962	ST_7	1.000	0.782	0.221	0.500	1.000	0.923
ST_8	0.435	0.610	0.416	0.500	1.000	0.808	ST_8	0.238	0.950	0.416	0.500	0.889	0.692
ST_9	0.348	0.000	0.312	0.500	0.727	0.423	ST_9	0.000	0.000	0.325	0.500	0.333	0.038
ST_{10}	0.304	0.675	0.221	0.500	1.000	0.923	ST_{10}	0.571	0.778	0.221	0.500	0.889	0.846
ST_{11}	0.609	1.000	0.000	0.500	1.000	1.000	ST_{11}	0.190	0.874	0.000	0.500	0.889	0.654
ST_{12}	0.000	0.006	1.000	1.000	0.636	0.000	ST_{12}	0.190	0.141	1.000	1.000	0.778	0.000
ST_{13}	0.696	0.384	0.221	0.500	1.000	0.923	ST_{13}	0.429	0.639	0.221	0.500	0.778	0.615
ST_{14}	0.609	0.408	0.221	0.500	1.000	0.846	ST_{14}	0.810	0.516	0.221	0.500	1.000	0.923
ST_{15}	0.261	0.199	0.610	0.500	0.364	0.192	ST_{15}	0.333	0.432	0.545	0.500	0.333	0.346
ST_{16}	0.478	0.441	0.416	0.500	0.727	0.654	ST_{16}	0.286	0.683	0.416	0.500	0.556	0.462
ST_{17}	0.652	0.736	0.221	0.500	1.000	0.923	ST_{17}	0.810	1.000	0.221	0.500	1.000	1.000

$$x_{N-11} = \frac{71 - 81}{58 - 81} = 0.435, x_{S-42} = \frac{9009 - 11669}{4330 - 11669} = 0.362. \tag{23}$$

Normalization for benefit criteria is performed using equation (3), for example,

$$x_{N-13} = \frac{6.2 - 4.3}{12 - 4.3} = 0.247, x_{S-14} = \frac{2 - 1}{3 - 1} = 0.500. \tag{24}$$

Step 3: the symmetric linear correlation matrix (m_{ij}) is shown in Table 3.

Step 4: determination of the objective weights of criteria, shown in Table 4.

After applying all the steps of the CRITIC method and the weighted normalized matrix shown in Table 5, it can be seen that the third criterion, road width (m), is the most significant with a value of 0.220 for the N-direction and a value of 0.204 for the S-direction. It is interesting to note that the sixth criterion, the average number of accidents (per km), is the second most significant and has an identical value of 0.187 for both directions. Essentially, the differences in the values of the criteria are not dominant in any case.

4.3. Determining Criteria Weights Using DEA-1 and DEA-2 Models. By applying equation (6), the individual values of the criteria for each DMU are obtained. An example of obtaining the values of criteria for DMU17-N is shown in Appendix. After solving this model shown in Appendix in Lingo 17 software, the following values are obtained: $w_1 = 0.005$, $w_2 = 0.000$, $w_3 = 0.095$, $w_4 = 0.000$, $w_5 = 0.000$, and $w_6 = 0.111$. It is necessary to form such a model for all 17 DMUs in order to obtain individual values. By solving all 17 models, the weights shown in Table 6 are obtained.

By applying equations (7) and (8), the values of the criteria according to the DEA-1 model are obtained as follows:

$$\begin{aligned}
&V_{1DEA-1} = 0.002, V_{2DEA-1} = 0.000, V_{3DEA-1} = 0.021, V_{4DEA-1} = 0.024, V_{5DEA-1} = 0.034, V_{6DEA-1} = 0.073,\\
&V_{1DEA-1} = \frac{0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0.007 + 0.015 + 0 + 0 + 0.007 + 0 + 0 + 0.005}{17} = 0.002,\\
&w_{1DEA-1} = 0.013, w_{2DEA-1} = 0.000, w_{3DEA-1} = 0.139, w_{4DEA-1} = 0.154, V_{5DEA-1} = 0.221, V_{6DEA-1} = 0.472,\\
&w_{1DEA-1} = \frac{0.002}{0.154} = 0.013.
\end{aligned} \tag{25}$$

Table 3: Symmetric linear correlation matrix.

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1.000	0.612	−0.516	−0.062	0.550	0.727	C_1	1.000	0.497	−0.279	0.031	0.547	0.690
C_2	0.612	1.000	−0.534	−0.007	0.584	0.787	C_2	0.497	1.000	−0.453	−0.040	0.637	0.764
C_3	−0.516	−0.534	1.000	0.626	−0.403	−0.650	C_3	−0.279	−0.453	1.000	0.635	−0.188	−0.573
C_4	−0.062	−0.007	0.626	1.000	0.055	−0.019	C_4	0.031	−0.040	0.635	1.000	0.380	−0.104
C_5	0.550	0.584	−0.403	0.055	1.000	0.815	C_5	0.547	0.637	−0.188	0.380	1.000	0.776
C_6	0.727	0.787	−0.650	−0.019	0.815	1.000	C_6	0.690	0.764	−0.573	−0.104	0.776	1.000

Table 4: Results of applying the CRITIC method.

N	$1-r_{ij}$						S	$1-r_{ij}$					
C_1	0.000	0.388	1.516	1.062	0.450	0.273	C_1	0.000	0.503	1.279	0.969	0.453	0.310
C_2	0.388	0.000	1.534	1.007	0.416	0.213	C_2	0.503	0.000	1.453	1.040	0.363	0.236
C_3	1.516	1.534	0.000	0.374	1.403	1.650	C_3	1.279	1.453	0.000	0.365	1.188	1.573
C_4	1.062	1.007	0.374	0.000	0.945	1.019	C_4	0.969	1.040	0.365	0.000	0.620	1.104
C_5	0.450	0.416	1.403	0.945	0.000	0.185	C_5	0.453	0.363	1.188	0.620	0.000	0.224
C_6	0.273	0.213	1.650	1.019	0.185	0.000	C_6	0.310	0.236	1.573	1.104	0.224	0.000
ST_{DEV}	0.250	0.304	0.216	0.177	0.294	0.356	ST_{DEV}	0.273	0.305	0.210	0.177	0.310	0.327
$\sum$	3.689	3.558	6.477	4.406	3.399	3.340	$\sum$	3.513	3.595	5.857	4.098	2.848	3.447
C_j	0.922	1.082	1.401	0.779	0.998	1.190	C_j	0.958	1.096	1.228	0.724	0.883	1.127
$\sum C_j$	6.371						$\sum C_j$	6.016					
W_j	0.145	0.170	0.220	0.122	0.157	0.187	W_j	0.159	0.182	0.204	0.120	0.147	0.187

Table 5: The weighted normalized matrix.

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
AAI	0.041	0.018	0.060	0.037	0.058	0.083	AAI	0.039	0.023	0.033	0.048	0.074	0.057
ST_1	0.047	0.040	0.087	0.073	0.109	0.171	ST_1	0.044	0.052	0.048	0.097	0.126	0.104
ST_2	0.044	0.021	0.091	0.073	0.109	0.110	ST_2	0.042	0.028	0.052	0.097	0.126	0.077
ST_3	0.042	0.018	0.085	0.037	0.097	0.086	ST_3	0.040	0.026	0.048	0.048	0.080	0.068
ST_4	0.043	0.021	0.084	0.073	0.109	0.211	ST_4	0.041	0.029	0.050	0.097	0.126	0.161
ST_5	0.046	0.020	0.105	0.073	0.058	0.086	ST_5	0.043	0.029	0.058	0.097	0.074	0.059
ST_6	0.044	0.025	0.098	0.073	0.079	0.130	ST_6	0.041	0.043	0.054	0.097	0.177	0.118
ST_7	0.057	0.030	0.084	0.073	0.217	0.342	ST_7	0.053	0.044	0.046	0.097	0.295	0.252
ST_8	0.047	0.031	0.105	0.073	0.217	0.228	ST_8	0.042	0.056	0.058	0.097	0.221	0.136
ST_9	0.045	0.018	0.094	0.073	0.124	0.124	ST_9	0.039	0.023	0.053	0.097	0.098	0.059
ST_{10}	0.045	0.034	0.084	0.073	0.217	0.304	ST_{10}	0.046	0.044	0.046	0.097	0.221	0.196
ST_{11}	0.049	0.057	0.060	0.073	0.217	0.391	ST_{11}	0.041	0.050	0.033	0.097	0.221	0.126
ST_{12}	0.041	0.018	0.168	0.110	0.109	0.083	ST_{12}	0.041	0.025	0.093	0.145	0.177	0.057
ST_{13}	0.051	0.025	0.084	0.073	0.217	0.304	ST_{13}	0.044	0.038	0.046	0.097	0.177	0.118
ST_{14}	0.049	0.025	0.084	0.073	0.217	0.249	ST_{14}	0.050	0.033	0.046	0.097	0.295	0.252
ST_{15}	0.044	0.021	0.126	0.073	0.079	0.098	ST_{15}	0.043	0.031	0.066	0.097	0.098	0.080
ST_{16}	0.047	0.026	0.105	0.073	0.124	0.171	ST_{16}	0.042	0.040	0.058	0.097	0.126	0.093
ST_{17}	0.050	0.036	0.084	0.073	0.217	0.304	ST_{17}	0.050	0.061	0.046	0.097	0.295	0.353
AI	0.057	0.057	0.168	0.110	0.217	0.391	AI	0.053	0.061	0.093	0.145	0.295	0.353

Table 6: Values for criteria obtained using the DEA model.

DEA-N	w_1	w_2	w_3	w_4	w_5	w_6	DEA-S	w_1	w_2	w_3	w_4	w_5	w_6
ST_1	0.000	0.000	0.024	0.000	0.083	0.063	ST_1	0.000	0.000	0.000	0.015	0.088	0.059
ST_2	0.000	0.000	0.018	0.000	0.048	0.040	ST_2	0.000	0.000	0.000	0.000	0.036	0.043
ST_3	0.000	0.000	0.000	0.000	0.051	0.031	ST_3	0.000	0.000	0.000	0.000	0.060	0.038
ST_4	0.000	0.000	0.000	0.038	0.115	0.077	ST_4	0.000	0.000	0.000	0.023	0.136	0.091
ST_5	0.000	0.000	0.000	0.000	0.051	0.031	ST_5	0.000	0.000	0.000	0.000	0.052	0.033
ST_6	0.000	0.000	0.000	0.000	0.077	0.048	ST_6	0.000	0.000	0.006	0.000	0.099	0.067
ST_7	0.000	0.000	0.000	0.366	0.000	0.125	ST_7	0.000	0.000	0.061	0.000	0.000	0.143
ST_8	0.000	0.000	0.111	0.000	0.000	0.083	ST_8	0.000	0.000	0.007	0.000	0.115	0.077
ST_9	0.000	0.000	0.000	0.000	0.032	0.045	ST_9	0.000	0.000	0.000	0.000	0.028	0.033
ST_{10}	0.007	0.000	0.034	0.000	0.000	0.111	ST_{10}	0.000	0.000	0.000	0.000	0.093	0.111
ST_{11}	0.015	0.000	0.000	0.000	0.000	0.143	ST_{11}	0.001	0.000	0.000	0.000	0.105	0.071
ST_{12}	0.000	0.000	0.040	0.000	0.000	0.030	ST_{12}	0.000	0.000	0.014	0.000	0.000	0.032
ST_{13}	0.000	0.000	0.000	0.000	0.000	0.111	ST_{13}	0.000	0.000	0.000	0.000	0.056	0.067
ST_{14}	0.007	0.000	0.000	0.000	0.000	0.091	ST_{14}	0.000	0.000	0.000	0.183	0.000	0.143
ST_{15}	0.000	0.000	0.014	0.000	0.048	0.036	ST_{15}	0.000	0.000	0.004	0.000	0.068	0.045
ST_{16}	0.000	0.000	0.029	0.000	0.075	0.062	ST_{16}	0.000	0.000	0.005	0.000	0.078	0.053
ST_{17}	0.005	0.000	0.095	0.000	0.000	0.111	ST_{17}	0.000	0.000	0.000	0.500	0.000	0.200

By applying equations (9) and (10), the values of the criteria according to the DEA-2 model are obtained as follows:

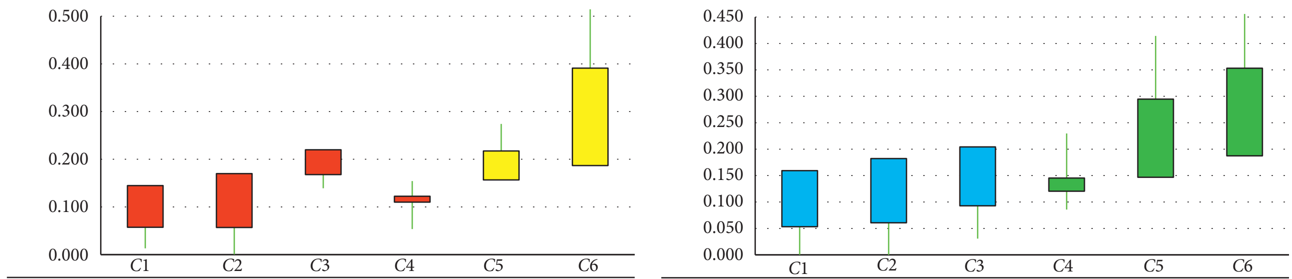
$$
\begin{aligned}
&V_{1\text{DEA}-2} = 0, V_{2\text{DEA}-2} = 0, V_{3\text{DEA}-2} = 0.141, V_{4\text{DEA}-2} = 0, V_{5\text{DEA}-2} = 0.488, V_{6\text{DEA}-2} = 0.371,\\
&V_{3\text{DEA}-2} = \frac{0.024}{0.170} = 0.141,\\
&w_{1\text{DEA}-2} = 0.014, w_{2\text{DEA}-2} = 0.000, w_{3\text{DEA}-2} = 0.144, w_{4\text{DEA}-2} = 0.054, V_{5\text{DEA}-2} = 0.274, V_{6\text{DEA}-2} = 0.515,\\
&w_{1\text{DEA}-2} = \frac{0+0+0+0+0+0+0+0+0+0.046+0.095+0+0+0.071+0+0+0.024}{17} = 0.014.
\end{aligned} \tag{26}
$$

The previous calculation refers to the N-direction, while the values for the S-direction are obtained in an identical way, which together with the previous calculations and the final values are shown in Figures 3 and 4.

4.4. Determining the Final Criteria Weights. The final values of the criteria are obtained by averaging the weight values of the criteria obtained by individual methods: CRITIC, DEA-1, and DEA-2. Figure 3 presents the individual and final values of the criteria for the N-direction (Figure 3(a)) and the S-direction (Figure 3(b)).

From Figure 3, it can be seen that there is a difference in applying different approaches and that different values are obtained. This is the reason for their integration when obtaining the final values. Using the CRITIC method, the following values are obtained: $w_1 = 0.145$, $w_2 = 0.170$, $w_3 = 0.220$, $w_4 = 0.122$, $w_5 = 0.157$, and $w_6 = 0.187$ for the N-direction and $w_1 = 0.159$, $w_2 = 0.182$, $w_3 = 0.204$, $w_4 = 0.120$, $w_5 = 0.147$, and $w_6 = 0.187$ for the S-direction. In the previous section of the paper, the values obtained using DEA models are explained. The DEA-1 model for the N-direction implies the values $w_1 = 0.013$, $w_2 = 0.0003$, $w_3 = 0.139$, $w_4 = 0.154$, $w_5 = 0.221$, and $w_6 = 0.472$ and for the S-direction, $w_1 = 0.0003$, $w_2 = 0.0001$, $w_3 = 0.031$, $w_4 = 0.300$, $w_5 = 0.323$, and $w_6 = 0.416$. Applying a different approach, i.e., the DEA-2 model, the values of the criteria for the N-direction are $w_1 = 0.014$, $w_2 = 0.000$, $w_3 = 0.144$, $w_4 = 0.054$, $w_5 = 0.274$, and $w_6 = 0.515$, while for the S-direction, they are $w_1 = 0.0003$, $w_2 = 0.0001$, $w_3 = 0.044$, $w_4 = 0.086$, $w_5 = 0.414$, and $w_6 = 0.456$. Observing the range of weight values of the criteria, including the final values, the largest deviation is for the sixth criterion with a value of 0.328 for the N-direction. There is a slightly smaller deviation for the sixth and fifth criterion for the S-direction. For other criteria, the range of values is smaller.

The final values of the criteria further included in the MARCOS method are $w_1 = 0.057$, $w_2 = 0.057$, $w_3 = 0.168$, $w_4 = 0.110$, $w_5 = 0.217$, and $w_6 = 0.391$ for the N-direction and $w_1 = 0.053$, $w_2 = 0.061$, $w_3 = 0.093$, $w_4 = 0.145$, $w_5 = 0.295$, and $w_6 = 0.353$ for the S-direction. Figure 4 also shows the ranks, i.e., the significance of all criteria according to each individual model and for the final values. The most significant criterion according to DEA-1 and



	C1	C2	C3	C4	C5	C6
CRITIC	0.145	0.170	0.220	0.122	0.157	0.187
DEA-1	0.0130	0.0003	0.1392	0.1541	0.2212	0.4722
DEA-2	0.014	0.000	0.144	0.054	0.274	0.515
Final W_j	0.057	0.057	0.168	0.110	0.217	0.391

(a)

	C1	C2	C3	C4	C5	C6
CRITIC	0.159	0.182	0.204	0.120	0.147	0.187
DEA-1	0.0003	0.0001	0.0307	0.2297	0.3231	0.4162
DEA-2	0.0003	0.0001	0.0437	0.0858	0.4142	0.4559
Final W_j	0.053	0.061	0.093	0.145	0.295	0.353

(b)

FIGURE 3: Criteria weights for the N- (a) and S-direction (b) using different approaches.

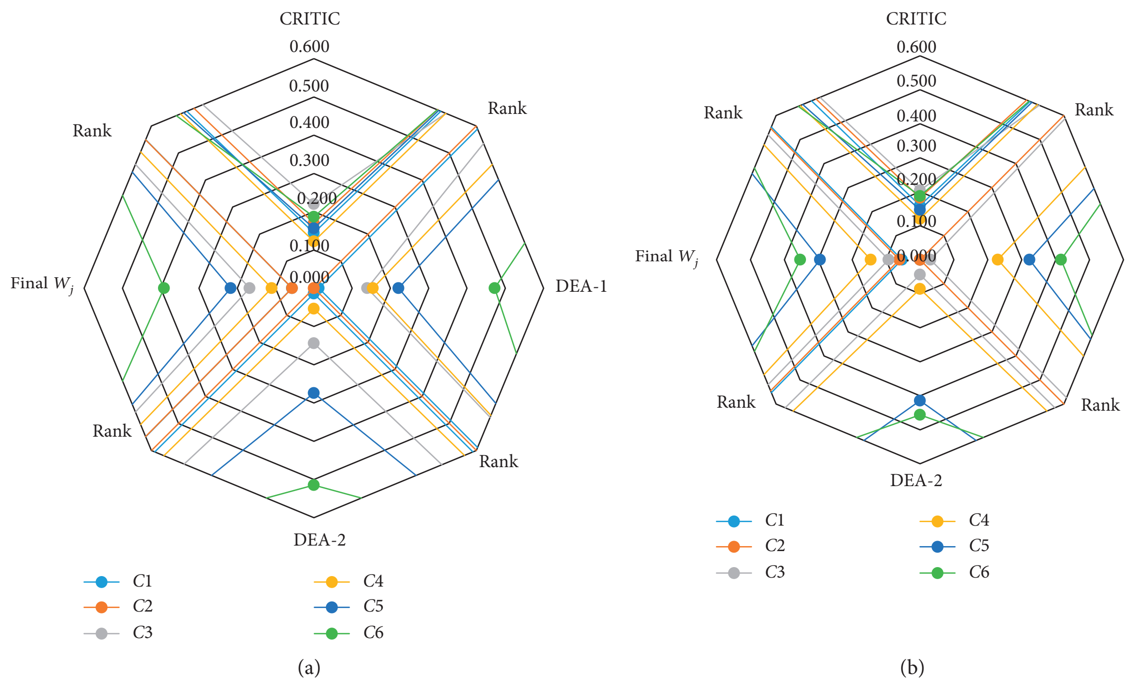


FIGURE 4: Criteria weights and ranks for the N- (a) and S-direction (b) using different approaches.

DEA-2 models and the final values is the average number of accidents (per km), which is understandable, while the same criterion is the second according to the CRIITIC method. The second most significant criterion is the number of access (per km) for all models, except for the already mentioned CRITIC, where it is in the fourth position. The third most significant criterion is road width (m) according to the final values and the DEA-2 model, while by applying DEA-1, it is in the fourth place, i.e., in the first place by applying the CRITIC method. The fourth criterion, the number of lanes, is positioned in the fourth place, while the last two places occupy the first and second criterion, respectively. The listed ranks and significance refer to the left side of the figure which implies the N-direction. When it comes to the significance of the criteria for the S-direction, it can be concluded that the ranks are more correlated than for the N-direction. The difference in the final values in terms of ranks is only for the third and fourth criterion, which change positions with each other.

4.5. Evaluation of Alternatives Using the MARCOS Method. The following section of the paper presents the evaluation of alternatives using the MARCOS method. For each step of the method, an example of the calculation is given in order to facilitate the monitoring of the obtained results. Table 7 shows an extended initial decision matrix obtained when Table 1 is expanded with an ideal (AI) and an anti-ideal (AAI) solution depending on the type of criteria. It is important to emphasize that the third and fourth criterion are of the benefit type (orientation max), while the others are of the cost type (orientation min).

Applying equation (14), the normalized values for cost criteria are obtained, e.g., $n_{N11} = 58/71 = 0.817, n_{S11} =$

Table 7: An extended initial decision matrix.

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
AAI	81	10055	4.3	1	15	33	AAI	78	11669	4.3	1	12	31
ST_1	71	4611	6.2	2	8	16	ST_1	69	5082	6.2	2	7	17
ST_2	76	8908	6.5	2	8	25	ST_2	73	9359	6.7	2	7	23
ST_3	79	9938	6.1	1	9	32	ST_3	75	10133	6.2	1	11	26
ST_4	77	8888	6.0	2	8	13	ST_4	74	9009	6.4	2	7	11
ST_5	72	9285	7.5	2	15	32	ST_5	70	9133	7.5	2	12	30
ST_6	75	7409	7.0	2	11	21	ST_6	74	6171	7	2	5	15
ST_7	58	6040	6.0	2	4	8	ST_7	57	5929	6	2	3	7
ST_8	71	5888	7.5	2	4	12	ST_8	73	4696	7.5	2	4	13
ST_9	73	10055	6.7	2	7	22	ST_9	78	11669	6.8	2	9	30
ST_{10}	74	5444	6.0	2	4	9	ST_{10}	66	5962	6	2	4	9
ST_{11}	67	3227	4.3	2	4	7	ST_{11}	74	5257	4.3	2	4	14
ST_{12}	81	10016	12.0	3	8	33	ST_{12}	74	10636	12	3	5	31
ST_{13}	65	7434	6.0	2	4	9	ST_{13}	69	6980	6	2	5	15
ST_{14}	67	7267	6.0	2	4	11	ST_{14}	61	7879	6	2	3	7
ST_{15}	75	8693	9.0	2	11	28	ST_{15}	71	8500	8.5	2	9	22
ST_{16}	70	7047	7.5	2	7	16	ST_{16}	72	6654	7.5	2	7	19
ST_{17}	66	5029	6.0	2	4	9	ST_{17}	61	4330	6	2	3	5
AI	58	3227	12.0	3	4	7	AI	57	4330	12.0	3	3	5

Table 8: Normalized matrix.

N	C_1	C_2	C_3	C_4	C_5	C_6	S	C_1	C_2	C_3	C_4	C_5	C_6
AAI	0.716	0.321	0.358	0.333	0.267	0.212	AAI	0.731	0.371	0.358	0.333	0.250	0.161
ST_1	0.817	0.700	0.517	0.667	0.500	0.438	ST_1	0.826	0.852	0.517	0.667	0.429	0.294
ST_2	0.763	0.362	0.542	0.667	0.500	0.280	ST_2	0.781	0.463	0.558	0.667	0.429	0.217
ST_3	0.734	0.325	0.508	0.333	0.444	0.219	ST_3	0.760	0.427	0.517	0.333	0.273	0.192
ST_4	0.753	0.363	0.500	0.667	0.500	0.538	ST_4	0.770	0.481	0.533	0.667	0.429	0.455
ST_5	0.806	0.348	0.625	0.667	0.267	0.219	ST_5	0.814	0.474	0.625	0.667	0.250	0.167
ST_6	0.773	0.436	0.583	0.667	0.364	0.333	ST_6	0.770	0.702	0.583	0.667	0.600	0.333
ST_7	1.000	0.534	0.500	0.667	1.000	0.875	ST_7	1.000	0.730	0.500	0.667	1.000	0.714
ST_8	0.817	0.548	0.625	0.667	1.000	0.583	ST_8	0.781	0.922	0.625	0.667	0.750	0.385
ST_9	0.795	0.321	0.558	0.667	0.571	0.318	ST_9	0.731	0.371	0.567	0.667	0.333	0.167
ST_{10}	0.784	0.593	0.500	0.667	1.000	0.778	ST_{10}	0.864	0.726	0.500	0.667	0.750	0.556
ST_{11}	0.866	1.000	0.358	0.667	1.000	1.000	ST_{11}	0.770	0.824	0.358	0.667	0.750	0.357
ST_{12}	0.716	0.322	1.000	1.000	0.500	0.212	ST_{12}	0.770	0.407	1.000	1.000	0.600	0.161
ST_{13}	0.892	0.434	0.500	0.667	1.000	0.778	ST_{13}	0.826	0.620	0.500	0.667	0.600	0.333
ST_{14}	0.866	0.444	0.500	0.667	1.000	0.636	ST_{14}	0.934	0.550	0.500	0.667	1.000	0.714
ST_{15}	0.773	0.371	0.750	0.667	0.364	0.250	ST_{15}	0.803	0.509	0.708	0.667	0.333	0.227
ST_{16}	0.829	0.458	0.625	0.667	0.571	0.438	ST_{16}	0.792	0.651	0.625	0.667	0.429	0.263
ST_{17}	0.879	0.642	0.500	0.667	1.000	0.778	ST_{17}	0.934	1.000	0.500	0.667	1.000	1.000
AI	1.000	1.000	1.000	1.000	1.000	1.000	AI	1.000	1.000	1.000	1.000	1.000	1.000

57/69 = 0.826, and for benefit criteria using equation (15), $n_{N13} = 6.2/12 = 0.517, n_{S14} = 2/3 = 0.667$, and a complete normalized matrix, shown in Table 8, is obtained.

The next step is weighting the normalized matrix using equation (16) by multiplying all the values of the normalized matrix with the values of the criteria. The weighted normalized matrix is shown in Table 5.

Applying equations (17)–(22), the final results of Table 9 are obtained using the MARCOS method. The results are obtained as follows.

By applying equation (19), all the values (by rows) for alternatives are summarized as follows:

$$S_{\mathrm{NAAI}} = 0.041 + 0.018 + 0.060 + 0.037 + 0.058 + 0.083 = 0.297,$$
$$S_{\mathrm{SAAI}} = 0.039 + 0.023 + 0.033 + 0.048 + 0.074 + 0.057 = 0.274. \quad (27)$$

Similarly, the values for the remaining alternatives are obtained for both directions.

By applying equation (17), the utility degrees in relation to the anti-ideal solution are calculated. The example of the calculation is

$$K_{N1}^{-} = \frac{0.526}{0.297} = 1.773, K_{S1}^{-} = \frac{0.471}{0.274} = 1.719, \quad (28)$$

Table 9: Alternative ranking obtained using the MARCOS method.

N	S_i	K_i^-	K_i^+	fK^-	fK^+	K_i	Rank	S	S_i	K_i^-	K_i^+	fK^-	fK^+	K_i	Rank
AAI	0.297	1.000						AAI	0.274	1.000					
ST_1	0.526	1.773	0.526	0.771	0.229	0.493	11	ST_1	0.471	1.719	0.471	0.215	0.785	0.445	11
ST_2	0.446	1.504	0.446	0.771	0.229	0.418	14	ST_2	0.421	1.539	0.421	0.215	0.785	0.398	13
ST_3	0.364	1.228	0.364	0.771	0.229	0.341	17	ST_3	0.311	1.136	0.311	0.215	0.785	0.294	17
ST_4	0.540	1.820	0.540	0.771	0.229	0.506	9	ST_4	0.503	1.839	0.503	0.215	0.785	0.475	10
ST_5	0.387	1.305	0.387	0.771	0.229	0.363	16	ST_5	0.360	1.313	0.360	0.215	0.785	0.340	16
ST_6	0.449	1.514	0.449	0.771	0.229	0.421	13	ST_6	0.529	1.933	0.529	0.215	0.785	0.500	8
ST_7	0.804	2.710	0.804	0.771	0.229	0.753	2	ST_7	0.788	2.877	0.788	0.215	0.785	0.744	2
ST_8	0.701	2.363	0.701	0.771	0.229	0.657	6	ST_8	0.609	2.225	0.609	0.215	0.785	0.575	5
ST_9	0.479	1.615	0.479	0.771	0.229	0.449	12	ST_9	0.368	1.344	0.368	0.215	0.785	0.348	15
ST_{10}	0.757	2.551	0.757	0.771	0.229	0.709	4	ST_{10}	0.651	2.376	0.651	0.215	0.785	0.614	4
ST_{11}	0.848	2.857	0.848	0.771	0.229	0.794	1	ST_{11}	0.568	2.076	0.568	0.215	0.785	0.537	6
ST_{12}	0.528	1.781	0.528	0.771	0.229	0.495	10	ST_{12}	0.538	1.964	0.538	0.215	0.785	0.508	7
ST_{13}	0.754	2.541	0.754	0.771	0.229	0.706	5	ST_{13}	0.520	1.897	0.520	0.215	0.785	0.491	9
ST_{14}	0.698	2.352	0.698	0.771	0.229	0.654	7	ST_{14}	0.773	2.824	0.773	0.215	0.785	0.730	3
ST_{15}	0.441	1.486	0.441	0.771	0.229	0.413	15	ST_{15}	0.415	1.515	0.415	0.215	0.785	0.392	14
ST_{16}	0.547	1.842	0.547	0.771	0.229	0.512	8	ST_{16}	0.456	1.665	0.456	0.215	0.785	0.430	12
ST_{17}	0.765	2.579	0.765	0.771	0.229	0.717	3	ST_{17}	0.902	3.293	0.902	0.215	0.785	0.852	1
AI	1.000							AI	1.000						

while using equation (18), the utility degrees in relation to the ideal solution are obtained, e.g.,

$$K_{N+}^{-} = \frac{0.526}{1.000} = 0.526, K_{S1}^{-} = \frac{0.471}{0.297} = 0.471. \tag{29}$$

The utility function in terms of the anti-ideal solution is obtained using equation (21) as follows:

$$\begin{aligned} f\left(K_{N1}^{-}\right) &= \frac{0.526}{0.526 + 1.773} = 0.229, \\ f\left(K_{S1}^{-}\right) &= \frac{0.471}{0.471 + 1.719} = 0.215, \end{aligned} \tag{30}$$

while the utility function in terms of the ideal solution is obtained using equation (22) as follows:

$$\begin{aligned} f\left(K_{N1}^{+}\right) &= \frac{1.773}{0.526 + 1.773} = 0.771, \\ f\left(K_{S1}^{+}\right) &= \frac{1.719}{0.471 + 1.719} = 0.785. \end{aligned} \tag{31}$$

Finally, the utility function of alternative A1 is obtained by applying equation (20):

$$\begin{aligned} f\left(K_{N1}\right) &= \frac{0.526 + 1.773}{1 + 1 - 0.771/0.771 + 1 - 0.229/0.229} = 0.493, \\ f\left(K_{S1}\right) &= \frac{0.471 + 1.719}{1 + 1 - 0.785/0.785 + 1 - 0.215/0.215} = 0.445. \end{aligned} \tag{32}$$

After applying the whole methodology, the results for both directions are summarized in Table 9. When it comes to the rank, i.e., determination of the traffic safety level in 17 streets of the city of Bloemfontein, it can be noticed that alternative A11, i.e., Van Schalkwyk Street, is the safest with a value of 0.794 for the N-direction. Volkspele Drive is the second in terms of safety, with Eric Rosendorf Street and Gardenia Avenue in the third and fourth place, respectively. Another alternative A13, i.e., Edeling Street, can be put into a group of safe streets comparing all alternatives. The group of most risky streets includes Wynand Mouton Drive, Paul Kruger Drive North, Benade Drive (N), Totius Street, and Paul Kruger Drive South with a range of values from 0.341 to 0.421.

As already mentioned in the previous section of the paper, data have been collected for both directions, and the evaluation is performed accordingly, so it is evident that there are differences in terms of safety of individual streets. When it comes to the S-direction, the group of the five safest streets includes the following, respectively: Eric Rosendorf Street, Volkspele Drive, Stals Road, Gardenia Avenue, and Pellissier Drive. The group of least safe streets for the S-direction includes Wynand Mouton Drive, Paul Kruger Drive North, Paul Kruger Drive (E), and Benade Drive (N).

Three streets that belong to the group of safe regardless of the direction are Eric Rosendorf Street, third and first positions, Volkspele Drive, second place for both directions, and Gardenia Avenue which is in the fourth place. In terms of the most risky streets for both directions, Wynand Mouton Drive is in the last place, Paul Kruger Drive North in the 16th place, Benade Drive (N) in the 15th and 14th place, respectively, and Totius Street in the 14th and 13th place, respectively.

5. Sensitivity Analysis

Verification of previously obtained results was performed through a multiphase sensitivity analysis. Validity tests refer to the (a) formation of reverse rank matrices in which the

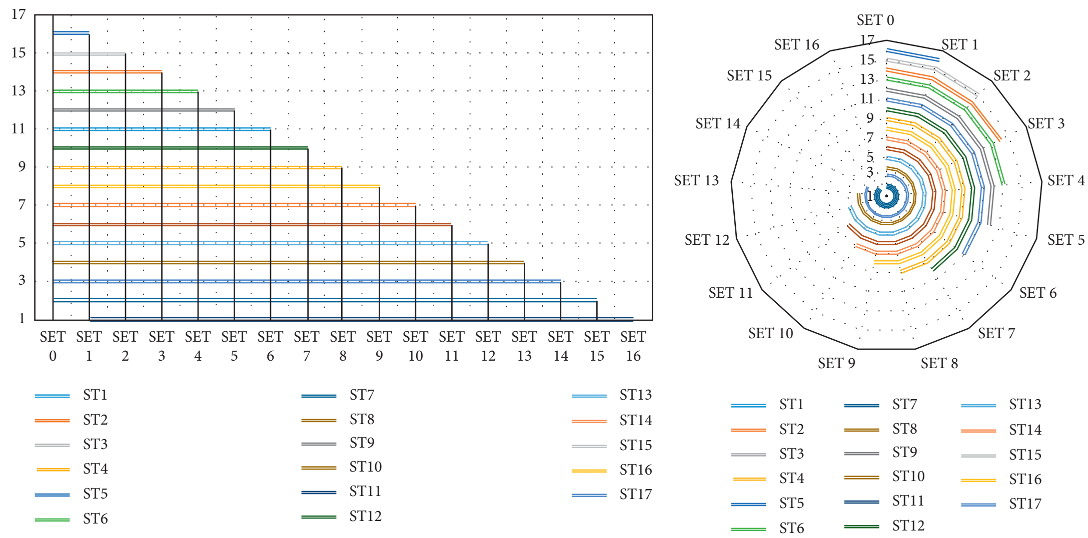


Figure 5: Results of reverse rank for both directions.

worst alternative is eliminated from further calculation, (b) change of criterion weight in a dynamic environment, (c) evaluation of alternatives based on individually obtained values of criteria weights using CRITIC, DEA-1, and DEA-2 methods; in addition, a scenario is created in which all criteria have equal significance, (d) comparative analysis of the obtained results with five other MCDM methods, (e) calculation of SCC for all ranks obtained by applying different approaches, and (f) calculation of standard deviation of ranks obtained by applying different approaches.

5.1. Reverse Rank Matrix. In this part of the sensitivity analysis, the worst alternative is eliminated through 16 scenarios. In each of the scenarios, the last-ranked alternative is eliminated, and a full calculation is performed again, until one alternative remains, as is the case in scenario 16.

Figure 5 presents the results of the ranks of alternatives through previously formed scenarios for both directions. As can be seen, there is no change in ranks in any case, which means that the model is stable, and the results are valid in such conditions.

5.2. Changing Criteria Weights. In this phase of the validation test, the impact of changing the three most important criteria $C6$, $C5$, and $C3$ for the N-direction and $C6$, $C5$, and $C4$ for the S-direction on ranking results was analyzed. Applying equation (33), a total of 18 scenarios were formed.

$$W_{n\beta} = \left(1 - W_{n\alpha}\right)\frac{W_\beta}{\left(1 - W_n\right)}. \tag{33}$$

The sixth criterion was changed in scenarios $S1$–$S6$, criterion $C5$ was changed in scenarios $S7$–$S12$, and criterion $C3$ was changed in scenarios $S13$–$S18$ for the N-direction. In equation (33), $\widetilde{W}_{n\beta}$ represents the new value of criteria $C1$–$C5$ for scenarios $S1$–$S6$ and then $C1$–$C4$ and $C5$ for scenarios $S7$–$S12$, i.e., $C1$-$C2$, $C4$, and $C5$-$C6$ for scenarios $S13$–$S18$. $\widetilde{W}_{n\alpha}$ represents the corrected value of criteria $C6$, $C5$, and $C3$, respectively, by groups of scenarios, $\widetilde{W}_\beta$ represents the original value of the criterion considered, and $\widetilde{W}_n$ represents the original value of the criterion whose value is reduced, in this case, $C6$, $C5$, and $C3$.

For the S-direction, the difference is that, in scenarios $S13$–$S18$, the value of criterion $C4$ was changed instead of $C3$.

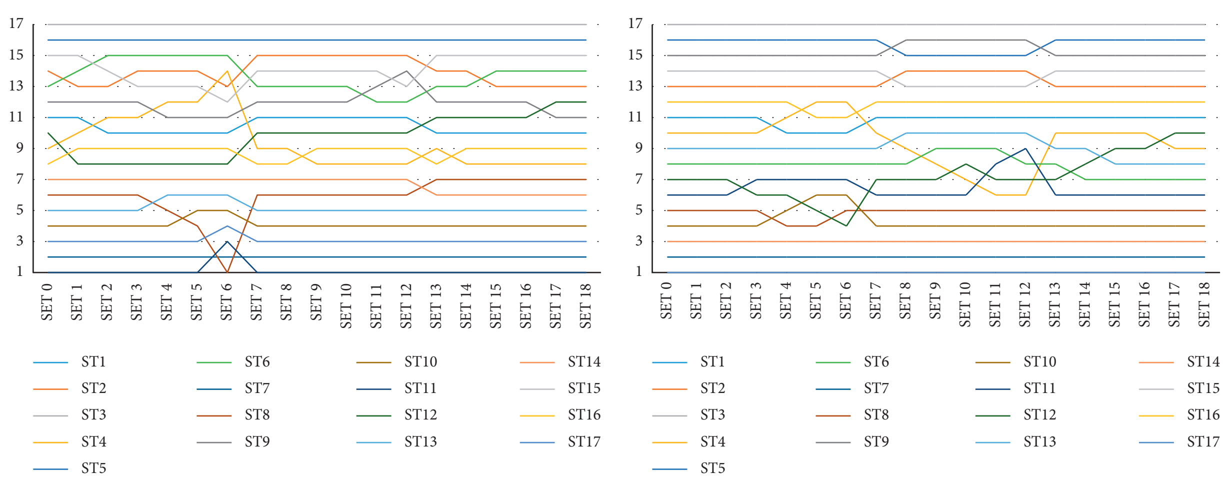
In all scenarios, the value of criteria was reduced by 15%, while the values of the remaining criteria were proportionally corrected by applying equation (33). After forming 18 new vectors of the weight coefficients of the criteria (Table 10), new results were obtained, as presented in Figure 6.

Figure 6(a) presents the ranks of alternatives for the N-direction due to the formation of 18 scenarios with new criteria weights. As can be seen, the rank changes due to the simulation of different values of the criteria, which means that the results are sensitive to the significance of the criteria. The biggest changes compared to the initial rank (SET 0) occur in the sixth set when alternative ST11 falls from the first to the third place. The consequence of such a change is in the value of the sixth criterion, which is only 0.039. If we take into account that, in real conditions, the sixth criterion should not have such a low value, it remains the best alternative option. In the sixth scenario, dominant criteria are the fifth and the third, which consequently influence the sixth-ranked alternative to become the first compared to the initial ranking. In other scenarios, there is also a change in ranks, but they are negligible compared to the above scenario.

When it comes to changes of ranks for the S-direction, Figure 6(b), smaller changes can be noticed, i.e., greater stability of the initial rank. The best three alternatives ST17, ST7, and ST14 do not change the ranks of the alternatives at all regardless of the criteria values. In addition, there are fewer changes through the other scenarios, with the

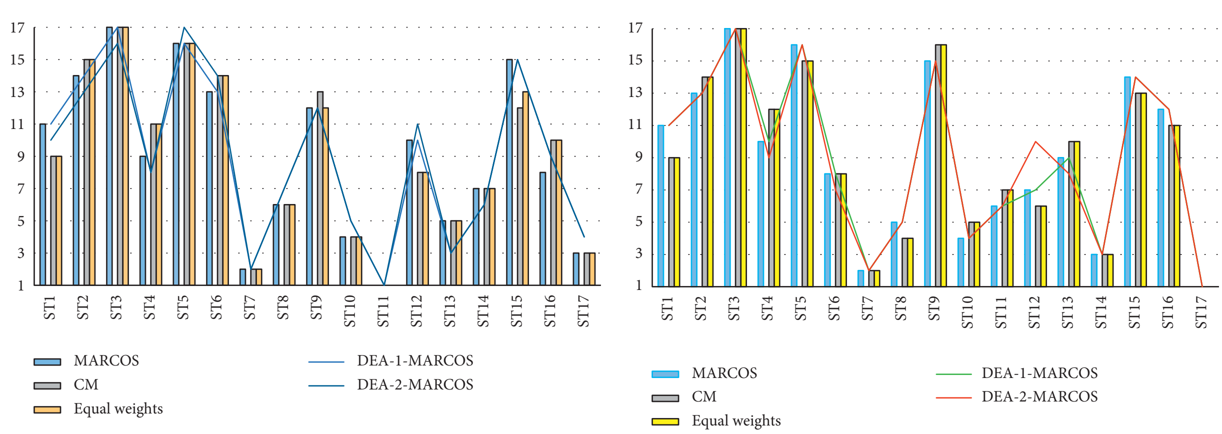
Table 10: New criteria weights through 18 scenarios.

N	w_1	w_2	w_3	w_4	w_5	w_6	S	w_1	w_2	w_3	w_4	w_5	w_6
S_1	0.063	0.062	0.184	0.121	0.238	0.332	S_1	0.058	0.066	0.100	0.157	0.319	0.300
S_2	0.068	0.068	0.200	0.131	0.259	0.274	S_2	0.062	0.071	0.108	0.169	0.343	0.247
S_3	0.074	0.073	0.216	0.142	0.280	0.215	S_3	0.066	0.076	0.116	0.181	0.367	0.194
S_4	0.079	0.079	0.232	0.152	0.301	0.156	S_4	0.071	0.081	0.123	0.193	0.391	0.141
S_5	0.085	0.084	0.248	0.163	0.322	0.098	S_5	0.075	0.086	0.131	0.205	0.415	0.088
S_6	0.090	0.090	0.265	0.174	0.343	0.039	S_6	0.079	0.091	0.138	0.217	0.439	0.035
S_7	0.060	0.059	0.175	0.115	0.185	0.407	S_7	0.057	0.065	0.099	0.154	0.250	0.375
S_8	0.062	0.061	0.182	0.119	0.152	0.424	S_8	0.060	0.068	0.104	0.163	0.206	0.397
S_9	0.064	0.064	0.189	0.124	0.120	0.440	S_9	0.063	0.072	0.110	0.173	0.162	0.420
S_{10}	0.067	0.066	0.196	0.128	0.087	0.456	S_{10}	0.067	0.076	0.116	0.182	0.118	0.442
S_{11}	0.069	0.069	0.203	0.133	0.054	0.473	S_{11}	0.070	0.080	0.122	0.191	0.074	0.464
S_{12}	0.071	0.071	0.210	0.137	0.022	0.489	S_{12}	0.073	0.084	0.128	0.200	0.029	0.486
S_{13}	0.059	0.058	0.143	0.113	0.224	0.403	S_{13}	0.055	0.062	0.095	0.123	0.302	0.362
S_{14}	0.061	0.060	0.117	0.117	0.230	0.415	S_{14}	0.056	0.064	0.098	0.102	0.310	0.371
S_{15}	0.062	0.062	0.092	0.120	0.237	0.427	S_{15}	0.057	0.065	0.100	0.080	0.317	0.380
S_{16}	0.064	0.064	0.067	0.123	0.244	0.438	S_{16}	0.059	0.067	0.102	0.058	0.325	0.389
S_{17}	0.066	0.065	0.042	0.127	0.250	0.450	S_{17}	0.060	0.069	0.105	0.036	0.332	0.398
S_{18}	0.068	0.067	0.017	0.130	0.257	0.462	S_{18}	0.061	0.070	0.107	0.015	0.340	0.407



(a) (b)

Figure 6: Results of using different criteria weights for the (a) N-direction and (b) S-direction.



(a) (b)

Figure 7: Results of sensitivity analysis with various approaches for determining criteria weights.

exception of SET11 and SET12 in which changes occur by four positions, which refer to ST4 which moves from the tenth position to the sixth. Taking into account the large changes in the significance of the criteria, it can be concluded that the changes in the ranks are not huge, which will be proven later through the calculation of the correlation of ranks.

In addition to creating dynamic matrices in which the values of the criteria weights change, this part of the sensitivity analysis shows a comparison of the ranks of the proposed model with CRITIC-MARCOS (CM), DEA-1-MARCOS, and DEA-2-MARCOS models and an approach with equal criteria weights, which is shown in Figure 7.

Figure 7(a) presents the ranks for the N-direction under different approaches to determine the weight values of the criteria. The first two best alternatives retain their positions regardless of the approach applied, while ST17 falls from the third position to the fourth using the DEA-1-MARCOS and DEA-2-MARCOS models, respectively. The biggest changes are related to the change of rank by two places compared to the initial results. When it comes to the S-direction, Figure 7(b), the results are similar, with three best-positioned alternatives retaining their places for all applied approaches. In addition, it can be concluded that the model is sensitive to the application of different approaches, but the results are highly correlated.

5.3. Comparison with Other MCDM Methods. In this section of the paper, a comparative analysis is performed with five other MCDM methods: ARAS—additive ratio assessment [29], MABAC—multiattributive border approximation area comparison [30, 31], SAW—simple additive weighting method [32], WASPAS—weighted aggregated sum product assessment [33, 34], and EDAS—evaluation based on distance from average solution [35]. Figure 8 shows the results of a comparative analysis for the N-direction, while Figure 9 shows a comparative analysis for the S-direction.

By applying the MABAC method, alternative ST11 takes the second position, while by applying all other methods, it represents the best solution. Essentially, the two best alternatives, ST11 and ST7, change their ranks with each other when calculating with the MABAC method. Alternative ST17 is in the third position using all MCDM methods. When it comes to the fourth and fifth position, the situation is the same as for the previously mentioned changes where ST10 and ST13 change their ranks with each other in the MABAC method. The biggest changes are in relation to the MABAC method, where one alternative can change its position by two ranks, while the application of other methods leads to a shift of rank by only one position in some cases.

A comparative analysis for the S-direction shows that the completely observed model has minor deviations in the ranks since, e.g., the first six positioned alternatives, ST17, ST7, ST14, ST10, ST8, and ST11, do not change their positions regardless of the applied method. When we observe individual rank deviations, there is a much different situation since there are deviations by three positions using the ARA method when the ST12 alternative moves from the seventh to the tenth position. An even more drastic change relates to the application of the MABAC method and the ST12 alternative when it changes its place by five positions and comes in the 12th place. Regarding other alternatives and methods, changes in rankings compared to the initial results are practically negligible.

5.4. Calculation of SCC and ST_{DEV} for All Parts of the Sensitivity Analysis. This part of the sensitivity analysis refers to the calculation of the Spearman correlation coefficient for all previously applied approaches as well as the calculation of the standard deviation shown in Figure 10.

Observing the results shown in green, it can be noticed that the largest deviation of 2.251 is for alternative ST12 which changes its position by three to five places, and it refers to a comparative analysis for the S-direction. Then, the fourth alternative ST4 shows the largest subsequent deviation in ranks of 0.753 which results in a change by one to two positions. Alternative ST13 has a deviation of 0.548 because it changes its position by one place in the calculation of three methods (MABAC, WASPAS, and EDAS). Alternatives ST1, ST6, and ST16 show a deviation of 0.516 because they change by one position in two cases. Alternative ST5 has a deviation of 0.408 because only by applying the EDAS method, it changes its rank by one position. All remaining alternatives have a standard deviation of zero, which means that they retain their ranks by applying all methods. When it comes to deviations for the N-direction, they are generally individually smaller because the largest standard deviation is 0.753 for ST1, ST4, and ST12, which means that there is a change of rank by two positions. Alternatives ST3, ST5, and ST16 have a ST_{DEV} of 0.516, which means a change of rank by one position. Other alternatives have deviations of 0.408 or zero. Observing the results obtained by applying different approaches to determine the weights of the criteria, larger deviations are noticed for both directions, in a range of 0–1.643 for S1 and 0–1.517 for N1.

Table 11 and Figures 11 and 12 show the Spearman and WS [36] correlation coefficient of all ranks obtained by different models and approaches through a whole sensitivity analysis.

When it comes to the ranks for a comparative analysis of the obtained results, the calculated SCC shows the following correlations: MARCOS and SAW methods have a complete correlation, SCC = 1.000 for both directions. For the N-direction, the MARCOS and WASPAS methods have an almost full correlation of 0.998 resulting from the change of alternatives ST1 and ST12 by one position. ARAS with WASPAS and EDAS for the N-direction and ARAS with WASPAS and MABAC with EDAS for the S-direction have the same correlation value. SAW and ARAS for the N-direction have SCC = 0.995. MARCOS with EDAS for the N-direction and MABAC with WASPAS for the S-direction have the correlation value of 0.993. ARAS and MABAC and WASPAS and EDAS for the S-direction have a correlation of 0.990. MABAC and WASPAS for the N-direction and ARAS and EDAS for the S-direction have SCC of 0.988. MARCOS

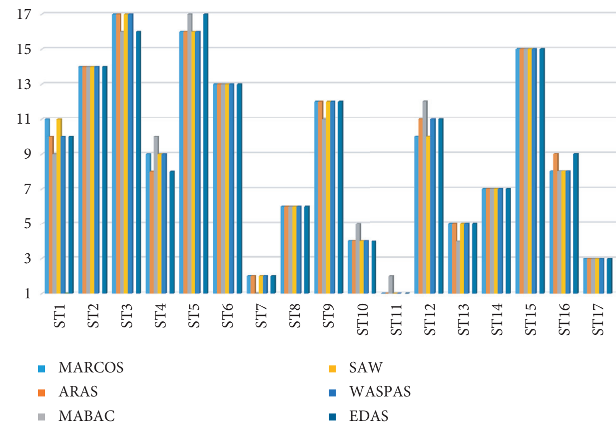


Figure 8: Comparison to other MCDM methods for the N-direction.

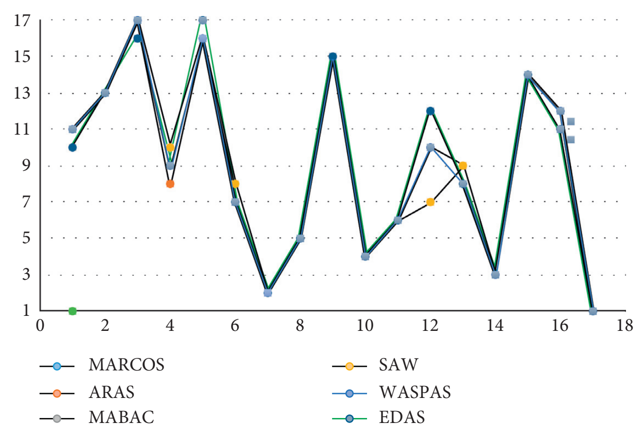


Figure 9: Comparison to other MCDM methods for the S-direction.

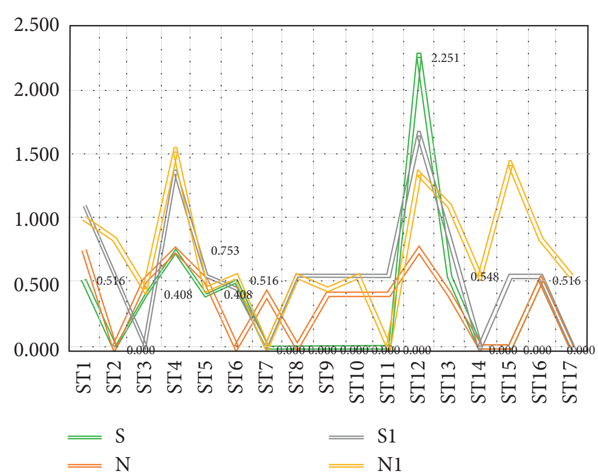


Figure 10: ST_{DEV} for results obtained using all approaches.

Table 11: SCC and WS coefficients for ranks obtained using various MCDM methods for ranking alternatives and determining criteria weights.

AV	N	MARCOS	ARAS	MABAC	SAW	WASPAS	EDAS	AV
0.986	MARCOS	1.000	0.985	0.980	1.000	0.998	0.993	0.993
1.000	ARAS	0.999	1.000	0.983	0.995	0.998	0.998	0.995
0.962	MABAC	0.944	0.943	1.000	0.980	0.988	0.985	0.988
0.986	SAW	1.000	0.999	0.944	1.000	0.998	0.993	0.997
0.986	WASPAS	1.000	0.999	0.944	1.000	1.000	0.955	0.978
0.999	EDAS	0.999	1.000	0.994	0.999	0.999	1.000	0.990
AV	S	MARCOS	ARAS	MABAC	SAW	WASPAS	EDAS	AV
1.000	MARCOS	1.000	0.983	0.963	1.000	0.985	0.961	0.982
1.000	ARAS	0.999	1.000	0.990	0.983	0.998	0.988	0.992
1.000	MABAC	0.999	1.000	1.000	0.963	0.993	0.998	0.988
0.999	SAW	1.000	0.998	0.999	1.000	0.985	0.961	0.982
1.000	WASPAS	0.999	1.000	1.000	0.999	1.000	0.990	0.995
1.000	EDAS	0.999	1.000	1.000	0.999	1.000	1.000	0.988
	N	MARCOS	CM	Equal weights	DEA-1-MARCOS		DEA-2-MARCOS	
SCC	MARCOS	1.000	0.966	0.973	0.988		0.980	
WS		1.000	0.999	0.999	0.998		0.998	
	S	MARCOS	CM	Equal weights	DEA-1-MARCOS		DEA-2-MARCOS	
SCC	MARCOS	1.000	0.978	0.792	0.848		0.855	
WS		1.000	0.997	0.997	1.000		0.999	

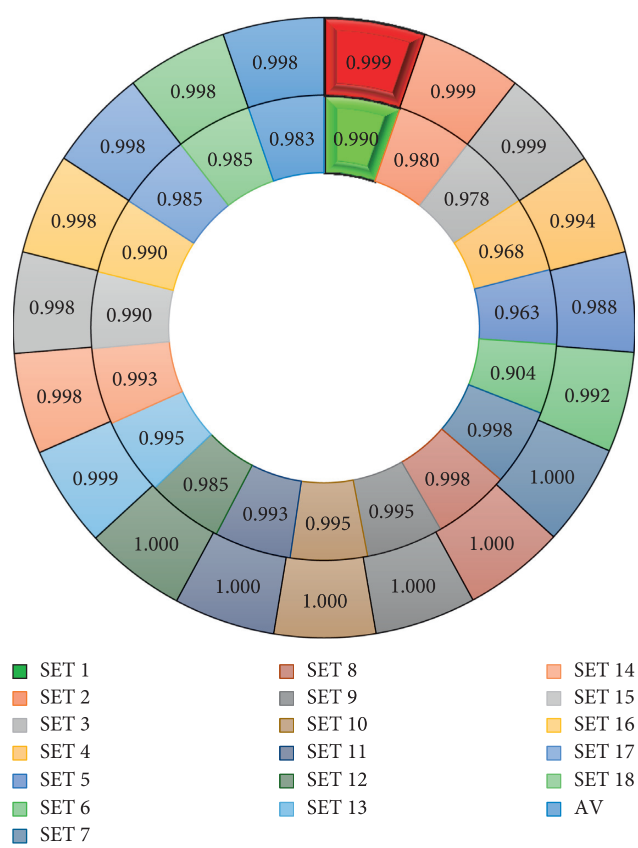


Figure 11: SCC and WS for ranks obtained with changing criteria weights for the N-direction.

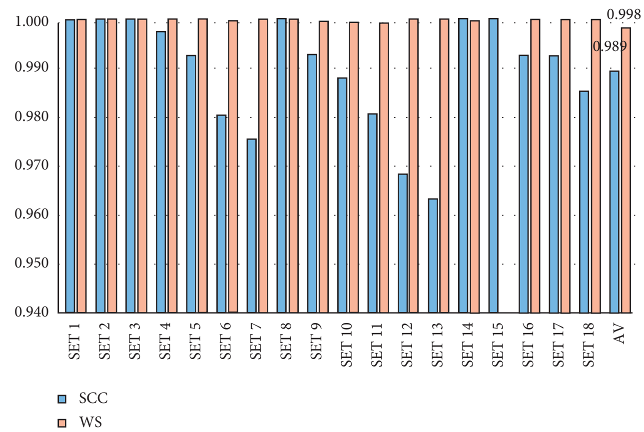


Figure 12: SCC and WS for ranks obtained with changing criteria weights for the S-direction.

has the lowest correlation with MABAC for both directions, 0.980 and 0.963, respectively. Since the SAW method has a full correlation with MARCOS, it means that it has the same correlation with other models as the MARCOS method does. Taking into account the values of SCC according to Subotić et al. [37] and Muravev and Mijić [38], it can be concluded that the ranks of all alternatives according to a comparative analysis are very high, i.e., almost completely correlated. After additional calculation of WS coefficient (marked with grey color), it can be concluded that ranks have extremely high correlation.

Comparing the correlation values of the MARCOS method with approaches in which the weight values of the criteria have been calculated, it can be noticed that there is an extremely high correlation which ranges from 0.966 to 0.988. MARCOS has the highest correlation with DEA-1-MARCOS with a value of 0.988, while with DEA-2-MARCOS, it has a slightly lower correlation with a value of 0.980. When calculating with equal criteria weights and inserting them in the MARCOS method, a correlation of 0.973 compared to the initial results is obtained. The results have the lowest correlation with comparisons by the CM model (0.966). These correlations refer to the N-direction, while for the S-direction, the correlation is quite lower and ranges from 0.848 to 0.978.

Figure 11 shows the SCC and WS values for the ranks through 18 different scenarios in which the changes of criteria weights for the N-direction were made. The average value of SCC is 0.983, which means an extremely high correlation. The average value of WS is 0.998, which means that ranks have almost full correlation. Although the model is sensitive to changes in the weights of the criteria and a change in ranks has been established based on the calculated SCC and WS, it can be concluded that changes in ranks are not large.

Figure 12 shows the SCC and WS values for the ranks through 18 different scenarios in which the changes of the criteria weights for the S-direction were made. The results show similarities with the N-direction since the average correlation value, in this case, is 0.989 for SCC and 0.998 for WS coefficient, which is a very high correlation.

6. Conclusion

Implementing the developed model, the following results are obtained: alternative A11, i.e., Van Schalkwyk Street, is the safest with a value of 0.794 for the N-direction. Volkspele Drive is the second in terms of safety, with Eric Rosendorf Street and Gardenia Avenue in the third and fourth place, respectively. Another alternative A13, i.e., Edeling Street, can be put into a group of safe streets comparing all alternatives. The group of most risky streets includes Wynand Mouton Drive, Paul Kruger Drive North, Benade Drive (N), Totius Street, and Paul Kruger Drive South whose values range from 0.341 to 0.421. As already mentioned in the paper, data were collected for both directions, and the evaluation was performed accordingly, so it is evident that there are differences in terms of safety for individual streets. When it comes to the S-direction, the group of the five safest streets includes the following, respectively: Eric Rosendorf Street, Volkspele Drive, Stals Road, Gardenia Avenue, and Pellissier Drive. The group of least safe streets for the S-direction includes Wynand Mouton Drive, Paul Kruger Drive North, Paul Kruger Drive (E), and Benade Drive (N). Three streets that belong to the group of safe ones regardless of the direction are Eric Rosendorf Street, third and first positions, Volkspele Drive,second position for both directions, and Gardenia Avenue, which is in the fourth place. In terms of the most risky streets for both directions, Wynand Mouton Drive is in the last place, Paul Kruger Drive North in the 16th place, Benade Drive (N) in the 15th and 14th place, respectively, and Totius Street in the 14th and 13th place, respectively.

In order to validate the proposed model and the results obtained by its application, an extensive sensitivity analysis was performed consisting of (a) a reverse rank matrix, (b) a change of criterion weight in a dynamic environment, (c) an evaluation of alternatives based on individually obtained values of criteria weights, (d) a comparative analysis of obtained results with five other MCDM methods, (e) calculation of Spearman correlation coefficient (SCC) for all ranks obtained by applying different approaches, and (f) calculation of standard deviation of ranks obtained by applying different approaches. The validation results show that taking into account the large changes in the significance of the criteria, it can be concluded that changes in the ranks are not large, which was proven through the SCC calculation. Using DEA-1-MARCOS, i.e., DEA-2-MARCOS, and CM models, it can be concluded that the model is sensitive to the application of different approaches, but the results are highly correlated. A comparative analysis also confirmed the validity of the results, as well as the calculated SCC for all approaches and the calculated standard deviation.

Based on the findings from the model in terms of the ranking of vulnerable streets, the streets can be prioritized to take up road geometry and traffic-related intervention measures which could include applying the control measures to restrict the speed, optimal assignment of traffic volume during the peak hours, limiting the number of access streets, and the number of lanes, as well as providing adequate median width.

The scope of the study was confined to the development of the model based on road and traffic-related parameters, and the human and driver behaviour or weather-related parameters were not considered. However, the integration of such parameters to make the model more inclusive and holistic is the future scope of this research. However, at the current state, the model can enable assessment of the vulnerable streets adequately and prioritize them based on which traffic safety measures can be taken.

Appendix

Determining Criteria Weights Using DEA-1 and DEA-2 Models

An example of obtaining the values of criteria for DMU17-N is as follows:

$$\begin{aligned}
\text{Max} = {} & 66 * w_1 + 5029 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5, \\
& (71 * w_1 + 4611 * w_2 + 6.2 * w_3 + 2 * w_4 + 8 * w_5) - (16 * w_6) <= 0, \\
& (76 * w_1 + 8908 * w_2 + 6.5 * w_3 + 2 * w_4 + 8 * w_5) - (25 * w_6) <= 0, \\
& (79 * w_1 + 9938 * w_2 + 6.1 * w_3 + 1 * w_4 + 9 * w_5) - (32 * w_6) <= 0, \\
& (77 * w_1 + 8888 * w_2 + 6 * w_3 + 2 * w_4 + 8 * w_5) - (13 * w_6) <= 0, \\
& (72 * w_1 + 9285 * w_2 + 7.5 * w_3 + 2 * w_4 + 15 * w_5) - (32 * w_6) <= 0, \\
& (75 * w_1 + 7409 * w_2 + 7 * w_3 + 2 * w_4 + 11 * w_5) - (21 * w_6) <= 0, \\
& (58 * w_1 + 6040 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5) - (8 * w_6) <= 0, \\
& (71 * w_1 + 5888 * w_2 + 7.5 * w_3 + 2 * w_4 + 4 * w_5) - (12 * w_6) <= 0, \\
& (73 * w_1 + 10055 * w_2 + 6.7 * w_3 + 2 * w_4 + 7 * w_5) - (22 * w_6) <= 0, \\
& (74 * w_1 + 5444 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5) - (9 * w_6) <= 0; \\
& (67 * w_1 + 3227 * w_2 + 4.3 * w_3 + 2 * w_4 + 4 * w_5) - (7 * w_6) <= 0, \\
& (81 * w_1 + 10016 * w_2 + 12 * w_3 + 3 * w_4 + 8 * w_5) - (33 * w_6) <= 0, \\
& (65 * w_1 + 7434 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5) - (9 * w_6) <= 0, \\
& (67 * w_1 + 7267 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5) - (11 * w_6) <= 0, \\
& (75 * w_1 + 8693 * w_2 + 9 * w_3 + 2 * w_4 + 11 * w_5) - (28 * w_6) <= 0, \\
& (70 * w_1 + 7047 * w_2 + 7.5 * w_3 + 2 * w_4 + 7 * w_5) - (16 * w_6) <= 0, \\
& (66 * w_1 + 5029 * w_2 + 6 * w_3 + 2 * w_4 + 4 * w_5) - (9 * w_6) <= 0, \\
& 9 * w_6 = 1, \\
& w_1 >= 0, w_2 >= 0, w_3 >= 0, w_4 >= 0, w_5 >= 0, w_6 >= 0.
\end{aligned} \tag{A.1}$$

Data Availability

The data used to support the findings of this study are included within this article. However, the reader may contact the corresponding author for more details on the data.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

If There Appears a Path to Improve Chinese Logistics Industry Efficiency in Low-Carbon Perspective? A Qualitative Comparative Analysis of Provincial Data

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Taking the data of 30 Chinese provinces as a sample in which CO_2 emission is denoted by undesirable output, this paper calculated the efficiencies of the logistics industry by applying the Data Envelopment Analysis (DEA) method and analyzed the factors that affect logistics industry efficiency by applying the Qualitative Comparative Analysis (QCA) method based on configuration thinking. It is found that the efficiency of China's low-carbon logistics industry has presented an increasing trend and the efficiency gaps among the regions have been enlarged in the last 10 years. Two highly efficient paths have been formed in the three years after 2015. The path of management opening type has a high coverage ratio; logistics management level and operation are the core factors that improve logistics efficiency. The path of economy driving type covers few cases and it mainly relies on relative priority to influence and drive the development of regional logistics.

1. Introduction

As a basic and strategic industry for the economic development of a country or region, the efficiency of the logistics industry not only directly affects the economic situation of a country or region at the macrolevel but also has great significance for the stability and smoothness of the enterprise supply chain and the improvement of the overall competitiveness at the microlevel. At the same time, the logistics industry has strong dependence on energy. With the rapid development of the logistics industry, its total energy consumption is unceasingly rising, followed by the increase of carbon emissions [1]. It has become a necessary trend for the sustainable development of China's logistics industry to develop healthy, efficient, and low-carbon logistics. However, China's logistics industry management is practiced generally in an extensive mode and the application of advanced management and technology is insufficient in the promotion of logistics efficiency, which caused a huge disadvantageous influence on resources and environment. In recent years, the Chinese government has issued a series of policies and documents to promote the development of logistics industry, which plays a vital part in guiding the development of logistics industry in the whole country and every provincial region. In response to the demand raised by the country, every region actively accelerates the development of the logistics industry, which says "accelerate the development of modern logistics industry, promote the adjustment of industrial structure, reduce the cost, and improve logistics efficiency." It is a noteworthy subject to examine and view the integral operation efficiency of logistics in the low-carbon perspective.

Increasing efficiency is one of the principal questions studied in economics and management research. The increase of social-economic efficiency depends on the increase of enterprises' efficiency. Nevertheless, all the enterprises stay in the outside environment and their operations are necessarily influenced by the other environmental conditions, so the efficiency of the logistics industry is necessarily influenced by the operation and management level and regional environmental factors together. There has already been quite a good deal of literature that selected and evaluated the influence of environmental factors on logistics efficiency, but there is a lack of attention paid to estimating the logistics industry's management level. Meanwhile, for analyzing the effect of environmental factors, the traditional statistic methods usually were applied and based on the atomic perspective and focused on analyzing the unique "net effect" of a single variable [2].

However, most causes and conditions of the occurrence of social phenomenon are not dependent on each other and the independent variables produce multicollinearity because of interrelated relationships, which show that the unique effect of a single variable could be covered by the correlated variable. Though the test on multicollinearity is performed before the analysis of model or the analysis of model is performed with the method of adjusting variables, it is hard to explain three and more cross variables. Therefore, as for explaining the occurrence of social phenomenon, it is preferable to take on an integral and assembled method; especially, for the multiple concurrence property of antecedent, it is suitable to seek a corresponding path in configuration view [3].

This research selected the logistics data with a provincial level of 30 provinces in China during a decade to search and observe whether the low-carbon logistics efficiency with provincial level is increased and the corresponding paths are formed. This paper has two contributions: (1) this is innovatively the first time to bring the management and operation level of logistics enterprise into the analysis of the influence of logistics industry efficiency on the basis of the calculation of low-carbon logistics efficiency of different regions; that is to say, the total amount of the regional A-class logistics enterprise is used to measure the management and operation level of the logistics industry; (2) it is creatively used in configuration views with the method of Qualitative Comparative Analysis (QCA), which is more suitable to explain social phenomenon. The empirical analysis is conducted for exploring the specific paths to improve Chinese logistics industry efficiency in a low-carbon view.

This paper is organized as follows: Section 1 presents the introduction. Section 2 sums up the relative literature. Section 3 presents the study design. Section 4 presents data and variable selection. Section 5 presents statistics results. Section 6 analyzes research results. The final section is about conclusions and implications.

2. Literature Summary

2.1. The Method of Logistics Industry Efficiency Research. Research of logistics industry always is a hot spot to which the scholars pay attention. The representative research methods just are parametric method and nonparametric method; here, the former is Stochastic Frontier Analysis (SFA), and the latter is Data Envelopment Analysis (DEA) [4, 5]. SFA can distinguish the effect of technical inefficiency factors and statistics error on efficiency, and yet it needs to set a specific function form just for individual output variables and put forward higher requirements for the distribution characteristics of error terms. The DEA model does not need to consider the form of production function and is able to consider multiple output indexes, so it is extensively used in every field. For instance, Min and Joo [6] analyzed the third-part logistics operation efficiency with the DEA method. Hamdan and Rogers [7] calculated the efficiency of 19 American warehouses. Anthony et al. [8] think that DEA is a nonstatistical method methodology that is used to measure performance in a relative manner and each producer unit or decision-maker is compared to the best unit in that industry. And through the method of DEA, there is no need for a definite form of production function as it is in the economy, and this technique can be used with minimal data.

For the influence factors of efficiency, Blagojević et al. [9] studied the efficiency evaluation of railway enterprises by using the DEA method, which included resources, operation, finance, quality, and safety into the evaluation criteria. Fried et al. [10] think that the three factors of ineffectiveness, which are management, environment variables, and random noise, can influence the DEA model to analyze decision unit efficiency, but there is always a lack of better index to measure the management factors directly. In addition, because there may be relativity among the factors and the convergence speed of efficiency values obtained though calculation is lower, there is obviously a lack of means for conducting the 2-stage DEA analysis [11]. The method of the 3-stage DEA builds a linear regress model with slack variable to explained variable to eliminate the influence of environmental factors and random interference. Though it is thought and more accurate efficiency can be obtained, the relativity among variables cannot be obtained as usual; moreover, the obtained efficiency value is only used in comparison and evaluation and cannot be measured in contrast to specific management index [12]. Hassanpour [13] thinks that DEA is a prominent procedure in the decision-making process with a pivotal role in the Sustainable Development (SD) assay and Environmental Impact Assessment (EIA) is the first step of SD assay.

2.2. Low-Carbon Logistics Industry Efficiency Research. With the conspicuously negative influence of the logistics industry on environment, the scholars begin to bring energy consumption and carbon emission into the evaluation system of logistics industry efficiency [14]. For example, Rogers and Weber [15] measured the energy efficiency of the load-carrying transport industry by taking energy consumption, labor investment, and highway mileage as input indexes, taking the added value of the load-carrying transport industry as desirable output, and taking CO_2 emission and total traffic deaths as undesirable output. Yao et al. [16] in one belt, one road, selected the data from provinces from 2010 to 2015. Using the three-stage DEA and Malmquist models, the carbon dioxide emissions from undesirable outputs were taken as input variables, and the efficiency of the logistics industry in the provinces along the route was measured from static and dynamic.

Tang and Lu [17] used the 3-stage DEA model to comprehensively measure and evaluate the logistics industry efficiency of the ten provinces and municipalities in East China. As a kind of undesirable output, CO_2 emission is analyzed as input indexes. Taking the bad output indexes as input variables to deal with is a common method in calculating efficiency, which is expected to be as little as possible [18].

2.3. The Empirical Research on Chinese Logistics Industry Efficiency. Chinese scholars have conducted a great deal of empirical researches on logistics industry efficiency and low-carbon logistics efficiency. They analyzed the annual data and panel data for concrete enterprises or provincial regions. In the research of the provincial regions, the influence of many specific elements shows different results. Just like the understanding of economic environment and the degree of opening to the outside world, in theory, it is generally deemed that they should positively increase logistics efficiency, so that some authors empirically obtained the positive effect of the level of economic development on logistics efficiency [19, 20]. In contrast, the results showed that there was no direct positive correlation between the level of economic development and regional logistics industry efficiency [21, 22]. Although others drew the conclusion that there is positive influence between the degree of opening to the outside world and logistics efficiency [23, 24], the conclusion is that the degree of opening to the outside world cannot positively influence logistics efficiency [22, 25]. Deng et al. [26] considered carbon emissions, used the DEA method to measure and evaluate the logistics performance of 30 provinces and cities in China, and analyzed the characteristics of the efficiency of China's logistics industry on the overall level and space.

To a certain extent, it is closely related to data selection, variable choice, and research method to analyze the reason why divergence exists in the understanding of influence factor in the above literature about logistics efficiency. Firstly, logistics data itself leads to the instability of conclusion. In recent years, the development of logistics has been in a high-speed and fluctuating state. There was a quite big difference among different years and different regions, which did not form an identical regularity. Secondly, due to the availability of data, the support of selected variables was finite, or the key variables were omitted. For instance, the higher management level necessarily promoted the increase of logistics efficiency, but the degree of management level is not easily measured and compared, so the influence of this important index was not considered in the literature. Thirdly, when the 2-stage DEA or 3-stage DEA is applied, for all of them, the traditional statistics method should be used to set up a regress model, which still focuses on the analysis of the unique "net effect" of a single variable [2]; however, it does not apply the configuration method which is more suitable for the study of social phenomena, accepting the interaction between variables rather than being independent of each other.

Therefore, it is a new perspective to research development of the Chinese logistics industry to pay attention to the operation and management level of logistics enterprise, which analyzes the combined actions of regional environment factors on low-carbon efficiency with the configuration method and explores if the effective path to increase logistics industry efficiency was formed during the process of the development of Chinese logistics in recent years.

3. Research Design

This section introduces the research and designs ideas of this paper. Firstly, based on certain data collection, this paper uses the method of DEA. In this method, CO_2 emission is regarded as the unexpected output to calculate the efficiency of low-carbon logistics. Then, based on the perspective of configuration analysis, the low-carbon logistics is analyzed. Efficiency is the explained variable, and management level, economic environment, openness, government regulation, and technological innovation are the five variables. In order to improve the efficiency of China's logistics industry, the QCA method is used to analyze the influence between explanatory variables and explained variables.

3.1. The Evaluation Method of Efficiency for the Low-Carbon Logistics Industry. For the conditions of each China's province of either the input or the output, the efficiency in the low carbon of the logistics industry should be firstly evaluated with DEA. DEA was used to evaluate the relative effectiveness of the operations' performance with the principle of "more investment, more output" for an organization or an object (decision unit DMU) [27]. Zhou and Ang [28] further proposed DEA's efficiency evaluation model that includes an undesirable output. In this paper, we choose the input-oriented BCC model and use CO_2 as an undesirable output to evaluate the efficiency of China's provincial low-carbon logistics industry.

3.2. The Path Analysis Method for Efficiency Improvement of Low-Carbon Logistics Industry. The traditional statistics methods (including regress analysis, typical correlation analysis, discrimination analysis, and cluster analysis) are not good for revealing the complexity of variable relationship and multiple and concurrent relationships of cause and effect among various antecedents, and each factor is considered as the antecedent of result in these methods. Instead, this research explores the specific path of increasing efficiency of the low-carbon logistics industry using the method of QCA, which is good at explaining the social phenomenon. QCA is initiated by an American sociologist, Ragin, in the 1980s, a "case-oriented" method for qualitative and quantitative cross-case comparison of causal complexity phenomena using Boolean algebra and set theory [3]. QCA consists of the crisp set QCA (csQCA) and fuzzy set QCA (fsQCA), where csQCA is a special case of fsQCA. This research uses fsQCA, which is extensively used in the literature for analyzing data.

Configuration and asymmetry are two characteristics of QCA. Based on the universal "multiple conjunctural causation" in the social phenomenon that roots in configuration thought of and with the holistic perspective method, QCA holds that organization is best understood as an interconnected structure and practical colony rather than the solid which is divided into units or slackly assembled together, so organization cannot be understood in the way of analyzing solitarily component parts [3]. After determining the specific results and conditions for explanation, the logical relationship between result and condition can be identified through cross-case comparison. Consequently, the condition combinations that lead to results can be simplified.

In general, this combination is not unique, and the multiple combinations are equivalent to each other. Every combination can be reviewed as a specific path. Therefore, different routes lead to the same destination. This implies that it can be explained that different cases may result in the same results. In addition, the corresponding condition or condition combination should be pointed out if they can be constituted as the “necessary” or “sufficient” condition.

The other characteristic of QCA is asymmetry. This can be expressed as “happy families are all alike and every unhappy family is in its own way,” and the reasons of success or failure are different. The cause-and-effect asymmetry softens the assumption of unity on causality effect in the linear regress, which can better explain the difference among cases, and the independent confuguration effect between conditions [3].

4. Selection of Data and Variables

4.1. Data Selection. The data used in this paper as observation samples are from the *China Statistical Yearbook* and the *China Energy Statistical Yea*rbook for thirty provinces, municipalities, and autonomous regions, from 2008 to 2017. Following Zhang et al. [29], we select data for industries of transportation, warehouse, and postal, as representatives of the development level of China’s logistics industry.

4.2. Variable Selection. The explained variable is the efficiency of the low-carbon logistics industry. For input-output, the efficiency of the logistics industry is defined as the ratio of the investment of economic elements in logistics activities to actual output [20]; in addition to the two indexes of logistics added value and the amount of freight turnover, CO_2 emission should be measured [22], calculated, and then used as the undesirable output. To calculate the efficiency, the output index should be disposed, which is expected to be as little as possible [18].

The explanatory variable represents the main factors that influence the efficiency of the regional low-carbon logistics industry. Factors that influence the efficiency of enterprises in the logistics industry depend on an enterprise’s inner management, including organization structure, business process, employee quality, and corporation culture, and the factors outside an enterprise, such as politics, economy, social culture, and technology (PEST). They mutually influence and restrain. The content of political economy, social culture, and technology is broad. For better measurement, the government’s rules and regulations, area economy, degree of opening, and scientific and technological innovation are used to reflect the content of PEST for a certain degree.

Concerning the different research emphasis of the existing literature, generally, four or five main influence factors are taken into consideration. To a different degree, the environmental factors appear in the existing research such as development level of regional economy, utilization ratio of logistics resource, marketization degree, informatization level, institutional factors, location factors, industrial structure, agglomeration degree of the logistics industry, degree of opening to the outside world, government’s support, and scientific and technological innovation. And yet, as for the management factors, there is a lack of analysis. This research adds the influence of management factors and brings the level of operation and management of logistics enterprise into the explanatory variables and at the same time considers the four factors of regional government’s rules and regulations, area economic environment, opening degree, and scientific and technological innovation. The five explained variables comparatively conform with the demand of the QCA method. Because QCA considers all possible combinations of explanatory conditions, the number of combinations increases exponentially with the addition of conditions by a factor of $2k$ (k = number of conditions). So, adding a variable will easily cause the result that the configuration exceeds the observed case in number; thus, the finite diversification of case emerges, and the ideal number is from 4 to 8 [2].

The input-output indexes and the description of all explanatory variables are shown in Table 1.

4.2.1. Investment Index. Labor investment is reflected by the gross payroll of an employee of the logistics industry in different regions. The fixed assets investment of the logistics industry in different regions is the basal data of capital investment. The capital stock is estimated with the perpetual inventory method. The depreciation fund is calculated by 10% [21]. Regarding the year of 2008 as the base period, the fixed assets stock in the base period is calculated by Goto and Suzuki’s method [30]. To eliminate the interference of price factors, capital stock is calculated by applying fixed assets investment indexes to deflate fixed assets investment.

4.2.2. Output Index. To eliminate the interference of price, all the added value of different regions in different years is deflated by the GDP deflation indexes of different regions regarding the year 2008 as the base period. The turnover volume of freight transport can better reflex the actual logistics situation; therefore, we choose the turnover volume of freight transport as an output index. For energy consumption output, the carbon emission of the logistics industry is taken as measure index; that is to say, according to the CO_2 emission coefficient of the corresponding energy published in ICPP of the UN, we calculate the main energy

Table 1: Model variable and description.

Variables		Description		Unit
Explained variable	Logistics industry total efficiency (TE): considering input and output, it is calculated by the DEA method	Input index	Labor (L): salary of employee of logistics	100 million
			Capital (K): fund stock of logistics	100 million
		Output index	Added value (Add)	100 million
			Freight turnover (turn)	Ton/kilometer
			Carbon emission	—
Explanatory variable	Operation and management level (5A)		The total amount of A-class logistics enterprise of different regions	Piece
	Economic environment (GDP)		Regional GDP (price deflated value)	100 million
	Opening degree (open)		The ratio of the total amount of imports and exports to GDP	—
	Regulations and rules (Regu)		Investment of environmental pollution treatment in every region	100 million
	Scientific and technological innovation (R&D)		R&D investment of different regions	100 million

consumption of the logistics industry in the different regions and sum up the CO_2 emission.

4.2.3. Explanatory Variable. The first explanatory variable is operation and management level. Comprehensive evaluation and certification of A-class logistics enterprise are carried out according to *the Classification and Evaluation Index for Logistics Enterprise*, which sets five classes from A to 5A and includes 16 to 18 items of index, involving 6 dimensions of enterprise operation situation, asset situation, service and management, employee quality, the informatization level, and so on. Therefore, to a certain extent, the total amount of the A-class enterprise of different regions reflects the strength and the operation and management level of the mentioned above logistics enterprise. This kind of certification is organized by the China Federation of Logistics and Purchasing. Except in the year of 2012, it was just only organized once; in the other years, it is organized once every six months at the beginning of a year and at the end of a year. The amount of the enterprises that passed certification at the beginning of a year was counted in the total number of A-class enterprises of the previous year, and the amount of the enterprises that passed certification in the second half of a year was counted in the total number of A-class enterprises of this year.

The other explanatory variables are environmental factors. The development of area economy can effectively promote the development of the logistics industry. The GDP of different regions represents the regional economic environment. The variables can comprehensively reflect the overall level of economic development in a region. To eliminate the interference of price, the price index of different regions is used to deflate it, and its unit is 100 million Yuan. The degree of opening is reflected by the ratio of the total export-import volume to GDP. The government's regulations and rules are characterized by investment of environmental pollution treatment from the view of environmental pollution treatment. The regional R&D fund index is chosen to reflect the level of scientific and technological innovation.

5. Statistics Result

This section will be divided into three parts to describe the statistical results. First, we make a statistical description of the collected data. To understand the characteristics of each variable. Then, based on the existing data, the DEA method is used to calculate the efficiency of the low-carbon logistics industry. Finally, the QCA method is used to analyze the configuration of explanatory variables and explained variables.

5.1. Descriptive Statistics. All the following statistical analysis is conducted annually. For the input-output indexes and the factors that influence logistics efficiency, we first conduct a descriptive statistical analysis year by year to understand the characters of variables. The result is shown in Tables 2 and 3.

Over ten years, the labor investment of the logistics industry increased by 175.60%, and capital investment increased by 227.65%. In the aspect of output, the added value of the logistics industry increased by 100.31%, and the volume of freight turnover increased by 152.89%. During the ten years, the carbon emission increased by 50.20% on average and assumed a trend of overall fluctuation amplitude diminution and overall decline. The average increase of the years of 2010 and 2011 is above 8% but it decreased to a certain extent in 2013. After 2014, the increase ratio is about 4%–6%, and it may be related to the technological progress and the continuous effects of China's energy-saving and emission reduction policies.

The increase of A-class logistics enterprises in number shows that the logistics enterprises attach great importance to management and improve their operation level, which plays a vital role in increasing the overall development of the logistics industry. But from the fact that in 2017 the maximum is 591 and the minimum is only 16, we can see the

Table 2: Descriptive statistics of logistics industry input and output in China from 2008 to 2017.

Variable		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Labor investment	Mean	66.77	74.95	82.59	94.76	105.94	141.21	155.68	166.39	172.66	184.02
	Std dev	48.79	55.85	62.84	73.90	77.67	100.50	115.63	122.69	126.12	135.05
	Min	8.31	9.53	9.91	11.53	15.68	18.64	19.10	19.74	20.23	21.61
	Max	212.18	246.96	272.36	314.76	344.39	454.46	541.41	576.72	575.70	626.25
Capital investment	Mean	2500.12	2936.80	3453.53	3851.60	4297.92	4860.36	5543.16	6363.75	7257.56	8191.60
	Std dev	2369.01	2322.24	2345.33	2369.98	2459.91	2678.08	2934.04	3238.70	3574.19	4053.53
	Min	275.88	338.16	420.08	472.07	524.26	607.40	736.12	896.70	1137.47	1303.84
	Max	12689.56	12201.66	12059.83	11704.68	11525.87	11839.37	12336.75	13411.82	14856.21	16951.35
Carbon emission	Mean	434.19	460.79	500.35	541.52	578.06	545.35	579.56	604.44	636.37	652.09
	Std dev	299.54	315.05	335.88	355.69	377.91	306.19	318.49	331.38	369.20	389.13
	Min	51.32	57.19	63.92	68.42	69.53	72.75	77.63	84.76	97.40	103.28
	Max	1245.51	1317.52	1444.30	1541.65	1718.77	1490.06	1559.13	1624.51	1814.82	1847.16
Added value of logistics industry	Mean	571.22	611.73	675.51	730.45	808.85	879.35	927.51	1001.72	1052.85	1144.22
	Std dev	422.39	440.87	494.65	550.43	605.13	660.69	652.18	698.87	728.09	804.58
	Min	40.72	48.29	55.37	56.01	59.03	60.88	66.74	76.27	81.19	93.20
	Max	1873.58	1791.99	1970.05	2228.63	2397.61	2622.93	2474.68	2659.78	2821.83	3185.55
Freight turnover volume	Mean	2500.10	3701.67	4349.08	4951.01	5285.28	4873.82	5494.66	5218.03	5558.58	6322.44
	Std dev	3234.36	3363.54	4070.71	4452.12	4477.61	3972.49	4739.53	4640.51	5267.77	6516.76
	Min	335.66	364.16	419.68	486.38	527.62	451.95	506.94	445.58	475.80	519.46
	Max	16029.84	14372.56	18918.15	20309.56	20373.37	14332.71	18633.36	19495.88	21801.65	27919.79

Table 3: Descriptive statistics of logistics industry efficiency explanatory variables from 2008 to 2017.

Variable		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Management level (5A)	Mean	14.37	24.67	35.07	42.83	59.27	76.07	93.07	108.00	127.47	151.90
	Std dev	16.79	27.43	38.10	46.25	64.71	79.75	95.38	110.52	130.39	156.73
	Min	0.00	2.00	3.00	6.00	10.00	10.00	12.00	13.00	14.00	16.00
	Max	62.00	101.00	153.00	191.00	268.00	325.00	378.00	435.00	506.00	591.00
Economic environment (GDP)	Mean	10894.13	12163.55	13758.40	15378.69	16957.23	18558.66	20089.41	21656.03	23240.75	24920.95
	Std dev	8652.10	9582.53	10748.84	11832.36	12868.62	14001.82	15147.13	16367.12	17595.76	19234.03
	Min	961.53	1058.64	1220.62	1385.40	1555.14	1723.10	1881.62	2035.92	2198.79	2359.30
	Max	35696.50	39159.00	44014.70	48416.20	52364.80	56815.80	61226.80	66122.20	71083.70	76445.81
Opening to the outside world (Open)	Mean	0.24	0.22	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.05
	Std dev	0.25	0.24	0.04	0.05	0.06	0.06	0.06	0.06	0.05	0.07
	Min	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Max	1.05	1.02	0.18	0.20	0.22	0.23	0.24	0.21	0.18	0.26
Regulations and rules (Regu)	Mean	316.96	305.91	285.43	303.56	298.55	264.10	221.74	208.93	138.14	126.34
	Std dev	221.43	210.97	197.35	203.11	196.31	181.22	157.20	251.79	97.04	119.37
	Min	41.10	30.30	22.20	21.10	26.60	24.10	26.20	17.00	12.30	12.70
	Max	948.80	780.80	952.50	880.60	881.00	739.10	623.90	1416.20	459.50	519.70
Scientific and technological innovation (R&D)	Mean	89.38	107.03	147.36	199.82	240.04	277.26	308.88	333.89	365.18	400.42
	Std dev	110.09	127.79	175.13	241.20	289.72	333.30	371.98	409.73	451.37	509.41
	Min	0.63	1.44	4.75	5.78	7.81	8.95	9.25	6.50	7.79	7.48
	Max	410.96	500.07	719.96	899.89	1080.31	1239.57	1376.54	1520.55	1676.27	1865.03

greater difference among regions. In terms of the external environment, the national economy has developed at a high speed. After the year of 2009, the average value of the degree of opening to the outside world varied slightly, but by comparing the maximum with the minimum, the difference among the regions can be obviously seen. As for the government's rules and regulations, the average investment of environmental pollution treatment shows a trend of decline, and the level of scientific and technological innovation shows an increase in fluctuation.

5.2. Calculation of Low-Carbon Logistics Industry Efficiency. By using Deap2.1, the low-carbon logistics industry efficiency of 30 provinces, municipalities, and autonomous regions from 2008 to 2017 was calculated year by year. Table 4 shows the annual average efficiency of the low-carbon logistics industry in East, Central, and West China.

From Table 4, the national comprehensive efficiency was lower from 2008 to 2017. The average values are between 0.580 and 0.652, pure technical efficiency is between 0.689 and 0.751, and scale efficiency is between 0.844 and 0.905. The pure technical efficiency is lower than the mean of scale efficiency, but the increasing trend is clearer than that of the mean of pure technical efficiency; therefore, the increase of mean of pure technical efficiency contributed relatively more to the efficiency of low-carbon logistics. Concerning regions, the comprehensive efficiency of East China is higher than that of Central China, and that of Central China is higher than that of West China. The low-carbon efficiency of East China assumes an increasing trend in general and the efficiency of West China fluctuates and shows a declining trend in recent years, which bears relation to higher investment of fixed assets. Statistics of the ten years between 2008 and 2017 show that the average growth ratio of fixed assets investment of the logistics industry in East China, Central China, and West China, respectively, is 13.6%, 17.3%, and 23.8%. West China is a strategically important area for China's development in the future. Increasing the economic level not only is a question to cover the gap but also is the security for China's advance to become an economic powerhouse [24]. Therefore, the construction and upgrade of base facilities of this area still need to be enforced unceasingly in order to recover its hub function of traffic and transport in the connection of Eurasian Land Bridge.

5.3. Efficiency Configuration of the Low-Carbon Logistics Industry. Combining the above calculated provincial comprehensive efficiency with the five explanatory variables, this research conducted a specific analysis by using fsQCA as follows.

5.3.1. Calibration. In the fsQCA method, it needs to determine the fuzzy set, which is different from the routine variables and must be calibrated, namely, to assign a value to the set as the membership degree [3]. For calibration, combining theory with practical knowledge or standards, three thresholds for full membership, full nonmembership, and the crossover point need to be set. Then every variable is converted to a degree of set membership between 0 and 1. This research sets three anchor points of the five explanatory variables and high efficiency of the logistics industry, respectively, as upper quartile, average of upper quartile and lower quartile, and lower quartile in the sample data sequence [31]. The calibration principle of the nonhigh efficiency is the opposite of high efficiency. After the anchor points have been set, all variables will be calibrated with the calibration function in the software fsQCA 3.0.

5.3.2. Results. Firstly, an analysis of necessary condition is performed, which is to test if the single condition (nonstable included) could become the necessary condition of high efficiency. It depends on the consistency value of the result, when the value is above 0.9, just like the coefficient significance of regress analysis, the variables can be thought of as the necessary condition of the explained results. Through the software fsQCA 3.0 to test the data from 2008 to 2017 year by year for the necessary condition of operation, it has been obtained that all the values of consistency between single variables and the explained variables are less than 0.9, which means the data does not constitute necessary condition. And this demonstrates that all the explanatory forces of single antecedents for high (or nonhigh) efficiency are weaker, so these antecedents need to bring into fsQCA for configuration.

According to the commonly used setting method, the frequency threshold is set to 1, the consistency threshold is set to 0.8, and the proportional reduction in inconsistency (PRI) is set to 0.70 [32]. The fsQCA analysis is conducted on the data from 2008 to 2017 year by year. The numbers of high-efficiency cases, nonefficient cases, and the overall coverage (OCV) are shown in Table 5.

As can be seen in Table 5, from 2008 to 2014, the number of high-efficiency cases is relatively small, and the coverage (CV) is between 0 and 0.38. Among them, the five-year average from 2008 to 2012 is less than 0.2, so path analysis is of little significance. However, in the past three years (i.e., 2015–2017), the number of high-efficiency cases has increased significantly, with more than 9 high-efficiency cases in the three years, and the configuration coverage (CV) is 0.580, 0.578, and 0.552, all above 0.550. Therefore, the following is a specific analysis of the path of 2015–2017.

The fsQCA can produce three results: complex solution, parsimonious solution, and intermediate solution. It is generally considered that the intermediate solution can best reflect the research results, and if the antecedent condition appears in both the parsimonious solution and the intermediate solution, it is the core condition; if only the intermediate solution appears, it is considered the peripheral condition [3].

If the presence or absence of the five conditional variables may improve the efficiency of the logistics industry, the operation of fsQCA software can obtain the configuration (path) with high efficiency and nonhigh efficiency, as well as the consistency (CS), overall solution consistency (OCS), and overall solution coverage (OCV). The high-efficiency configuration of 2015–2017 is shown in Table 6.

Taking 2017 as a sample, three high-efficiency configurations (showed in Table 6) were obtained through running the software fs/QCA, which consistency are, respectively, 0.851, 0.872, and 0.901. It indicates that all the three

Table 4: Regional comprehensive and average efficiency from the perspective of low carbon in 2008–2017.

Annual efficiency value	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
Eastern comprehensive efficiency	0.623	0.664	0.718	0.738	0.753	0.689	0.718	0.760	0.777	0.795	0.724
Central comprehensive efficiency	0.631	0.632	0.631	0.621	0.659	0.661	0.691	0.700	0.718	0.740	0.668
Western comprehensive efficiency	0.486	0.525	0.512	0.503	0.522	0.509	0.463	0.468	0.455	0.416	0.486
Mean of combined efficiency	0.580	0.608	0.623	0.625	0.648	0.621	0.625	0.645	0.652	0.652	0.628
Mean of pure technical efficiency	0.692	0.689	0.693	0.692	0.719	0.706	0.718	0.737	0.751	0.751	0.715
Mean of scale efficiency	0.844	0.888	0.902	0.905	0.902	0.887	0.879	0.879	0.869	0.864	0.882

Table 5: Analysis results of cases using fsQCA in 2008–2017.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Number of high-efficiency cases	3	1	2	2	1	3	4	9	10	10
Overall coverage (OCV)	0.172	0.113	0.195	0.153	0.176	0.214	0.379	0.580	0.578	0.552
Number of nonhigh-efficiency cases	5	1	7	5	11	6	5	6	9	9
Overall coverage (OCV)	0.372	0.145	0.342	0.272	0.480	0.342	0.255	0.374	0.605	0.517

Table 6: High-efficiency configuration of the regional logistics industry in 2015–2017.

Configuration	Solution							
	2015		2016			2017		
	1	2	1a	1b	2	1a	1b	2
Management level (5A)	●	⊗	●	●	⊗	●	●	⊗
Economic environment (GDP)	●	●	●	⊗	●	●	⊗	●
Opening to the outside world (open)	●	⊗	●	⊗	⊗	●	⊗	⊗
Regulations and rules (Regu)		●		●	●		●	●
Scientific and technological innovation (R&D)	●	●	●	⊗	●	●	⊗	●
Consistency	0.907	0.899	0.926	0.844	0.905	0.851	0.872	0.901
Raw coverage	0.475	0.180	0.435	0.071	0.160	0.415	0.080	0.142
Unique coverage	0.401	0.105	0.367	0.021	0.071	0.363	0.044	0.089
Overall solution consistency	0.914			0.933			0.878	
Overall solution coverage	0.580			0.578			0.552	

Black circles indicate the presence of a condition, and circles with "×" indicate its absence. Large circles indicate core conditions; small circles indicate peripheral conditions. Blank spaces indicate "do not care."

configurations are sufficient condition. The overall solution consistency (OCS) is 0.898, and it further indicates that the three configurations which covered most cases are indeed sufficient condition of high efficiency. It follows from the fact that the overall solution coverage (OCV) is 0.552; the three configurations explained the reason of 55.2% high efficiency.

The situation of nonhigh-efficiency configuration is shown in Table 7 (for the year of 2015, set the consistency threshold as 0.77). The result of that in 2017 shows that there are 2 nonhigh-efficiency configurations (showed in Table 7). The consistency of configuration 1 is 0.854, which indicates that this configuration is the sufficient condition of the nonhigh efficiency, and the overall solution coverage (OCV) is 0.517, which means that this configuration explains the reason of 51.1% nonhigh efficiency. As for configuration 2, the consistency is 2, whereas the overall solution coverage (OCV) is only 0.101 and only Henan case can be included. In 2015 and 2016, there are, respectively, 3 and 1 nonhigh-efficiency configurations. Their overall consistency (OCS) is, respectively, 0.790 and 0.834, which indicates that they are sufficient conditions of nonhigh efficiency.

6. The Analysis of Research Result

6.1. The Main Path with High Efficiency Conspicuously Emerges. In association with Tables 5 and 6, since 2015, the paths of high efficiency of the logistics industry have formed preliminarily. By the analyzing the core conditions that constitute variable, we can sum up two paths. One is open management type (configuration 1 in 2015 and configuration 1a in 2016 and 2017; at the same time, configuration 1b in 2016 and 2017 just have one case and display a higher management level, for this reason, which are sorted into this type). The other is economy-oriented type (configuration 2 of that in 2015, 2016, and 2017).

6.1.1. Open Management-Type Path. This is a quite solid main path that had formed in the three years (marked by a shadow background). In the configuration of "$5A \times GDP \times Open \times R\&D$," high operation and management (5A) and high openness (Open) are two core conditions of high efficiency, and high economic environment (GDP) and high scientific and technological innovation

Table 7: Nonhigh-efficiency configuration of the regional logistics industry in 2015–2017.

Configuration	Solution					
	2015			2016	2017	
	1a	1b	2	1	1	2
Management level (5A)	⊗	⊗	●	⊗	⊗	●
Economic environment (GDP)	⊗	⊗	●	⊗	⊗	●
Opening to the outside world (open)		⊗	⊗		⊗	⊗
Regulations and rules (Regu)	⊗		⊗	⊗	⊗	⊗
Scientific and technological innovation (R&D)	⊗	⊗	●	⊗	⊗	●
Consistency	0.800	0.763	0.815	0.834	0.854	0.800
Raw coverage	0.555	0.544	0.129	0.605	0.517	0.101
Unique coverage	0.090	0.079	0.094	0.605	0.477	0.061
Overall solution consistency		0.790		0.834	0.841	
Overall solution coverage		0.728		0.605	0.578	

(R&D) are peripheral conditions. The sufficiency of this kind of path indicates that the level of operation and management and the degree of opening play an important role in increasing the efficiency of the logistics industry. The cases covered by this path in the three years are exactly the same. They are such provinces in East China as Jiangsu, Guangdong, Zhejiang, Fujian, Shanghai, Shandong, and Liaoning. As for the other configuration mode, the coverage is lower. This main path's formation reflects that the management mode of the logistics industry of every region is turning from extensive to intensive, its idea is turning from close to open, and its science and technology are turning from traditional to modern. This is the result of the leading and support of the national logistics policies for many years also is an initial appearance of the effects of carrying out *Medium and long-term planning for logistics industry development (2014–2020)*.

The A-class logistics enterprise's evaluation and identification are organized and implemented by the China Federation of Logistics and Purchasing. By January 2019, 27 batches of 5680 A-class enterprises have passed the evaluation and identification. More and more logistics enterprises that represent the direction and level of the development of the logistics industry have entered the rank of A-class logistics enterprise. From the first batch of 26 enterprises that passed identification to August 2018, the 496 enterprises of the 26th batch (79 enterprises upgraded included) that passed identification, the amount of A-class logistics enterprise grew rapidly, and the identification work was advanced continuously. Among the logistics enterprises across the country, this situation really has promoted communication and study, demonstration, and lead, and at the same time, it has played a positive role in promoting the development of logistics industry in the way of standardization, modernization, and scale. By improving the level of logistics management, the efficiency of regional and even national logistics industry has been significantly improved.

Meanwhile, in order to play a better role, the high level of operation and management must associate with the other core condition-opened regional environment. Yu et al. [33] hold that the international trade influences the productivity of both trade parties, even the third party. Particularly, with regard to the import part, the existence of import learning effect and competitive effect impels the enterprise to reduce the cost and reform productive idea to extremely promote the productivity of enterprise. Therefore, in a certain region, the opened regional environment will certainly drive the whole logistics industry to increase the management awareness and management level; as a result, the high efficiency of the logistics industry will be realized.

In the empirical results, for those seven provinces and municipalities, besides the high level of operation and management and the high open degree, their indexes of economic environment and R&D are higher too, and R&D index reflects the level of scientific and technological innovation. But, as the peripheral condition, they only play the auxiliary and secondary roles. The government's rules and regulations did not appear, so the fact indicates that the investment of environmental pollution treatment for CO_2 emission of logistics industry did not produce a benefit. The development of the logistics industry in those regions depends on their own internal strength so that it is sustainable. In addition, the 1b configuration in 2016 and 2017 only includes the case of Jiangxi, and the efficiency is mainly achieved through the level of logistics management and nonhigh scientific and technological innovation.

6.1.2. Economy-Oriented Path. Configuration 2 in all the years of 2015, 2016, and 2017 includes the two provinces of Henan and Hebei, and all the constituent factors are "~5A × GDP × ~Open × Regu × R&D." The core factors and peripheral condition of that in 2016 are not the same as that in 2015 and 2017, but in the three years, the nonhigh operation and management is their common factor. Specifically, in 2015 and 2017, the low-carbon logistics efficiency of the two provinces is due to the comparative advantage of the economic environment, which plays the role of the core factors. In 2016, the government's rules and regulations as well as scientific and technological innovation are core factors. The economic environment takes the role of peripheral condition.

The regional economic situation is the base of logistics development, but if it just depends on that base, the long-term influence on increasing logistics efficiency is insufficient. The coverage of this path is low, so it should be considered to convert the development thinking to depending on increasing the level of operation and management to increase logistics efficiency.

6.2. Different Nonhigh-Efficiency Path in Different Years. The nonhigh-efficiency path possesses asymmetry to high efficiency and the paths in different years are not the same. In 2015, configuration 1a is "~5A × ~GDP × ~Regu × ~RandD," while configuration 1b is"~5A × ~GDP × ~Open × ~RandD," in which the factors of "~Regu" and "~Open" are alternative, "~RandD" is the common core factor of two paths, and "~5A" and "~GDP" are the common peripheral factors. With comparison to configuration 1 in 2016 and 2017, the peripheral factors of "~5A" and "~GDP" are their common factors, whereas the core factors of that in 2016 are "~Regu" and "~RandD," and core factors of that in 2017 are "~Open" and "~Regu." This kind of situation in the three years is different. Further analysis is performed on configuration 1a in 2015 and configuration 1a in 2016 and 2017. The coverage, respectively, is 0.555, 0.60, and 0.517, while there are 7 commonly covered cases includes Qinghai, Hainan, Yunnan, Guizhou, Gansu, Jilin, and Ningxia, which indicates that the explanatory force on nonhigh efficiency is stronger. All the consistency is above 0.8, which indicates that these configurations constitute the sufficient condition of nonhigh efficiency.

In 2015 and 2017, there are two identical configuration 2, that is "5A × GDP × ~Open × ~Regu × RandD," and the core factor is "~Open × ~Regu." It can be seen that the reasons that cause high efficiency mainly lie on the nonhigh degree of opening to the outside world and nonhigh rules and regulations, whereas the coverage of this configuration is lower. The coverage in 2015 is 0.129; there are only two cases of Hubei and Sichuan. The coverage in 2017 is 0.101; there is only one case of Hunan.

7. Conclusion and Enlightenment

In recent years, led and driven by a series of China's logistics policies, the national logistics industry is developing rapidly; meanwhile, concerning the actual efficiency of the logistics industry, there is a big difference among the different provinces and municipalities. At the end of February 2019, China's government issued *the opinions on promoting the high-quality development of logistics industry and forming strong domestic market*. The opinion points out that the high-quality development of logistics is an important component of the high-quality development of economy and is an indispensable important strength to drive the high-quality development of economy as well. Therefore, we should not only understand the influence of logistics on economy but also understand the fact that the high-quality development of the logistics industry has become an important handle of improving industrial development and investment environment for now and a period in future, which is the key to cultivating the new energy for the development of regional economy.

7.1. The Main Research Conclusions. From configuration perspective, this research analyzes the constitution of the path with high efficiency and nonhigh efficiency of the low-carbon logistics industry and explored more enlightenment for the development of the logistics industry in different provinces and municipalities. The main research conclusions are as follows:

(1) In recent years, the development of the efficiency of China's low-carbon logistics industry assumed an increasing trend, concrete representations were that the scale efficiency is relatively high, and with a slight fluctuation, the pure technology efficiency is lower and still has a quite big increase space.

(2) In the three years since 2015, two paths of high efficiency had formed. Concerning the path of management open type, its coverage is higher; the core factors of increasing logistics efficiency are the level of operation and management and the degree of opening to the outside world. Concerning the path of economy-oriented type, there are fewer covered cases. Influencing and driving the development of the regional logistics industry mainly depend on the relative advantage of economic environment.

(3) In an inefficient path conforming to the asymmetric character and higher coverage, the core factors are nonhigh scientific and technological innovation and the level of opening and the common peripheral factors are nonhigh operation and management and economic level.

The theoretic contribution mainly manifests as follows: It is an innovation to consider the influence of management level on the efficiency of logistics industry. This research measured the operation and management level of the logistics industry with the total amount of regional A-class logistics enterprises and provided a better reference for future research to choose index. This research applied the QCA method which is more suitable for explaining the social phenomenon and brought the configuration thought into the empirical analysis on the influence factor of low-carbon logistics so as to provide a new theoretical perspective for explaining the phenomenon that the factors got from the previous literature by different scholars are contrary to each other and lay a foundation for the further research on the high-quality development of logistics industry.

7.2. The Main Enlightenment. The main enlightenment on the regional development is shown in the following aspects:

(1) The internal strength to increase the development of low-carbon logistics with high efficiency comes from the improvement of operation and management and open to the outside world. Presently, formed in the different provinces of East China, the "management open" type configuration provides a better experience and clear path for the development of the national logistics industry.

For the central and western regions of China, the key to push the development of logistics industry is to promote the development of high-quality logistics as an opportunity, open mind, learn benchmarking, and improve the level of management.

(2) Though nonhigh-efficiency configuration and high-efficiency configuration show asymmetry, the regions of West China display nonhigh-efficiency configuration generally, and the level of management and the total amount of economy are common peripheral factors which constitute the path. In comparison with the core factors of two high-efficiency paths, the commonness is worth getting more attention. After all, logistics serves the development of the whole economy, so the better economic environment is obvious stimulation and promotion for the increase of low-carbon efficiency, which is a traditional path; however, if we consider adopting the transformation development which depends on improving the level of operation and management, it should be very beneficial to increasing regional logistics efficiency. It is effective to pay attention to training, strengthen communication, and take community action as the leading measure.

7.3. Insufficient Research. Though this research has a certain theoretical and practical significance, there are still many defects. For instance, the analysis of influencing factors is not combined with more indexes, which may cause some paths to remain undetected, such as degree of marketization, space contiguity, and industrial cluster. Besides, the growth of carbon emission of logistics industry not only has a relation with fossil energy, which is directly consumed in logistics, but also has a close relationship with the carbon emission of other industries; it is worth being concerned in the further study.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Prediction of Responses in a Sustainable Dry Turning Operation: A Comparative Analysis

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In a turning operation, involving removal of material from the outer diameter of a rotating cylindrical workpiece using a single-point cutting tool, there exist complex relationships between various cutting parameters and responses. In this paper, a turning operation under dry environment is considered with cutting speed, feed rate, and depth of cut as the input parameters, as well as material removal rate, average surface roughness, and cutting force as the responses. Dry turning operation reduces energy consumption and machining cost, thus eventually resulting in sustainable machining. For the considered process, the corresponding response values are envisaged using four prediction models, that is, multivariate regression analysis, fuzzy logic, artificial neural network, and adaptive neurofuzzy inference system (ANFIS), and their prediction performance is contrasted using five statistical metrics, that is, root mean squared percent error, mean absolute percentage error, root mean squared log error, correlation coefficient, and root relative squared error. It is noticed that ANFIS model consisting of the advantages features of both fuzzy logic and neural network outperforms the other prediction models with respect to the computed values of the considered statistical measures. Based on their acceptable values, it can be propounded that the ANFIS model can be effectively employed for prediction of process responses while treating different machining parameters as the input variables.

1. Introduction

Manufacturing operations are among the paramount energy-intensive processes that consume large amount of energy and natural resources. Sustainable manufacturing focuses on economically viable machining processes to reduce environmental threats by conserving energy and other resources. Sustainable manufacturing can be defined as manufacturing of products/components using those machining processes which would minimize the negative environmental impacts and conserve energy and natural resources, which would be indirectly safe for the employees, communities, and consumers as well as being economically feasible. In the manufacturing domain, metal machining has now been more focused on adapting the concept of sustainability leading to its improved economic, environmental, and social performance. In conventional machining processes, the generated heat in the cutting zone is one of the major problems as it affects the mechanical properties of the workpiece, wearing out of cutting tool, and deteriorating surface roughness. In this context, improvement in machining conditions has become an imperative issue to dissipate the generated heat by the use of cutting fluids, which are major sources of waste generation and environmental deterioration. These cutting fluids are naturally not biodegradable and require treatment before their disposal. Moreover, when these fluids come in contact with the hot machining zone, they get vaporized producing toxic fumes hazardous to the human health. Maintenance of the lubrication system, power consumption, and disposal of cutting fluids are some of the major factors leading to growing environmental issues and increased manufacturing cost. Use of cryogenics can be considered as an alternative to sustainable manufacturing resulting in environmentally toxic-free machining operation with better surface finish. But its high maintenance and installation cost and excessive energy consumption hinder its widespread application. Thus, in the present-day manufacturing scenario, dry machining with no use of cutting fluids has become an optimal solution to sustainable manufacturing. Dixit et al. [1] established that dry machining could be an effective environment-friendly process due to no air and water pollution. Schultheiss et al. [2] also concluded that dry machining could be performed without the use of cutting fluid, while making it a more sustainable material removal method, allowing collection of chips more easily for waste recycling.

In the present-day manufacturing environment, machining is an inevitable operation to provide the desired shape geometry to a given workpiece component. Among all the available machining operations, turning operation using a nonrotary single-point cutting tool plays a key role in removing material from the outer diameter of a rotating cylindrical workpiece, while reducing its diameter to a specified dimension and achieving a smooth finish of the machined component [3]. During turning operation, the workpiece is rotated at a particular cutting speed and the cutting tool is fed against the workpiece at a specific depth of cut. Turning operation is usually performed in a conventional lathe, but when higher dimensional accuracy is required, automated lathe with computer numerical control technology can be employed [4]. It is quite suitable for machining of diverse materials, like hardened steels and alloy steels, heat-treated materials, superalloys, and so forth.

It has been observed that effective turning operation involves selection of various input parameters, like cutting speed (v), feed rate (f), depth of cut (d), nose radius of the tool, types of the work material and cutting tool, machining environment, type of the cutting fluid used, type of the insert, and so forth. On the other hand, the corresponding outputs (responses) are material removal rate (MRR), surface roughness (SR) (with respect to average surface roughness (Ra)), cutting force (Fc), cutting temperature, tool wear, acceleration, power consumption, and so forth. In order to achieve the desired turning performance with respect to enhanced product quality and reduced energy consumption, machining cost, and tool wear, a suitable combination of all the considered input parameters is always demanded [5]. Due to involvement of a large number of correlated input parameters, as well as high complexity and nonlinearity of the cutting mechanism, development of a representative model exhibiting the interrelationships between the turning parameters and responses seems to be a complicated and difficult task. Development of such mathematical models would usually help in understanding the process behaviour and predicting the responses based on a set of given cutting parameters. With continuous development of computational facilities, applications of various soft computing tools, mainly in the form of fuzzy logic, artificial neural network (ANN), evolutionary algorithms, adaptive neurofuzzy interference system (ANFIS), and so forth, have become quite popular among the research community to explore the unknown relationships between the input and output parameters and predict the machining behaviour with a high degree of accuracy [6].

In predictive modelling, various statistical algorithms and machine learning techniques are usually employed to identify the likelihood of future outcomes based on historical data. It is simply a mathematical process that seeks to foresee future events or outcomes while analyzing existent patterns in the historical data. Its goal is to go beyond knowing what has happened to provide a best assessment of what would happen in future. In this paper, based on a set of 27 pieces of experimental data, an attempt is put forward to envisage values of Ra, Fc, and MRR using three input parameters (v, f, and d) in a dry turning operation while applying four prediction models, that is, regression analysis, fuzzy logic, ANN, and ANFIS. The relative performance of these prediction models is also compared with respect to some important statistical measures. The effects of turning parameters on the responses under consideration are also investigated.

2. Literature Review

Table 1 provides a list of different input turning parameters, responses, and soft computing techniques (prediction models) applied by the past researchers while modelling and predicting the mechanism of cutting operation in dry machining environment. The results of this literature survey in Table 1 show that different mathematical models, mainly in the form of regression analysis, ANN, support vector regression, and ANFIS, have been employed for prediction of different responses based on the given sets of diverse turning parameters. Application of fuzzy logic for modelling and prediction in turning operation is really scarce. It is also observed that those prediction models have been adopted individually for different turning operations and comparative studies with respect to their prediction performance are limited. Keeping in mind this research gap, this paper proposes the simultaneous applications of multivariate regression analysis, fuzzy logic, ANN, and ANFIS for envisaging the responses of a dry turning operation based on the training and testing datasets, and their performances are compared with respect to five statistical metrics, that is, root mean squared percent error (RMSPE), mean absolute percentage error (MAPE), root mean squared log error (RMSLE), correlation coefficient (R), and root relative squared error (RRSE). The corresponding "If-Then" rules for fuzzy logic and ANFIS models are also developed to help the machinist in understanding the influences of various turning parameters on the responses. It is revealed that ANFIS model having the advantages features of both fuzzy logic and ANN outperforms the other prediction models with respect to the considered statistical measures. Effect of different input membership functions on the prediction performance of ANFIS model is also investigated. Thus, application of

Table 1: Turning parameters, responses, and prediction models considered by the past researchers.

Sl. no.	Author(s)	Input parameters	Response(s)	Prediction model
1.	Koura et al. [7]	*v*, *f*, *d*	Ra	ANN
2.	Hanief and Wani [8]	*v*, *f*, *d*	Ra	Regression
3.	Mia et al. [9]	*v*, *f*, tool configuration, environment	Ra	ANOVA
4.	Benlahmidi et al. [10]	*v*, *f*, *d*, workpiece hardness	Ra, cutting pressure, cutting power	Regression
5.	Sharma and Krishnaiah [11]	*v*, *f*, *d*	Ra, MRR, power consumption	ANN, regression
6.	Panda et al. [12]	*v*, *f*, *d*	Flank wear, Ra, acceleration	Regression
7.	Pawan and Misra [13]	*v*, *f*, approach angle	Ra	Regression
8.	Aouici et al. [14]	*v*, *f*, cutting time	Ra, specific cutting force, flank wear	Regression
9.	Elbah et al. [15]	*v*, *f*, *d*, cutting radius	Ra, cutting force components, tool wear	Regression
10.	Rajbongshi and Sarma [16]	*v*, *f*, *d*	Ra, flank wear, Fc, feed force	ANN, regression
11.	Alajmi and Almeshal [17]	*v*, *f*, *d*	Ra	ANFIS
12.	Cica et al. [18]	*v*, *f*, *d*, environment	Machining force, cutting power, cutting pressure	Regression, support vector regression, Gaussian process regression, ANN
13.	Panda et al. [19]	*v*, *f*, *d*	Acceleration, flank wear, Ra	Regression
14.	Setia and Chauhan [20]	*v*, *f*, *d*	Cutting force components, cutting temperature	Regression
15.	This paper	*v*, *f*, *d*	Ra, Fc, MRR	Regression, ANN, fuzzy logic, ANFIS

ANFIS model can effectively frame the input-output relationship of the considered turning operation under dry environment.

3. Prediction Models

3.1. Regression Analysis. During any experiment, the observed dataset can be utilized to develop the existent relationship between the dependent parameter (response) and independent parameters (inputs) in the following form:

$$y = f\left(x_1, x_2, \&, x_n\right) + \varepsilon, \quad (1)$$

where f is the approximate function, x_i ($i = 1, 2, \ldots, n$) is the i^{th} input parameter, y is the response, and ε is the normally distributed statistical error. A quadratic function can also be formulated using the experimental dataset in the following form:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \varepsilon, \quad (2)$$

where β_0 is the Y-intercept coefficient, β_1–β_n are the main effect coefficients, and β_{ij} is the interaction coefficient. A well-developed regression model has the ability to determine the relative influence of one or more independent variables on the dependent variable and potentiality to identify outliers or anomalies in the dataset. It has also other advantages, like simplicity, interpretability, scientific acceptance, and so forth. But it also suffers from some disadvantages, like inability to deal with qualitative data, lengthy and complicated calculations, unchanged cause and effect relationship between the dependent and independent variables, chances of error during extrapolation, and so forth.

3.2. Fuzzy Logic. Fuzzy set theory, developed by Zadeh [21], deals with incomplete and vague information to achieve a rational conclusion for any problem, while converting the imprecise linguistic terms (such as "high" and "low") into numerical values using fuzzy membership functions. It states that, in a universe of discourse X, a fuzzy subset $\tilde{A}$ of X can be expressed using a membership function $f_{\tilde{A}}(x)$, mapping each element x in X to a real number R in unit interval of [0,1]. The function value $f_{\tilde{A}}(x)$ highlights the grade of membership of x in $\tilde{A}$.

A fuzzy logic unit contains a fuzzifier, membership functions, a fuzzy rule base, an inference engine, and a defuzzifier. In fuzzy-logic-based analysis, the membership functions are the inputs to the fuzzifier to fuzzify the input variables having some degree of uncertainty and ambiguity. A membership function maps each input value to a membership value between 0 and 1. The inference engine performs a fuzzy reasoning of the developed fuzzy rules to generate the corresponding fuzzy value [22, 23]. The defuzzifier finally transforms the fuzzy value into a crisp value. A fuzzy rule base consisting of a set of "If-Then" control rules is developed to depict the inference relationship between the input and output. A set of such fuzzy rules is shown as follows [24]:

$$\begin{aligned}
&\text{Rule 1: If } x_1 \text{ is } A_1 \text{ and } x_2 \text{ is } B_1 \text{ and } x_3 \text{ is } C_1 \text{ and } x_4 \text{ is } D_1\text{, Then output (O)is } E_1 \text{ else,}\\
&\text{Rule 2: If } x_1 \text{ is } A_2 \text{ and } x_2 \text{ is } B_2 \text{ and } x_3 \text{ is } C_2 \text{ and } x_4 \text{ is } D_2\text{, Then output (O)is } E_2\text{, else,}\\
&\text{Rule } n\text{: If } x_1 \text{ is } A_n \text{ and } x_2 \text{ is } B_n \text{ and } x_3 \text{ is } C_n \text{ and } x_4 \text{ is } D_n\text{, Then output (O)is } E_n\text{,}
\end{aligned} \tag{3}$$

where A_i, B_i, C_i, and D_i are the fuzzy subsets defined by the corresponding membership functions, that is, μ_{Ai}, μ_{Bi}, μ_{Ci}, and μ_{Di}, respectively. The inference engine performs fuzzy reasoning on fuzzy rules while considering max-min inference for generating a fuzzy value, $\mu_{c_0}(O)$.

$$\begin{aligned}
\mu_{C_0}(O) = &\left(\mu_{A_1}(x_1) \wedge \mu_{B_1}(x_2) \wedge \mu_{C_1}(x_3) \wedge \mu_{D_1}(x_4) \wedge \mu_{E_1}(O)\right)\vee\\
&\left(\mu_{A_2}(x_1) \wedge \mu_{B_2}(x_2) \wedge \mu_{C_2}(x_3) \wedge \mu_{D_2}(x_4) \wedge \mu_{E_2}(O)\right)\vee\\
&\left(\mu_{A_n}(x_1) \wedge \mu_{B_n}(x_2) \wedge \mu_{C_n}(x_3) \wedge \mu_{D_n}(x_4) \wedge \mu_{E_n}(O)\right),
\end{aligned} \tag{4}$$

where $\wedge$ is the minimum operation and $\vee$ is the maximum operation. Finally, a centric fuzzification method is adopted to convert the fuzzy multiresponse output, $\mu_{c_0}(O)$, into a crisp value (C).

$$C = \frac{\sum O\mu_{C_0}(O)}{\sum \mu_{C_0}(O)}. \tag{5}$$

As a prediction tool, fuzzy logic has some advantageous features, like the ability to deal with problems having imprecise and incomplete data, ability to model nonlinear functions of arbitrary complexity, being simple and easily interpretable, no requirement of a large dataset or even any dataset to train the model, and so forth. But fuzzy logic may not be always accurate as the results are perceived based on assumption and human knowledge. Accuracy of fuzzy logic also largely depends on proper selection of the corresponding membership function for mapping the interrelationship between the input and output variables. In fuzzy-logic-based modelling approach, the problem of finding out the appropriate membership functions and fuzzy rules is often an exhausting process of trial and error. It requires the end users to understand the data before training, which is usually difficult for a relatively large dataset.

3.3. ANN. The ANN, biologically inspired from human brain, devours outstanding ability to determine patterns and identify trends from complicated or imperfect dataset which are too complex to perceive by either humans or other computer techniques [25]. It is a computational modelling technique having hundreds of individual processing units (PE) (also called artificial neurons), coupled with coefficients (weights), which form the neural structure. Each PE has weighted inputs, an appropriate transfer function, and an output. Each neuron is capable of processing simple information. However, the real strength of neural computation comes into picture when these neurons are connected to form a network. Compared to ~100 billion neurons of human brain, ANN has hundred or thousand PEs. The ANN can be classified based on the transfer functions of the neurons, learning rule, and connection formula.

The neurons are the building blocks of an ANN, located in the network layers and designed to simulate functions of the biological neurons. There are input layer, output layer, and hidden layers in a typical ANN architecture. The input signals, multiplied by the corresponding weight factors and added together, are passed through a transfer function to generate the output for a neuron. The activation function is the weighed sum of the inputs to the neurons. The most commonly used transfer functions are pure linear transfer function (*purelin*) and tangent sigmoid function (*tansig*). For neuron connection, ANN has different architectures. Among them, feedforward architecture does not have a connection back from the output to the input neurons and, therefore, does not keep a record of its previous output values. On the other hand, feedback architecture has connections from output to input neurons. There are also different training/learning models among which backpropagation model or delta model is most widely utilized.

An ANN is initially trained to map the input dataset while adjusting the weights through a number of iterations. Estimation of the values of these weights is extremely crucial for development of a robust ANN model. The available input information is first fed through the network to derive the optimal weights for the neurons. These optimal weights are obtained using backpropagation of errors during the training/learning phase. The ANN analyzes the input and output values for a dataset and accordingly modifies the weights to bring the predicted values closer to the target values. The error in prediction is minimized through a repeated number of training cycles till it reaches a specified accuracy. A well-structured and trained ANN has an ability to deal with insufficient knowledge, potentiality to learn by itself while providing the output not limited to the input dataset, robust learning method for its effective training, as well as an ability to provide almost accurate results from an erroneous training dataset. On the other hand, ANN, being a black box type approach, suffers from overfitting of data and it does not provide any idea about how a particular response is predicted based on a given set of input variables.

3.4. ANFIS. An ANFIS is a hybrid predictive model integrating the adaptive capability of ANNs and qualitative rule-based reasoning of fuzzy logic [26, 27]. It harnesses the advantageous features of both ANNs and fuzzy logic while utilizing the mathematical properties of ANNs in tuning the rule-based fuzzy systems to approximate the human reasoning approach. In this model, an ANN is employed with the learning and computing capabilities in fuzzy logic, whereas fuzzy logic provides the advanced expert knowledge and fuzzy principles for use by the ANN. The integration of ANNs and fuzzy logic in ANFIS architecture makes it more systematic and less dependent on human expertise. It basically provides the mapping relation between the input and output data while employing a hybrid learning method to determine the optimal distribution of membership functions. The ANFIS architecture contains five layers, that is, fuzzy layer, product layer, normalization layer, defuzzification layer, and total output layer, with each layer consisting of several nodes described by the corresponding node function. The inputs to a specific layer are derived from the nodes of the previous layer. In this architecture, a fixed node is represented by a circle, whereas an adaptive node (where the parameters are modified during adaptation or training) is denoted by a square. In order to demonstrate the working principle of ANFIS model, it is assumed that there are two inputs (x and y) and one output (f_i). As it employs the first-order Sugeno fuzzy inference system, the corresponding rules can be framed as follows [28–30]:

Rule 1: if x is A_1 and y is B_1, then z is $f_1(x,y) = p_1x + q_1y + r_1$

Rule 2: if x is A_2 and y is B_2, then z is $f_2(x,y) = p_2x + q_2y + r_2$

Here, p_1, q_1, r_1, p_2, q_2, and r_2 are the linear parameters (consequent parameters), A_1, B_1, A_2, and B_2 are the nonlinear parameters, and $f_i(x,y)$ is the output of the first-order Sugeno fuzzy inference system. The architecture of ANFIS model is exhibited in Figure 1.

In the fuzzy layer, x and y are the input nodes, and A_1, B_1, A_2, and B_2 are the linguistic labels in the fuzzy theory (like "low" or "high") for deriving the membership function. This layer consists of adaptive nodes with the following node functions:

$$O_{1,i} = \mu_{A_i}(x) \text{for} \quad i = 1, 2, \tag{6}$$

$$O_{1,i} = \mu_{B_{i-2}}(y) \text{for} \quad i = 3, 4, \tag{7}$$

where $\mu(x)$ and $\mu(y)$ are the parameterized membership functions which usually follow bell shape with the maximum and minimum values as 1 and 0, respectively. With the changing parameter values, the bell-shaped function varies accordingly, thereby allowing various forms of the membership function for fuzzy set.

$$\mu(x) = \frac{1}{1 + \left[(x - c_i)^2 / a_i^2 \right]^{b_1}}, \tag{8}$$

where a_i, b_i, and c_i constitute the parameter set. These are also known as premise parameters.

In the product node, every node is a fixed node, with the node function to be multiplied by the input signals to serve as output.

$$O_{2,i} = w_i = \mu_{Ai}(x) \times \mu_{Bi}(y) \text{for} \quad i = 1, 2, \tag{9}$$

where w_i represents the firing strength of a rule.

Every node in the third layer is a fixed node, having the node function to normalize the firing strength while computing the ratio of the i^{th} node's firing strength to the sum of all rules' firing strength.

$$O_{3,i} = \overline{w_i} = \frac{w_i}{\sum w_i} \text{for} \quad i = 1, 2. \tag{10}$$

In the fourth layer, every node is an adaptive node. The defuzzification relationship between the input and output of this layer can be expressed as follows:

$$O_{4,i} = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i) \text{for} \quad i = 1, 2. \tag{11}$$

The last layer of ANFIS model consists of a fixed node, with node function to compute the overall output as

$$\begin{aligned} O_{5,i} &= \sum_i \overline{w}_i f_i = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_1}{w_1 + w_2} f_2, \\ &= (w_1 x) p_1 + (w_1 y) q_1 + (w_1) r_1 + (w_2 x) p_2 \\ &\quad + (w_2 y) q_2 + (w_2) r_2. \end{aligned} \tag{12}$$

The ANFIS adopts a hybrid learning algorithm combining the gradient method with the least-squares method to update the parameter values. The consequent parameters are identified by the least-squares estimate in the forward pass of the learning algorithm. On the other hand, the premise parameters are updated by the gradient descent algorithm in the backward pass. Being a hybrid prediction model, ANFIS has the advantages of both ANN and fuzzy logic, like robustness during learning and training, as well as high interpretability. It can deal with numerical as well as linguistic data, and it has the capability of fast learning, better adaptability, and potentiality to cater fuzziness, ambiguity, and uncertainty in the system under consideration. It can also effectively capture the nonlinear structure of a given process. It can be trained without relying solely on expert knowledge as applicable for a fuzzy logic model. Compared to ANN, it is more transparent to the end user with less memorization error. Despite its wide acceptance among the researchers, ANFIS model suffers from limitations, such as curse of dimensionality and computational expense.

4. Dry Turning Operation

During dry turning operation using a heavy-duty lathe (HMT Ltd., Model: NH26) on a round bar of AISI 304 stainless steel material (diameter of 60 mm and length of 200 mm), Nayak et al. [31] performed 27 experiments based on L_{27} orthogonal array design plan. For the turning operation, an ISO P30 grade uncoated cemented carbide insert was employed as the cutting tool, and v, f, and d were considered as the turning parameters. On the other hand, MRR (in mm^3/min), Fc (in N), and Ra (in μm) were treated as the responses/outputs. During the experiments, the setting of each of the turning parameters was varied at three different levels, as shown in Table 2. The experimental design plan along with the measured response values is provided in Table 3. Nayak et al. [31] applied grey relational analysis technique to determine the best parametric intermix of the considered turning parameters to simultaneously optimize

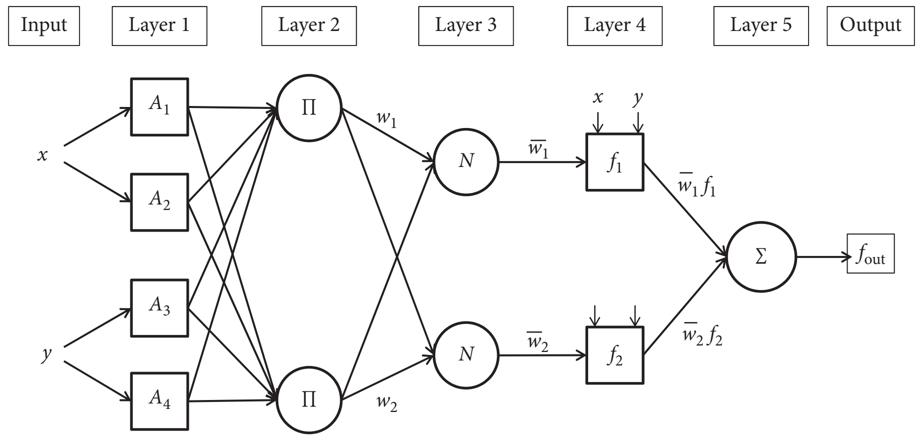

Figure 1: ANFIS structure.

Table 2: Turning parameters and their operating levels [31].

Turning parameter	Unit	Level of variation		
		1	2	3
Cutting speed	m/min	25	35	45
Feed rate	mm/rev	0.1	0.15	0.2
Depth of cut	mm	1	1.25	1.5

Table 3: Experimental dataset [31].

Run	v	f	d	Ra	Fc	MRR	Purpose
1	35	0.2	1.5	0.68	1453	10500	Training
2	25	0.2	1	0.72	1090	5000	Training
3	25	0.15	1	0.61	894	3750	Training
4	35	0.1	1	0.56	635	3500	Testing
5	25	0.1	1	0.49	676	2500	Testing
6	35	0.15	1	0.57	839	5250	Training
7	35	0.2	1.25	0.67	1141	8750	Training
8	45	0.15	1	0.54	780	6750	Training
9	45	0.1	1	0.64	605	4500	Testing
10	25	0.15	1.25	0.62	1085	4687.5	Testing
11	25	0.2	1.5	0.73	1549	7500	Training
12	35	0.1	1.25	0.46	770	4375	Training
13	25	0.1	1.25	0.50	820	3125	Training
14	25	0.2	1.25	0.72	1322	6250	Training
15	45	0.2	1.25	0.64	1183	11250	Training
16	45	0.1	1.25	0.44	734	5625	Training
17	45	0.2	1	0.63	975	9000	Testing
18	25	0.15	1.5	0.62	1271	5625	Testing
19	25	0.1	1.5	0.50	962	3750	Training
20	35	0.2	1	0.67	1022	7000	Training
21	45	0.2	1.5	0.64	1386	13500	Training
22	45	0.1	1.5	0.44	860	6750	Training
23	35	0.15	1.5	0.58	1192	7875	Testing
24	45	0.15	1.5	0.55	1137	10125	Testing
25	35	0.15	1.25	0.57	1018	6562.5	Testing
26	45	0.15	1.25	0.55	970	8437.5	Training
27	35	0.1	1.5	0.46	902	5250	Training

all the three responses. A confirmatory experiment was also conducted to validate the derived results. In this paper, 18 and 9 experimental datasets are randomly selected from Table 3 for training and testing purposes of fuzzy logic, ANN, and ANFIS models, respectively.

5. Prediction of Responses in Dry Turning Operation

In an attempt to contrast the performance of the considered prediction models, the corresponding response surface methodology-based regression equations are first developed exhibiting the relationships between the turning parameters and responses. From the analysis of variance (ANOVA) results (not shown here due to paucity of space), it can clearly be revealed that f (having p value < 0.05) is the most statistically significant turning parameter (contribution of 90.13%) influencing Ra value of the turned components. Similarly, for Fc, f and d are the two most significant turning parameters having 59.77% and 35.67% contributions, respectively. In this turning operation, MRR is maximally influenced by f (55.55% contribution), followed by v (20.83% contribution) and d (20% contribution). For MRR, some of the two-factor interactions also appear to be statistically significant.

$$\begin{aligned} y(Ra) = {} & 0.600 - 0.00826 \times v + 1.542 \times f - 0.199 \times d \\ & + 0.000081 \times v^2 + 0.85 \times f^2 \\ & + 0.0537 \times d^2 - 0.0020 \times v \times f + 0.00051 \times v \\ & \times d + 0.559 \times f \times d - 0.0074 \times v \times f \times d, \end{aligned} \tag{13}$$

$$\begin{aligned} y(Fc) = {} & 2757 - 52.0 \times v - 9551 \times f - 2096 \times d \\ & + 0.313 \times v^2 + 11284 \times f^2 + 555 \times d^2 \\ & + 163 \times v \times f + 22.2 \times v \times d + 9048 \times f \\ & \times d - 147 \times v \times f \times d, \end{aligned} \tag{14}$$

$$\begin{aligned} y(MRR) = {} & 4919 + 35 \times v - 23889 \times f - 5232 \times d \\ & + 0.184 \times v^2 \\ & + 49296 \times f^2 + 1816 \times d^2 - 174 \times v \times f - 34 \\ & \times v \times d + 7350 \times f \times d + 1092 \times v \times f \times d. \end{aligned} \tag{15}$$

During dry turning operation, the influences of v, f, and d on Ra, Fc, and MRR are pictorially demonstrated in Figures 2–4. It can be observed that, with increasing values of

v, surface quality of the turned components improves. At lower v value, formation of build-up edge increases due to higher adherence tendency between the tool and workpiece, resulting in poor surface quality. With increasing values of v, the cutting temperature also increases, which is responsible for better surface quality. On the other hand, higher values of f result in higher thrust force and vibration, increasing surface roughness of the machined components. It can also be noticed from Figure 2 that a value of d as 1.25 mm provides better surface finish and its higher value results in poor surface finish due to excessive tool wear. The effects of v, f, and d on Fc are exhibited in Figure 3. It can be revealed that an increase in the value of v causes higher heat generation in the machining zone during dry turning operation, which is responsible for thermal softening of the workpiece material and reduction in cutting forces. Increasing values of both f and d result in higher cutting forces. At higher f values, extra forces are required for the necessary plastic deformation for effective material removal during dry turning operation. In the similar direction, at higher values of d, there are increments in the cutting forces due to increase in the effective shear area at the tool and workpiece interface. It can also be noticed from Figure 4 that higher values of v, f, and d are all responsible for achieving higher MRR with more amount of material being removed from the workpiece.

In this paper, fuzzy logic designer, neural network toolbox, and neurofuzzy designer of MATLAB (2016a) are, respectively, employed for prediction of the responses using fuzzy logic, ANN, and ANFIS models. The prediction model based on fuzzy logic consists of three inputs, three outputs, and Mamdani inference system, and it generates 18 rules using the training dataset to envisage values of the considered machining responses for different combinations of turning parameters. For this fuzzy logic model, the type of the input and output membership functions is considered as generalized bell-shaped. Figure 5 exhibits the fuzzy rule viewer and the first rule from this figure is presented as follows.

If $v = 25$ m/min, $f = 0.1$ mm/rev, and $d = 1$ mm, then Ra = 0.556 μm, Fc = 767 N, and MRR = 3045 mm^3/min.

In the similar direction, the developed architecture for the ANN model with three nodes in the input layer, ten nodes in the hidden layer, and three nodes in the output layer is exhibited in Figure 6. As there are three turning parameters and three responses in the prediction model, the corresponding ANN architecture also consists of three input and three output layers. To have the minimum mean squared error (MSE) value along with a well-trained network, the number of nodes in the hidden layer is chosen as ten based on trial-and-error method. Addition of a greater number of nodes in the hidden layer would unnecessarily increase the ANN architecture with further increase in the training time. For training of this ANN model, Levenberg-Marquardt backpropagation algorithm is employed, whereas hyperbolic tangent sigmoid transfer function and pure linear transfer function are, respectively, utilized in the hidden layer and output layer.

In fuzzy logic and ANFIS models, choice of the most appropriate membership function for the input variables depends on the number of rules in the fuzzy inference system, mechanism of the fuzzy inference system, and defuzzification process. Like in the fuzzy logic model, in ANFIS model, generalized bell is also chosen as the membership function for the input variables due to its higher reliability, robustness, and ability to represent the input-output relationships more efficiently. Besides the generalized bell function, triangular, trapezoidal, and Gaussian can also be adopted as the membership functions for the input variables in ANFIS model. Figure 7 represents a typical generalized bell membership function, and the ANFIS architecture along with the related training parameters is provided in Table 4. The ANFIS architecture obtained from MATLAB Toolbox is exhibited in Figure 8.

In this ANFIS model, as there are three input parameters and a membership function with three levels ("low", "medium," and "high"), altogether $3^3 = 27$ rules are framed for each of the responses. The rule viewer developed for Ra is portrayed in Figure 9. As mentioned earlier, from the initial dataset with 27 experimental observations, 9 experimental runs are randomly utilized for testing of the ANFIS model. The predicted values of Ra, Fc, and MRR are provided in Table 5. It can be clearly noted from the first row of the rule viewer in Figure 9 that when $v = 25$ m/min, $f = 0.1$ mm/rev, and $d = 1$ mm, the value of Ra is obtained as 0.528 μm. From the other two rule viewers for Fc and MRR (not shown in this paper due to paucity of space), it can also be observed that, for this combination of v, f, and d, the predicted values of Fc and MRR are 682 N and 2579 mm^3/min, respectively. The comparisons between the actual Ra, Fc, and MRR values and their predicted values for all the four prediction tools are, respectively, presented in Figures 10–12. It can be revealed from these figures that the values of Ra, Fc, and MRR predicted using the developed ANFIS model closely match with their respective actual values. On the other hand, the prediction performance of regression analysis and ANN model is not at all satisfactory.

The prediction performance of the considered models is now validated based on various statistical metrics. The RMPSE is a popular measure to define the goodness of fit of a developed model that best describes the average percent error in predicting the considered turning responses. The mean absolute percentage error of the predicted values with respect to the actual values is estimated using MAPE. In RMSLE, introduction of the logarithm makes it possible to consider the relative difference between the actual and predicted values, while estimating percentual difference between them. It treats small differences between small actual and predicted values approximately the same as big differences between large actual and predicted values. The degree of association between the actual and predicted responses is estimated using R value. On the other hand, RRSE takes the total squared error and normalizes it while dividing by the total squared error of the simple predictor. While taking the square root of the relative squared error, the error is reduced to the same dimension as the response being predicted. Among these statistical metrics, lower values are

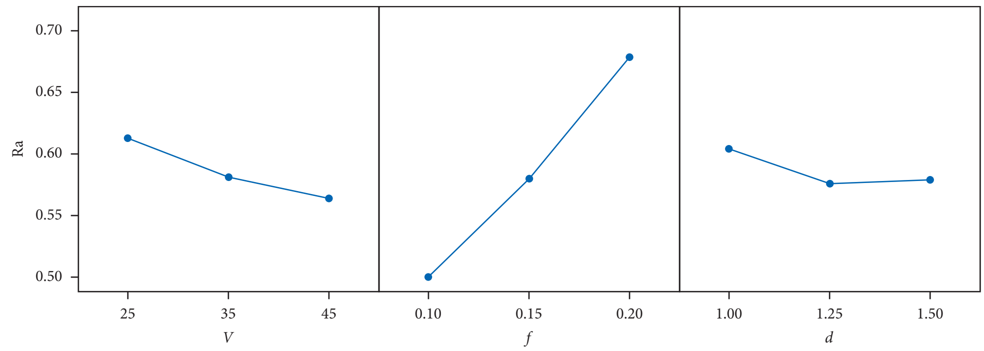

Figure 2: Effects of dry turning parameters on Ra.

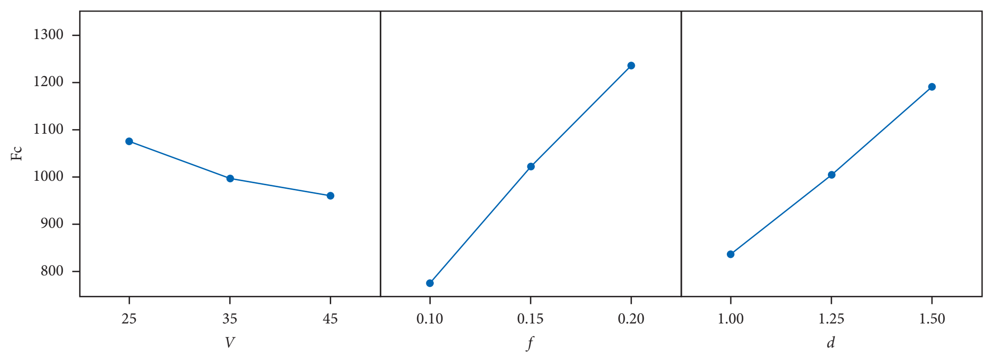

Figure 3: Effects of dry turning parameters on Fc.

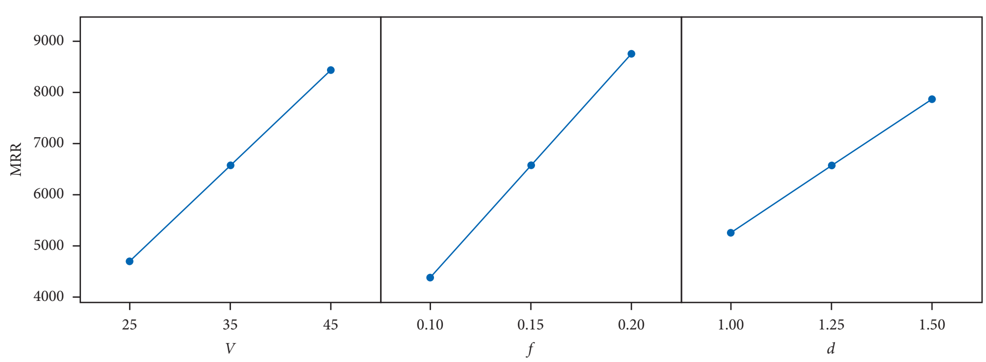

Figure 4: Effects of dry turning parameters on MRR.

required for RMSPE, MAPE, RMSLE, and RRSE, while higher R value is always preferred to validate the performance of any prediction tool. The mathematical formulations of these statistical metrics are presented as follows:

$$\text{RMSPE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{A_i - P_i}{A_i}\right)^2} \times 100, \quad (16)$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{A_i - P_i}{A_i}\right| \times 100, \quad (17)$$

$$\text{RMSLE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\log\left(P_i + 1\right) - \log\left(A_i + 1\right)\right)^2}, \quad (18)$$

$$R = \frac{\sum_{i=1}^{n}\left(A_i - \overline{A}\right)\left(P - \overline{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(A - \overline{A}\right)^2\left(P - \overline{P}\right)^2}}. \quad (19)$$

$$\text{RRSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - A_i\right)^2}{\sum_{i=1}^{n}\left(A_i - \overline{A}\right)^2}}, \quad (20)$$

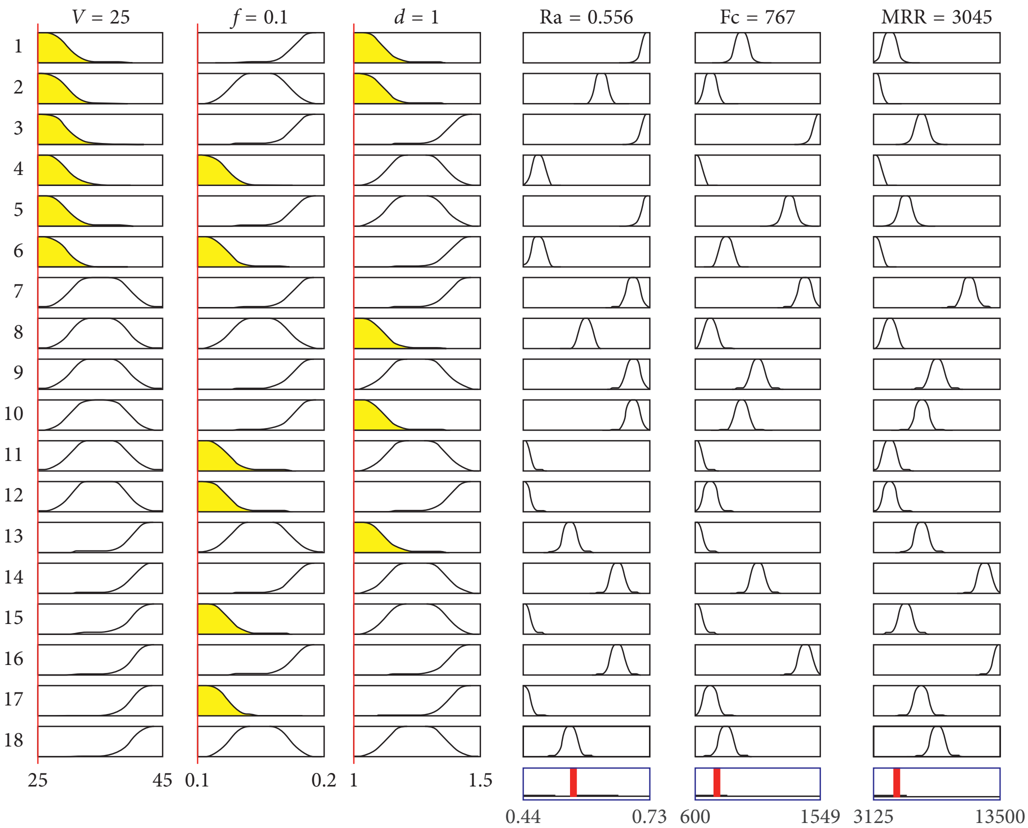

Figure 5: Fuzzy rule viewer.

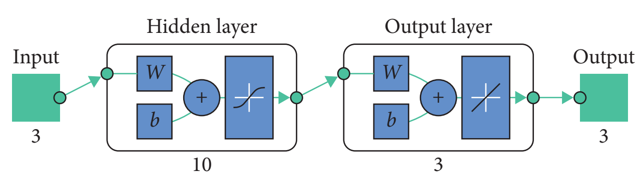

Figure 6: Developed ANN architecture.

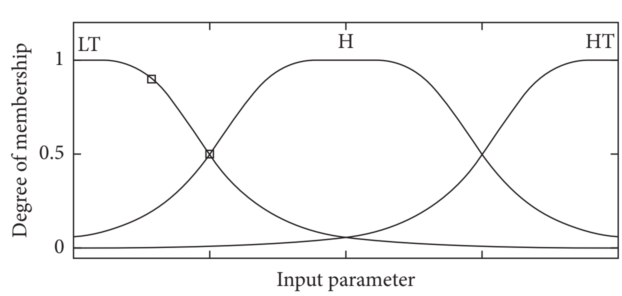

Figure 7: A generalized bell membership function.

where A_i and P_i are the actual and predicted response values, $\overline{A}$ and $\overline{P}$ are the means of all the actual and predicted response values, and n is the total number of observations in the testing dataset. Table 6 provides values of RMSPE, MAPE, RMSLE, R, and RRSE for the testing dataset when regression analysis, fuzzy logic, ANN, and ANFIS models are employed for prediction of Ra, Fc, and MRR values during the dry turning operation. These comparison results for Ra, Fc, and MRR values are also pictorially exhibited in Figures 13–15, respectively. From these figures, it can be noticed that ANFIS model excels over the others with respect to all the statistical measures for the three turning responses under consideration. Finally, the prediction performance of ANFIS model itself is contrasted in Table 7 for four different

Table 4: ANFIS architecture and training parameters.

Number of layers	5
Size of the input dataset	18×3
Number of outputs	3
Membership function	Generalized bell
Learning rules	Least-square estimation gradient descent algorithm
Inference system	Sugeno inference system
Training method	Hybrid method
Number of rules generated	27
Momentum constant	0.9
Number of epochs	500

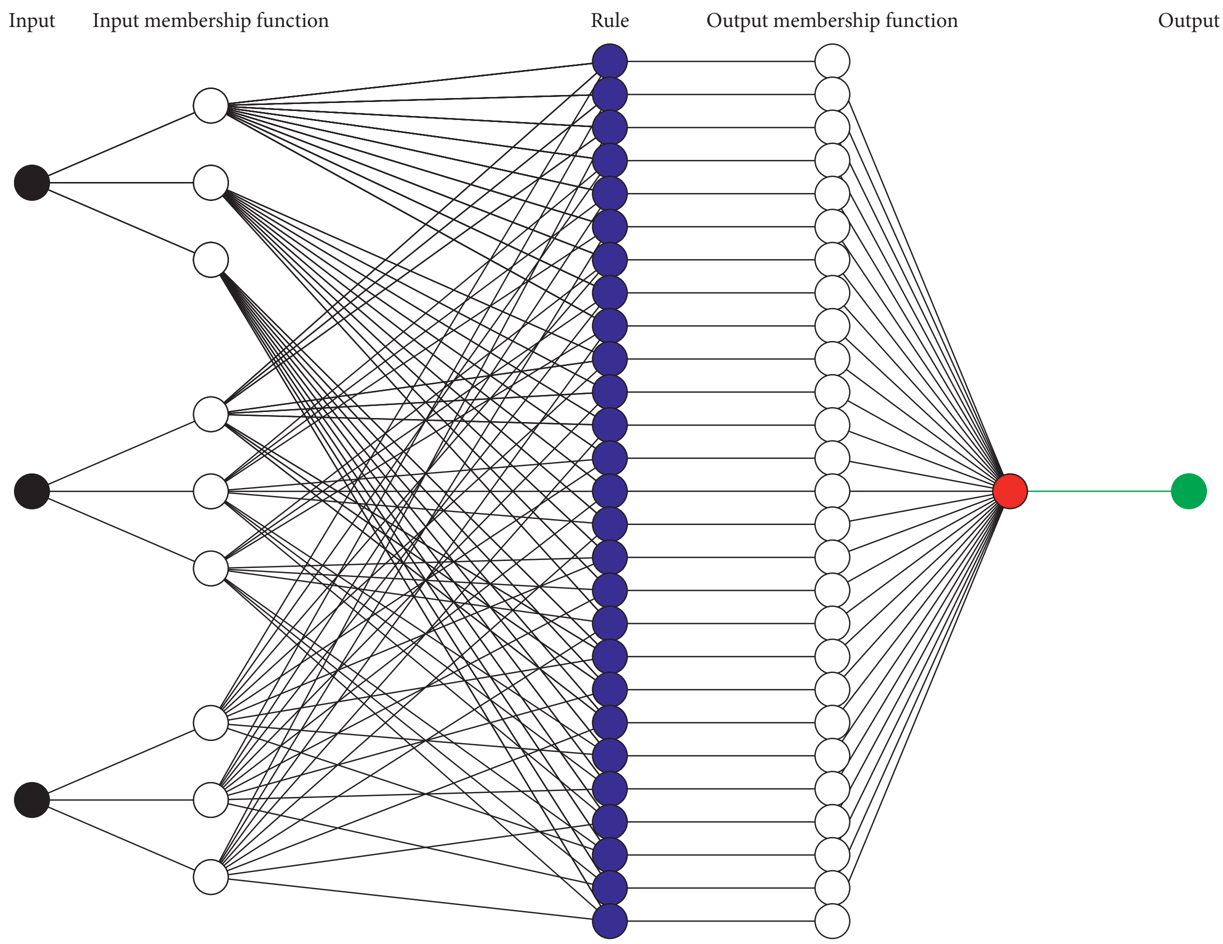

Figure 8: ANFIS architecture obtained from MATLAB Toolbox.

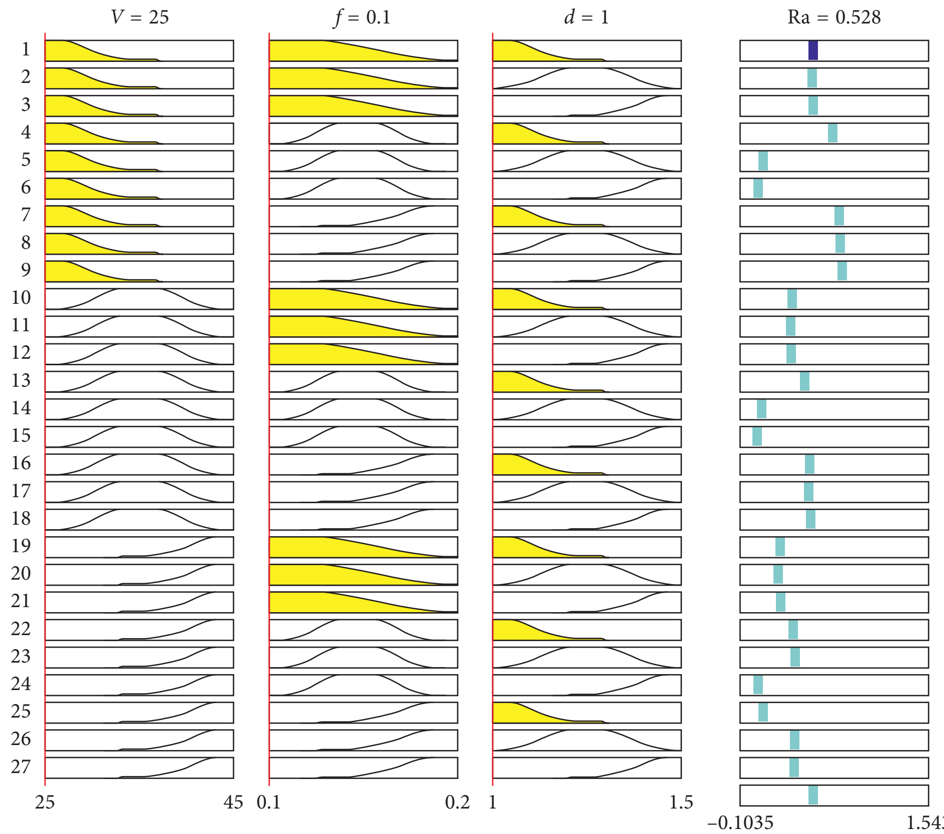

Figure 9: ANFIS rule viewer for Ra.

Table 5: Experimental data for testing and predicted response values for ANFIS model.

Exp. run	v	F	D	Ra		Fc		MRR	
				Actual	Predicted	Actual	Predicted	Actual	Predicted
1	25	0.1	1	0.49	0.528	676	682	2500	2579
2	25	0.15	1.25	0.62	0.616	1085	1025	4687.5	4753
3	25	0.15	1.5	0.62	0.598	1271	1286	5625	5302
4	35	0.1	1	0.56	0.541	635	689	3500	3390
5	35	0.15	1.5	0.58	0.562	1192	1175	7875	7427
6	35	0.15	1.25	0.57	0.561	1018	949	6562.5	6311
7	45	0.1	1	0.64	0.652	605	669	4500	4622
8	45	0.2	1	0.63	0.632	975	945	9000	9234
9	45	0.15	1.5	0.55	0.538	1137	1090	10125	10587

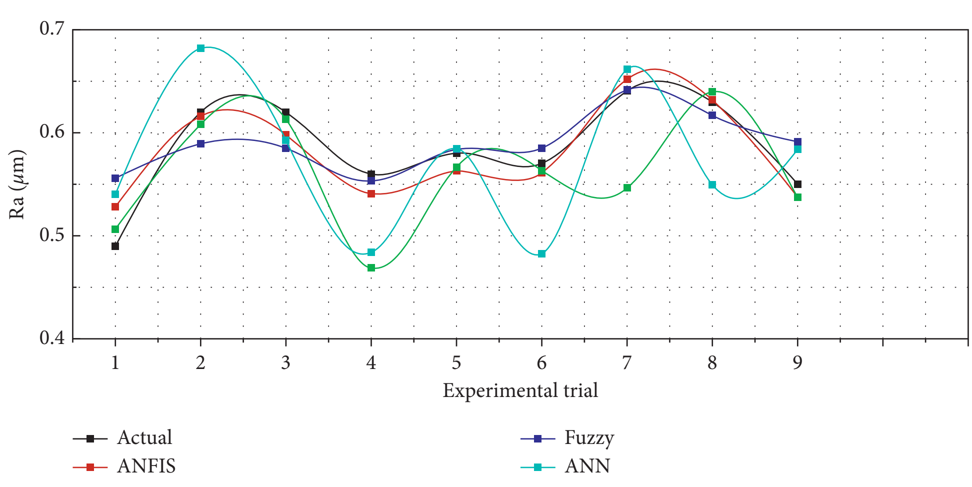

Figure 10: Comparison of actual and predicted response values for Ra.

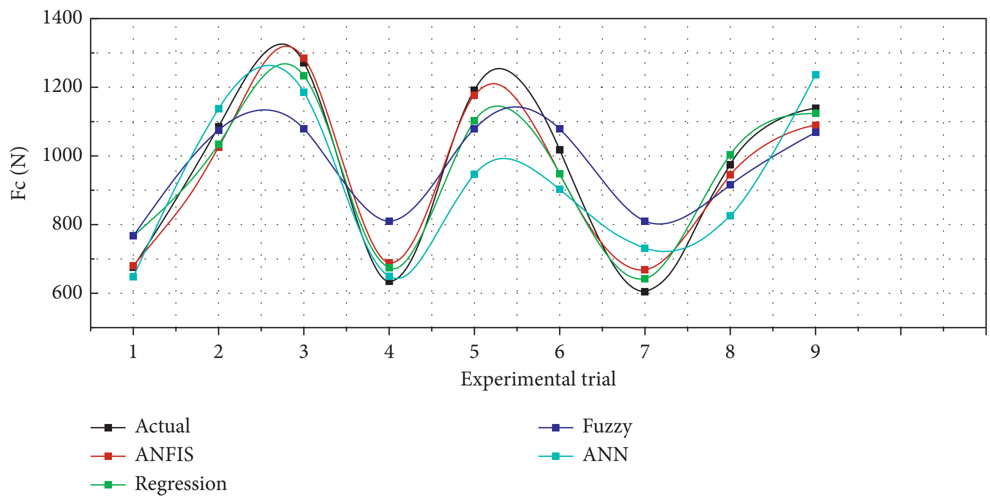

Figure 11: Comparison of actual and predicted response values for Fc.

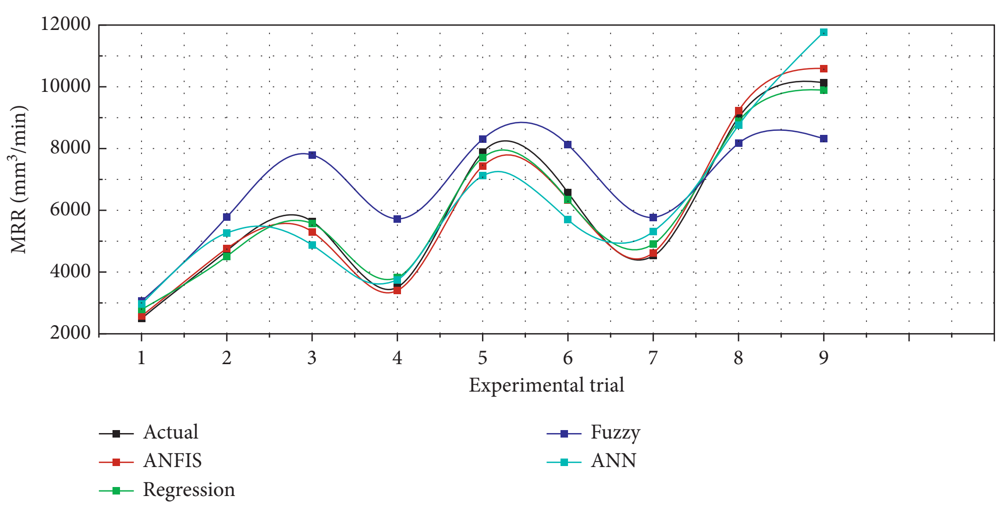

Figure 12: Comparison of actual and predicted response values for MRR.

Table 6: Performance indices for different prediction tools.

Statistical measure	Prediction tool											
	ANFIS			Fuzzy logic			ANN			Regression		
	Ra	Fc	MRR	Ra	Fc	MRR	Ra	Fc	MRR	Ra	Fc	MRR
RMSPE	3.4183	5.6912	3.8983	5.8422	16.7945	30.3183	9.7302	12.4016	13.1359	7.5517	6.8271	5.9817
MAPE	2.7109	4.6772	3.6486	4.2796	13.2355	25.5936	8.4765	10.5356	12.2847	4.9769	5.8978	4.8882
RMSLE	0.0716	0.1557	0.1309	0.0932	0.2573	0.3329	0.1252	0.2354	0.2353	0.1120	0.1702	0.1581
R	0.8451	0.9736	0.9888	0.5813	0.8795	0.7491	0.3008	0.7678	0.9022	0.4776	0.9693	0.9950
RRSE	0.4015	0.1926	0.1134	0.6830	0.5289	0.6062	1.2365	0.5067	0.3347	0.9867	0.2434	0.1015

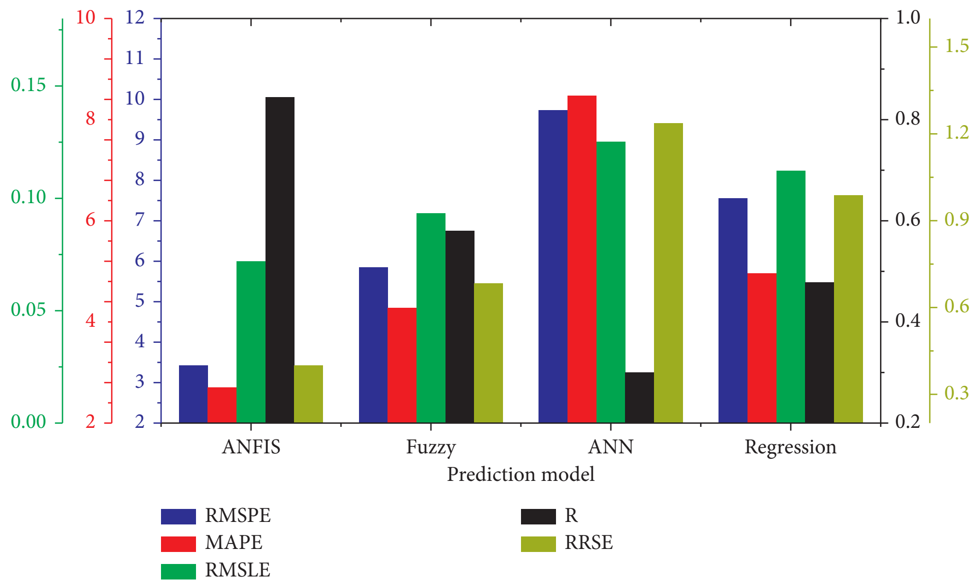

Figure 13: Performance indices of various models for Ra.

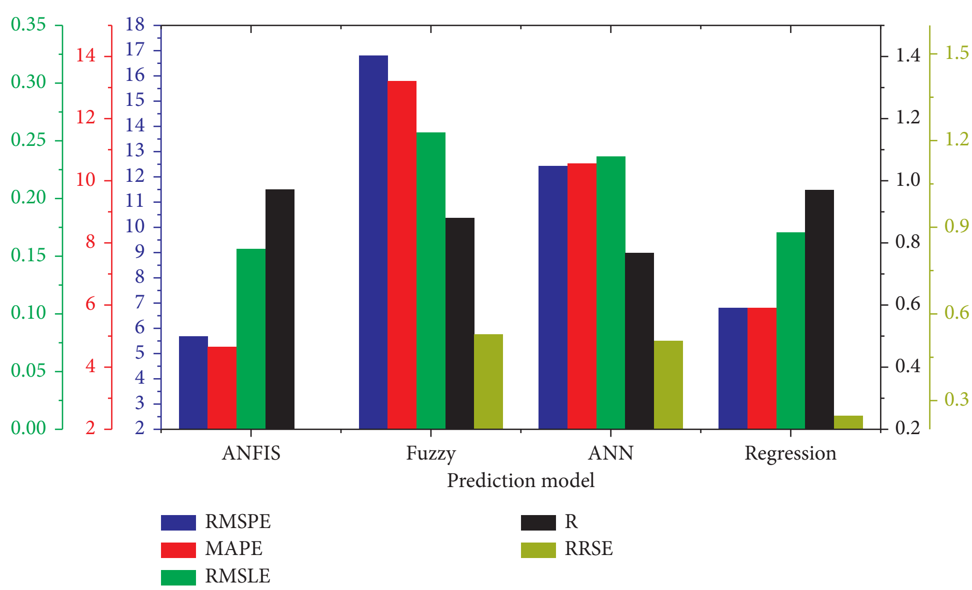

Figure 14: Performance indices of various models for Fc.

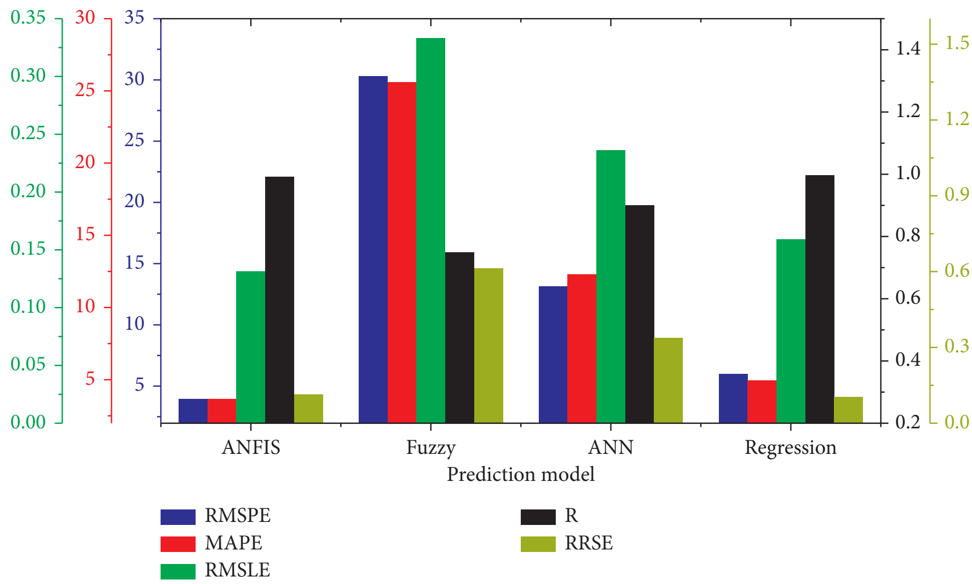

Figure 15: Performance indices of various models for MRR.

Table 7: Performance indices of ANFIS model for different membership functions.

Statistical measure	Membership function: Generalized bell			Gaussian			Trapezoidal			Triangular		
	Ra	Fc	MRR	Ra	Fc	MRR	Ra	Fc	MRR	Ra	Fc	MRR
RMSPE	3.4183	5.6912	3.8983	3.7161	6.3457	3.8466	3.9546	7.0451	5.4161	4.1897	9.4350	6.8082
MAPE	2.7109	4.6772	3.6486	3.3200	5.2817	3.4994	3.2481	6.6107	5.2262	3.7050	8.8452	6.6416
RMSLE	0.0716	0.1557	0.1309	0.0757	0.1628	0.1294	0.0774	0.1744	0.1531	0.0801	0.2037	0.1721
R	0.8451	0.9736	0.9888	0.8349	0.9670	0.9885	0.8094	0.9526	0.9776	0.8062	0.8523	0.9708
RRSE	0.4015	0.1926	0.1134	0.4547	0.2145	0.1155	0.4734	0.2685	0.1547	0.5120	0.3920	0.1861

types of input membership function, that is, generalized bell, Gaussian, trapezoidal, and triangular, with respect to RMSPE, MAPE, RMSLE, *R*, and RRSE values. It can be concluded that ANFIS model with the generalized bell membership function performs best as the prediction tool for this dry turning operation of AISI 304 stainless steel material.

6. Conclusions

In this paper, an endeavour is put forward to compare the performances of four prediction tools, that is, regression analysis, fuzzy logic, ANN, and ANFIS models, based on a set of 27 pieces of experimental data during dry turning operation on AISI 304 stainless steel work material. Five statistical metrics, that is, RMSPE, MAPE, RMSLE, *R*, and RRSE, are deployed for this purpose. It can be noticed that the developed ANFIS model outperforms the other prediction tools with respect to all the statistical measures. Again, among different membership functions for the input variables of ANFIS model, the best prediction performance is attained while using generalized bell membership function. It is also noticed that the fuzzy logic model develops only 18 rules using the training dataset, whereas 27 rules are generated in the ANFIS model, ensuring its better prediction performance as compared to fuzzy logic model. As the ANFIS model is developed incorporating the advantageous features of both fuzzy logic and ANN, it is expected that its prediction performance would be better than its constituent elements. Although all these models are developed using only 27 experimental runs, it is quite expected that additional experimental data (generated by simulation runs) may further increase their prediction accuracy. But it has been recommended that, after a certain point, feeding more data into a predictive model dose not improve accuracy. Thus, ANFIS model can be employed as an effective tool in predicting different response values based on experimental datasets from the conventional as well as non-conventional machining processes. As a future scope, the efficacy of other variants of ANFIS model, like ANFIS grid partitioning method and ANFIS subtractive clustering method, can be verified as the prediction tools in real-time sustainable manufacturing environment.

Data Availability

No data were used to support the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Differential Game Analysis of the Green Innovation Cooperation in Supply Chain under the Background of Dual-Driving

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Taking government environmental regulation and consumer's green preference into a unified analytical framework, this study constructed a differential game model. With the joint effect of supplier and manufacturer green innovation efforts on the dynamic change of the product's green level, it compared and analyzed the long-term dynamic equilibrium strategies of green innovation cooperation in a supply chain under decentralized and centralized decision-making situations. Accordingly, a scientific and reasonable profit-distribution contract was then proposed. On this basis, it further carried out a numerical simulation analysis on the dual-driving effects of the government and market. The results showed that the scientific and reasonable profit-distribution contract under the centralized decision-making situation, which was designed by using the Rubinstein bargaining game model, could effectively ensure that the supply chain members' sharing profits would realize "Dual Pareto Improvements." With the increase of the environmental regulation's intensity, the product's green level kept rising and tended to be stable. However, the overall equilibrium profit of the supply chain was characterized by "U" fluctuation, which first descended and then ascended. In addition, the product's green level, the green innovation investment and equilibrium (distributed) profits of supply chain members, and the overall profits of supply chain all increased with the consumers' green preference.

1. Introduction

The growing concern for environmental protection in recent years has forced countries to pursue low-carbon economics and sustainable development. At the 75th Session of the United Nations General Assembly (2020), China made a solemn commitment to the world that it would adopt more forceful policies and measures to peak its carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060. In China, strengthening environmental supervision will become an inevitable trend in the long term [1]. With the promulgation and implementation of a series of environmental regulations, enterprises have been subjected to increasingly serious administrative penalties for their pollution behaviors, and they have even been faced with the punishment of having their production limited or outright stopped for rectification. Meanwhile, with the continuously improving social awareness of environmental protection [2], more and more consumers tend to choose green products and are willing to pay higher prices for them to a certain degree [3]. Thus, under the background of stringent environmental regulations and consumers' green preference, the competitiveness and even survival of enterprises increasingly depend on whether they can respond to the requirements of sustainable development [4]. Numerous studies have shown that compared with general innovation, which only emphasizes economic performance, green innovation focuses on saving energy consumption and reducing pollutant emission in the production process through innovation, product development, and process optimization, so as to maximally reduce the negative impact on the environment [5]. Enterprises that implement green innovation often have a stronger competitive advantage than their competitors due to increased eco-efficiency and environmental image [6].

Besides, there is a growing recognition that individual businesses no longer compete as solely autonomous entities but rather as supply chains, in which the enterprises are interdependent [7, 8]. In other words, problems in any part of the supply chain may have a serious negative impact on other participants and can even lead to the rupture and failure of the whole supply chain [9]. On September 14, 2017, Schaeffler Greater China issued an Emergency Help Letter stating that Jielong, the only supplier of needle rolling raw materials in use, was ordered to stop production and dismantle the equipment due to its environmental problems. The supply shortage of needle rolling would result in the suspension of more than 200 models from 49 auto manufacturers. Thus, in the context of strong environmental regulation and green consumption upgrading, it is far from sufficient for enterprises to simply conduct their own environmental management compliance work well. They also need to cooperate with upstream/downstream supply chain partners on green innovation to improve the environmental performance, especially ones in complex industrial chains [10]. Green innovation cooperation in a supply chain refers to the cooperation between upstream and downstream members to carry out green innovation with the purpose of reducing or eliminating the negative impact of products or services on the environment [11]. For example, in order to incentivize the supplier to invest more in green innovation and make the product more environment friendly, the manufacturer is willing to share some of the spending [12]. Compared with other types of cooperation in supply chain, green innovation cooperation is driven not only by market factors (consumers' green preference) but also by government factors (environmental regulation). In practice, more than 1000 big firms, such as Lenovo, Bosch, Dell, and Apple, emphasize the importance of green investment and also motivate the upstream/downstream partners to drive and facilitate green innovation [13].

This paper is relevant to the current literature from two perspectives. The first is that we conducted research into the characteristics and driving factors of green innovation. The addition of the environmental dimension brings green innovation remarkable characteristics, including the explicit demand for environmental benefits, the dual externalities of technology and environment, and the push/pull effect of environmental regulations [14, 15]. Furthermore, the characteristics of dual externalities have severely hindered enterprises from investing in green innovation. Thus, environmental regulation has become an extremely important driving factor for green innovation. For example, the famous Porter hypothesis proposed by Porter and Van der Linde [16] believed that scientific and reasonable environmental regulation can stimulate enterprises' innovative behavior and consequently achieve a win-win situation of economic and environmental benefits. Similar to general innovation, market demand or customer pressure is another important driver of green innovation [17, 18]. The research on the characteristics and driving factors of green innovation has achieved fruitful results, laying a solid theoretical foundation for our study.

Combining the characteristics of green innovation, many scholars investigated the optimal decision and the influence of the driving factors on the equilibrium strategies in a green supply chain. This is the second part of our literature review. Benjaafar et al. [19] were the first to introduce different carbon emission policies (carbon tax, carbon cap-and-trade, carbon offsets, etc.) into a simple supply chain, providing a basic solution to carbon reduction. Du et al. [20] analyzed the possibility for manufacturers and suppliers to coordinate and cooperate in emission reduction under cap-and-trade emission policy. Chen et al. [21] endogenized government subsidy in a research joint venture and deduced the equilibrium strategies of the innovation effort level and cost sharing ratio. On this basis, many scholars have included market-driven effect into the analytical framework. For example, Zhang and Yousaf [22] and Meng et al. [23] analyzed the optimal innovation decisions in a supply chain by taking the comprehensive influence of government intervention and consumers' green preference into account. However, the above research studies on green innovation cooperation in a supply chain mainly focused on the analysis of static equilibrium strategies.

In fact, the supply chain environment management is a long-term dynamic process, and the effects of green innovation can be intertemporal. By constructing differential equations in which the variables evolve with time, differential game is usually used to analyze the conflict and cooperation problems in dynamic situations [24, 25]. In the recent research studies related to the green supply chain, scholars often use differential game theory to investigate the optimal decisions and the variation with time. Considering the impact of environmental regulation, Wang et al. [26] and Yu et al. [27] introduced carbon tax parameters when constructing the differential game models to explore the dynamic cooperation strategies of the low-carbon technology. Wei and Wang [28] analyzed the interaction between carbon reduction technology innovation and government intervention by using the differential game method. However, they did not take the consumers' green preference into account. Subsequently, Liu and Li [29] introduced low-carbon preference into the differential game models and analyzed the dynamic impacts of low-carbon reference on carbon reduction. Furthermore, Zu and Zeng [30] analyzed the dynamic optimization problem of energy-efficiency efforts and product pricing with considering the discontinuous market demand. However, they did not consider the impact of environmental regulation. Besides, differential game analysis has been well applied in analyzing dynamic equilibrium strategies of advertising investment, quality improvement, and so on [31, 32].

On the basis of the existing research results, we take government environmental regulation and consumers' green preference into a unified analysis framework, using the differential game model to study the cooperative innovation dynamic strategies. In addition, this study also proposes a scientific and rationale profit-distribution contract to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance.

Compared to existing research, the contribution of this paper is mainly reflected in three main aspects:

(1) This study comprehensively considers the dual-driving effect of government and market on the green innovation cooperation in a supply chain. As far as we can determine, existing studies mainly concentrated on the impact of a single driving factor on green innovation decisions in a supply chain either in terms of consumers' green preference or environmental regulation. There is still little research on the superposed effects of two driving factors. However, government regulation and market demand are the two most important drivers of green innovation [18]. In this study, both government regulation and consumers' green preference are included into the analytical framework when constructing the game models. Moreover, we also analyze and compare the optimal cooperation strategies for green innovation between supply chain members under the decentralized and centralized decision situations.

(2) This study analyses the optimal decisions dynamically rather than statically by using differential equations to describe the changes of product green level with the supply chain members' innovation efforts. To the best of our knowledge, research on the dynamic equilibrium strategies of the green innovation cooperation in a supply chain is very scarce, especially considering the dual-driving effects of the government and the market. In fact, green innovation, pollutant emissions, market demand, etc. are all dynamic phenomena [30, 33]. The investment of the members' innovation in the prior period will affect the products' green level and the relevant decisions in the next period. Thus, applying differential game theory to analyze the dynamic strategies in this study is closer to the reality of the situation. More importantly, the government and market dual-driving effect is also considered in this study when using differential game to analyze the dynamic strategies. This study will effectively extend the existing research.

(3) A scientifical and rational profit-distribution agreement under the centralized decision situations is proposed in this study. After analyzing the long-term dynamic equilibrium strategies of green innovation cooperation under decentralized and centralized decision situations, this study further designs a profit-distribution agreement by using the Rubinstein bargaining game model to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance. This study can provide a useful reference for the green innovation practice of supply chain members.

The remainder of the article is arranged as follows: Section 2 describes the problem and assumptions of the model. Section 3 discusses and compares the long-term dynamic equilibrium strategies under decentralized and centralized decision-making scenarios. Section 4 provides a profit-distribution contract for the supply chain. Some simulations and sensitivity analysis are given in Section 5. The conclusions and research prospects are given in Section 6.

2. Problem Description and Assumptions

2.1. Problem Description. This article assumes that the green supply chain consists of one large manufacturer (as leader) and one supplier (as follower). In order to meet the consumers' demand for green purchase, the supplier and manufacturer invest in green innovation by introducing new technologies, purchasing new equipment, and transforming existing technological processes, so as to reduce the energy consumption and pollutant emissions in the production process and improve the product's green level. In the context of sustainable development, more and more countries are actively implementing their carbon labeling plans, i.e., marking the carbon emissions of products in the production process with a quantified indicator and implementing the government regulations on the final products according to the carbon emission standards. Drawing from Zu et al. [34], the energy consumption standard and pollutant emissions constraints of the government only focus on the manufacturer without considering the emission cost or benefits incurred by the supplier. Meanwhile, Heydari et al. [35] found that it is more cost-effective for the government to provide subsidies or tax exemption for manufacturers rather than other members in the supply chain. Thus, we assume that the government rewards or punishes the manufacturer according to the product's green level. Besides, the large manufacturer, as the leader, is willing to bear part or all of the green innovation investment costs for supplier, in order to encourage the supplier to increase innovation investment and improve the greenness of their products. The research framework of this paper is shown in Figure 1.

2.2. Assumptions

Assumption 1. The supplier and the manufacturer will work together on green innovation to reduce energy consumption and pollutant discharge per unit product and improve the product's green level. With the passage of time, the product's green level will naturally decline due to the aging and backwardness of emission-reduction technologies, equipment, etc. Drawing from EI Ouardighi [36], we modify the classic goodwill model of Nerlove–Arrow [37] according to the characteristics of green innovation to describe the change of product's green level.

$$\dot{E}(t) = \alpha S(t) + \beta M(t) - \sigma E(t), \tag{1}$$

where $E(t) \geq 0$ is the product's green level at time t, and the initial green level $E(0)$ is assumed to be 0. This indicates that the supplier and manufacturer have not invested in green innovation prior to the initial time. $S(t) \geq 0$ and $M(t) \geq 0$, respectively, represent the green innovation efforts of the supplier and manufacturer at time t. $\alpha > 0$ and $\beta > 0$, respectively, represent the marginal contribution rates of green innovation efforts of the supplier and manufacturer to the product's green level. $\sigma > 0$ is the natural decay rate of the product's green level.

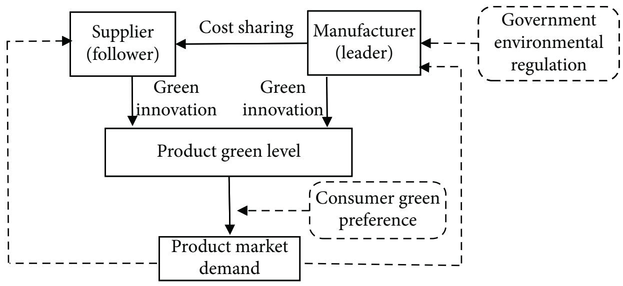


Figure 1: Framework of cooperative innovation in a green supply chain under the background of dual-driving.

Assumption 2. Like the method used by most scholars to deal with the green innovation cost, we assume that the green innovation cost of the supplier and manufacturer is a convex increasing function of green innovation efforts, namely,

$$C_S(t) = \frac{\eta_S}{2} S(t)^2, \quad C_M(t) = \frac{\eta_M}{2} M(t)^2, \tag{2}$$

where $C_S(t)$ and $C_M(t)$, respectively, represent the cost of green innovation efforts from the supplier and manufacturer at time t. The representation of innovation cost by the quadratic function is commonly used in the literature [29, 34] $\eta_S > 0$ and $\eta_M > 0$ respectively, represent the cost coefficients of green innovation efforts of the supplier and manufacturer.

Assumption 3. Regardless of the influence of green product prices, we assume that consumers with green preference will tend to buy products with higher green level [30, 38], namely,

$$D(t) = \overline{D} + \theta E(t), \tag{3}$$

where $D(t) \geq 0$ is the market demand for green products at time t and $\overline{D} > 0$ is the product market scale before green innovation from the supplier and manufacturer. $\theta > 0$ is the coefficient of consumer green preference, representing the positive impact of the product's green level on the market demand.

Assumption 4. In the context of the low-carbon economy, pollutant discharge behaviors of enterprises are regulated by the government environmental regulation, such as carbon tax, carbon trading, carbon cap, and innovation subsidies. Drawing from Wei and Wang [28], we assume that, in the context of low-carbon policies, the regulation cost or benefit of pollutant emission by enterprises is

$$T_g(t) = \varphi\left[\left(E_h - E(t) - E_g\right)D(t)\right], \tag{4}$$

where $T_g(t)$ is the regulation cost or benefit generated by pollutant emission of enterprises at time t under environmental regulation. $\varphi > 0$ is the intensity of government regulation, which can be expressed in various forms, such as government carbon tax rate, carbon trading price, and incentive/subsidy for unit emission reduction. $E_h \geq 0$ is the initial pollutant emission of unit product. $E_g \geq 0$ is the amount of pollution emitted per unit of product assigned by the government. Thus, $(E_h - E(t) - E_g)D(t) > 0$ indicates that the actual pollutant emission of the enterprise exceeds the carbon emission limit set by the government, so the enterprise needs to purchase the emission right or pay emission fee (tax). On the contrary, $(E_h - E(t) - E_g)D(t) < 0$ means that the enterprise can sell emission rights or obtain government subsidies. Without loss of generality, we assume $E_g = 0$, namely, $T_g(t) = \varphi(E_h - E(t))D(t)$.

Assumption 5. To encourage the supplier to increase innovation investment, the manufacturer that plays a dominant role in the supply chain will be willing to actively bear part or all of the green innovation costs for the supplier in order to improve the product's green level, expand the market scale, and reduce the costs required to comply with the environmental regulations. $\lambda(t)\,(0 \leq \lambda(t) \leq 1)$ is the proportion of green innovation cost shared by the manufacturer for the supplier at time t.

Assumption 6. This study aims to explore the optimal decision in green innovation cooperation between upstream and downstream enterprises in the green supply chain under the dual-driving of both government and market, while ignoring the influences of other factors such as product prices, inventory costs, and shortage costs. Without loss of generality, the inventory costs and shortage costs of the members in the supply chain are recorded as 0. π_S and π_M, respectively, represent the marginal profit of the supplier and the manufacturer. At any time, all members of the supply chain have the same discount factor, denoted as $\rho\,(\rho > 0)$. Supplier, manufacturer, and supply chain variables are, respectively, denoted by the subscripts S, M, and C. As a result, members of the supply chain and their overall long-term profits are as follows:

$$\begin{aligned}
J_S &= \int_0^{\infty} e^{-\rho t}\left[\pi_S(\overline{D} + \theta E(t)) - \frac{\eta_S(1-\lambda(t))}{2} S(t)^2\right] \mathrm{d}t, \\
J_M &= \int_0^{\infty} e^{-\rho t}\left[\left[\pi_M - \varphi(E_h - E(t))\right](\overline{D} + \theta E(t)) - \frac{\eta_M}{2} M(t)^2 - \frac{\eta_S \lambda(t)}{2} S(t)^2\right] \mathrm{d}t, \\
J_C &= \int_0^{\infty} e^{-\rho t}\left[\left[\pi_S + \pi_M - \varphi(E_h - E(t))\right](\overline{D} + \theta E(t)) - \frac{\eta_M}{2} M(t)^2 - \frac{\eta_S}{2} S(t)^2\right] \mathrm{d}t.
\end{aligned} \tag{5}$$

In summary, compared with the existing literature, the model constructed in this study has the following differences: (1) using the differential equation to describe the dynamic change of the product's green level; (2) while considering the impact of consumers' green preference on the demands, the environmental regulation intensity is also introduced to describe the cost or benefit of enterprises' environmental behavior.

All of the parameters in this model are atemporal constants. For the convenience of writing, t will not be listed.

3. Model Analysis

3.1. Decentralized Decision-Making Model. Under the decentralized decision-making situation, the manufacturer and the supplier have a two-stage Stackelberg game. In terms of the decision-making process, the manufacturer first determines its green innovation efforts and the proportion of green innovation costs to be borne by it for the supplier; then, the supplier further determines its optimal green innovation efforts. The decision-making model is (marked with a superscript D)

$$\begin{cases} \max\limits_{M,\lambda} J_M^D = \int_0^\infty e^{-\rho t}\left[\left[\pi_M - \varphi\left(E_h - E\right)\right]\left(\overline{D} + \theta E\right) - \dfrac{\eta_M}{2}M^2 - \dfrac{\eta_S\lambda}{2}S^2 \right]\mathrm{d}t, \\ \max\limits_{S} J_S^D = \int_0^\infty e^{-\rho t}\left[\pi_S\left(\overline{D} + \theta E\right) - \dfrac{\eta_S(1-\lambda)}{2}S^2 \right]\mathrm{d}t. \end{cases} \tag{6}$$

Theorem 1. *Under the decentralized decision-making situation, the long-term equilibrium strategies of the green innovation cooperation in the supply chain are as follows:*

(1) The optimal green innovation efforts of the supply chain members and the proportion of green innovation costs to be borne by the manufacturer for the supplier are

$$\begin{cases} S^{D*} = \dfrac{2\alpha m_1^*}{\eta_S}E^D + \dfrac{\alpha\left(2m_2^* + s_1^*\right)}{2\eta_S}, \\ M^{D*} = \dfrac{2\beta m_1^*}{\eta_M}E^D + \dfrac{\beta\left(m_2^* + s_1^*\right)}{\eta_M}, \\ \lambda^* = \dfrac{4m_1^*E^D + 2m_2^* - s_1^*}{4m_1^*E^D + 2m_2^* + s_1^*}. \end{cases} \tag{7}$$

(2) The optimal trajectory of the products' green level is

$$E^D(t) = E_{RSS}^D\left(1 - e^{-\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t}\right), \tag{8}$$

where $E_{RSS}^D = \left(\left(2m_2^*\left(\Delta_1 + \Delta_2\right) + s_1^*\left(\Delta_1 + 2\Delta_2\right)\right)/\left(2\left[\sigma - 2m_1^*\left(\Delta_1 + \Delta_2\right)\right]\right)\right)$ *is the stable value of the product's green level under the decentralized decision-making situation when the time factor approaches infinity* ($t \longrightarrow \infty$).

(3) The long-term profits of the supplier, manufacturer, and the whole supply chain are

$$\begin{cases} J_S^{D*} = s_1^*E_{RSS}^D + s_2^* - s_1^*E_{RSS}^D e^{-\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t}, \\ J_M^{D*} = m_1^*\left(E_{RSS}^D\right)^2 e^{-2\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t} - \left(2m_1^*E_{RSS}^D + m_2^*\right)E_{RSS}^D e^{-\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t} + \\ m_1^*\left(E_{RSS}^D\right)^2 + m_2^*E_{RSS}^D + m_3^*, \\ J_C^{D*} = m_1^*\left(E_{RSS}^D\right)^2 e^{-2\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t} - \left(2m_1^*E_{RSS}^D + m_2^* + s_1^*\right)E_{RSS}^D e^{-\left(\sigma - 2m_1^*\left(\Delta_1+\Delta_2\right)\right)t} + \\ m_1^*\left(E_{RSS}^D\right)^2 + m_2^*E_{RSS}^D + s_1^*E_{RSS}^D + s_2^* + m_3^*, \end{cases} \tag{9}$$

where m_1^*,m_2^*,m_3^*,s_1^*, and s_2^* satisfy the following formula:

$$\begin{cases} m_1^* = \dfrac{(\rho+2\sigma) - \sqrt{(\rho+2\sigma)^2 - 8\theta\varphi(\Delta_1+\Delta_2)}}{4(\Delta_1+\Delta_2)}, \\ s_1^* = \dfrac{4\theta\pi_S(\Delta_1+\Delta_2)}{\rho(3\Delta_1+2\Delta_2)+2\sigma\Delta_1+(\Delta_1+2\Delta_2)\sqrt{(\rho+2\sigma)^2-8\theta\varphi(\Delta_1+\Delta_2)}} \\ m_2^* = \dfrac{2}{\rho+\sqrt{(\rho+2\sigma)^2-8\theta\varphi(\Delta_1+\Delta_2)}}\{\theta(\pi_M-\varphi E_h)+\overline{D}\varphi+ \\ \dfrac{\Delta_1\theta\pi_S\left[\rho+2\sigma-\sqrt{(\rho+2\sigma)^2-8\theta\varphi(\Delta_1+\Delta_2)}\right]}{\rho(3\Delta_1+2\Delta_2)+2\sigma\Delta_1+(\Delta_1+2\Delta_2)\sqrt{(\rho+2\sigma)^2-8\theta\varphi(\Delta_1+\Delta_2)}}\Bigg\}, \\ s_2^* = \dfrac{\overline{D}\pi_S}{\rho} + \dfrac{(\Delta_1+2\Delta_2)s_1^*m_2^*}{2\rho} + \dfrac{\Delta_1 s_1^{*\,2}}{4\rho}, \\ m_3^* = \dfrac{\overline{D}(\pi_M-\varphi E_h)}{\rho} + \dfrac{m_2^{*\,2}(\Delta_1+\Delta_2)}{2\rho} + \dfrac{\Delta_1 s_1^* m_2^*}{2\rho} + \dfrac{\Delta_1 s_1^{*\,2}}{8\rho}, \\ \Delta_1 = \dfrac{\alpha^2}{\eta_S}, \\ \Delta_2 = \dfrac{\beta^2}{\eta_M}. \end{cases} \tag{10}$$

Both $(\rho+2\sigma)^2 \geq 8\theta\varphi(\Delta_1+\Delta_2)$ and $\sigma \geq 2m_1^*(\Delta_1+\Delta_1)$ need to be satisfied. For the sake of convenience, the subsequent research, analysis, and numerical simulation are conducted within this range.

Proof. Similar to many scholars, such as Liu and Li [29], Zu et al. [34], and Lu et al. [39], we try to seek a steady-state feedback Stackelberg equilibrium because the game is played over an infinite time horizon. Backward induction is used to solve the model.

Assume that, after time t, the optimal value function of the supplier's long-term profit is $J_S^{D*}(S) = e^{-\rho t}V_S^D(E)$, and for any $E \geq 0$, $V_S^D(E)$ satisfies the Hamilton–Jacobi–Bellman (HJB) equation:

$$\rho V_S^D(E) = \max_S\left\{\pi_S(\overline{D}+\theta E) - \frac{\eta_S(1-\lambda)}{2}S^2 + V_S^{D'}(\alpha S+\beta M-\sigma E)\right\}. \tag{11}$$

Find the first-order partial derivative for the supplier's optimal green innovation effort (S) on the right side of formula (11) and make it equal to zero to obtain

$$S = \frac{\alpha V_S^{D'}}{\eta_S(1-\lambda)}. \tag{12}$$

Similarly, assume that the optimal value function of the manufacturer's long-term profit after time t is $J_M^{D*}(M,\lambda) = e^{-\rho t}V_M^D(E)$, and for any $E \geq 0$, $V_M^D(E)$ satisfies the HJB equation:

$$\rho V_M^D(E) = \max_{M,\lambda}\left\{[\pi_M - \varphi(E_h - E)](\overline{D}+\theta E) - \frac{\eta_M}{2}M^2 - \frac{\eta_S\lambda}{2}S^2 + V_M^{D'}(\alpha S+\beta M-\sigma E)\right\}. \tag{13}$$

Find the first-order partial derivative for the manufacturer's optimal green innovation effort (M) and the optimal proportion on the right side of formula (13) and make them equal to zero to obtain

$$\begin{aligned} M &= \frac{\beta V_M^{\dot{D}}}{\eta_M}, \\ \lambda &= \frac{2V_M^{\dot{D}} - V_S^{\dot{D}}}{2V_M^{\dot{D}} + V_S^{\dot{D}}}. \end{aligned} \tag{14}$$

Substituting formulas (12) and (14) into HJB equations (11) and (13), we can obtain

$$\begin{cases} \rho V_S^D(E) = \pi_S(\overline{D} + \theta E) - \sigma V_S^{\dot{D}} E + \dfrac{\alpha^2 V_S^{\dot{D}}\left(2V_M^{\dot{D}} + V_S^{\dot{D}}\right)}{4\eta_S} + \dfrac{\beta^2 V_S^{\dot{D}} V_M^{\dot{D}}}{\eta_M}, \\ \rho V_M^D(E) = [\pi_M - \varphi(E_h - E)](\overline{D} + \theta E) - \sigma V_M^{\dot{D}} E + \dfrac{\alpha^2\left(2V_M^{\dot{D}} + V_S^{\dot{D}}\right)^2}{8\eta_S} + \dfrac{\beta^2 V_M^{D'2}}{2\eta_M}. \end{cases} \tag{15}$$

Assume that the analytical expressions of optimal value functions $V_S^D(E)$ and $V_M^D(E)$ with E are, respectively, $V_S^D(E) = s_1 E + s_2$ and $V_M^D(E) = m_1 E^2 + m_2 E + m_3$, where m_1, m_2, m_3, s_1, and s_2 are constants, and combine this with the method of undetermined coefficients to obtain

$$\begin{cases} \rho s_1 = \theta\pi_S - \sigma s_1 + s_1 m_1(\Delta_1 + 2\Delta_2), \\ \rho s_2 = \overline{D}\pi_S + \dfrac{(\Delta_1 + 2\Delta_2)s_1 m_2}{2} + \dfrac{\Delta_1 s_1^2}{4}, \\ \rho m_1 = \theta\varphi - 2\sigma m_1 + 2m_1^2(\Delta_1 + \Delta_2), \\ \rho m_2 = \theta(\pi_M - \varphi E_h) + \overline{D}\varphi - \sigma m_2 + 2m_1 m_2(\Delta_1 + \Delta_2) + \Delta_1 s_1 m_1, \\ \rho m_3 = \overline{D}(\pi_M - \varphi E_h) + \dfrac{m_2^2(\Delta_1 + \Delta_2)}{2} + \dfrac{\Delta_1 s_1 m_2}{2} + \dfrac{\Delta_1 s_1^2}{8}. \end{cases} \tag{16}$$

Solve m_1, m_2, m_3, s_1, and s_2, and ensure that, for any S^D, M^D, E^D, $V_S^D(E)$, and $V_M^D(E)$, they are nonnegative. The expressions of m_1^*, m_2^*, m_3^*, s_1^*, and s_2^* that meet the conditions are shown in formula (10). Furthermore, we obtain the optimal green innovation efforts of the supplier and the manufacturer (S^{D*}, M^{D*}) and the proportion of green innovation costs to be borne by the manufacturer for the supplier (λ^*) under the decentralized decision-making situation, as shown in Theorem 1 (1). In addition, the implicit condition of Theorem 1 is $(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2) \geq 0$.

Then, substitute S^{D*} and M^{D*} into equation (1) to obtain

$$\dot{E}^D(t) = m_2^*(\Delta_1 + \Delta_2) + s_1^*\left(\frac{\Delta_1}{2} + \Delta_2\right) - [\sigma - 2m_1^*(\Delta_1 + \Delta_2)]E. \tag{17}$$

Solve the differential equation (17) to obtain the optimal trajectory of the product's green level under the decentralized decision-making situation, as shown in Theorem 1 (2).

If $\sigma - 2m_1^*(\Delta_1 + \Delta_2) < 0$, when the time factor approaches infinity, $E^D(t)$ will also approach infinity. This is inconsistent with the reality. If $\sigma - 2m_1^*(\Delta_1 + \Delta_2) \geq 0$, E_{RSS}^D is the stable value of the product's green level when the time factor approaches infinity.

Furthermore, we obtain the long-term profits of supplier, manufacturer, and the whole green supply chain under the decentralized decision-making situation, as shown in Theorem 1 (3). □

3.2. Centralized Decision-Making Model. In this situation, the manufacturer and the supplier should work together to determine their optimal green innovation efforts for the purpose of maximizing supply chain profits. The strategic problem is (marked with a superscript C)

$$\max_{S,M} J_C^C = \int_0^{\infty} e^{-\rho t}\left\{\left[\pi_S + \pi_M - \varphi\left(E_h - E\right)\right]\left(\overline{D} + \theta E\right) - \frac{\eta_M}{2}M^2 - \frac{\eta_S}{2}S^2\right\}\mathrm{d}t. \tag{18}$$

Theorem 2. *Under the centralized decision-making situation, the long-term equilibrium strategies for the green innovation cooperation in the supply chain are as follows:*

(1) The optimal green innovation efforts of the supply chain members are

$$\begin{cases} S^{C*} = \dfrac{2\alpha c_1^*}{\eta_S}E^C + \dfrac{\alpha c_2^*}{\eta_S}, \\ M^{C*} = \dfrac{2\beta c_1^*}{\eta_M}E^C + \dfrac{\beta c_2^*}{\eta_M}. \end{cases} \tag{19}$$

(2) The optimal trajectory of the product's green level is

$$E^C(t) = E_{RSS}^C\left(1 - e^{-\left(\sigma - 2c_1^*\left(\Delta_1+\Delta_2\right)\right)t}\right), \tag{20}$$

where $E_{RSS}^C = \left(\left(2c_2^*\left(\Delta_1 + \Delta_2\right)\right)/\left(\sigma - 2c_1^*\left(\Delta_1 + \Delta_2\right)\right)\right)$ *is the stable value of the product's green level under centralized decision-making situation when the time factor approaches infinity* $(t \longrightarrow \infty)$.

(3) The long-term equilibrium profit of the whole green supply chain is

$$J_C^{C*} = c_1^*\left(E_{RSS}^C\right)^2 e^{-2\left(\sigma - 2c_1^*\left(\Delta_1+\Delta_2\right)\right)t} - \left(2c_1^* E_{RSS}^C + c_2^*\right)E_{RSS}^C e^{-\left(\sigma - 2c_1^*\left(\Delta_1+\Delta_2\right)\right)t} + c_1^*\left(E_{RSS}^C\right)^2 + c_2^* E_{RSS}^C + c_3^*, \tag{21}$$

where c_1^*, c_2^*, *and* c_3^* *satisfy the following formula:*

$$\begin{cases} c_1^* = \dfrac{(\rho + 2\sigma) - \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi\left(\Delta_1 + \Delta_2\right)}}{4\left(\Delta_1 + \Delta_2\right)}, \\ c_2^* = \dfrac{2\theta\left(\pi_S + \pi_M - \varphi E_h\right) + 2\overline{D}\varphi}{\rho + \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi\left(\Delta_1 + \Delta_2\right)}}, \\ c_3^* = \dfrac{\overline{D}\left(\pi_S + \pi_M - \varphi E_h\right)}{\rho} + \dfrac{\left(\Delta_1 + \Delta_2\right)c_2^{*2}}{2\rho}. \end{cases} \tag{22}$$

Both $(\rho + 2\sigma)^2 - 8\theta\varphi\left(\Delta_1 + \Delta_2\right) \geq 0$ *and* $\sigma - 2c_1^*\left(\Delta_1 + \Delta_1\right) \geq 0$ *need to be satisfied.*

Proof. Similarly, we assume that the optimal value function of the supplier's long-term profit after time t is $J_C^{C*}(S, M) = e^{-\rho t}V_C^C(E)$, and for any $E \geq 0$, $V_C^C(E)$ satisfies the HJB equation:

$$\rho V_C^C(E) = \max_{S,M}\left\{\left[\pi_S + \pi_M - \varphi\left(E_h - E\right)\right]\left(\overline{D} + \theta E\right) - \frac{\eta_M}{2}M^2 - \frac{\eta_S}{2}S^2 + V_C^{\acute{C}}(\alpha S + \beta M - \sigma E)\right\}. \tag{23}$$

Find the first-order partial derivative for the supplier's green innovation effort (S) and manufacturer's green innovation effort (M) on the right side of formula (23) and make them equal to zero to obtain

$$\begin{aligned} S &= \frac{\alpha V_C^{\acute{C}}}{\eta_S}, \\ M &= \frac{\beta V_C^{\acute{C}}}{\eta_M}. \end{aligned} \tag{24}$$

Substitute formula (24) into formula (23) to obtain

$$\begin{aligned} \rho V_C^C(E) &= \left[\pi_S + \pi_M - \varphi\left(E_h - E\right)\right]\left(\overline{D} + \theta E\right) - \sigma V_C^{\acute{C}}E \\ &\quad + \frac{\alpha^2\left(V_C^{\acute{C}}\right)^2}{2\eta_S} + \frac{\beta^2\left(V_C^{\acute{C}}\right)^2}{2\eta_M}. \end{aligned} \tag{25}$$

Similarly, assume $V_C^C(E) = c_1E^2 + c_2E + c_3$, where, c_1, c_2, and c_3 are constants, and combine this with the method of undetermined coefficients. We can obtain

$$\begin{cases} \rho c_1 = \theta\varphi - 2\sigma c_1 + 2c_1^2(\Delta_1 + \Delta_2), \\ \rho c_2 = \theta(\pi_S + \pi_M - \varphi E_h) + \overline{D}\varphi - \sigma c_2 + 2c_1c_2(\Delta_1 + \Delta_2), \\ \rho c_3 = \overline{D}(\pi_S + \pi_M - \varphi E_h) + \dfrac{c_2^2}{2}(\Delta_1 + \Delta_2). \end{cases} \quad (26)$$

Solve c_1, c_2, and c_3, and ensure that, for any S^C, M^C, E^C, and $V_C^C(E)$, they are nonnegative. The expressions of c_1^*, c_2^*, and c_3^* that meet the conditions are shown in formula (22). Furthermore, we obtain the optimal green innovation efforts of the supply chain members under the centralized decision-making situation, as shown in Theorem 2 (1).

Then, substitute the optimal green innovation strategy (formula (19)) into equation (1) to obtain

$$\dot{E}^C(t) = c_2^*(\Delta_1 + \Delta_2) - [\sigma - 2c_1^*(\Delta_1 + \Delta_2)]E. \quad (27)$$

Solve the differential equation (27), and obtain the optimal trajectory of the product's green level under the centralized decision-making situation, as shown in Theorem 2 (2). Similarly, if $\sigma - 2c_1^*(\Delta_1 + \Delta_2) \geq 0$, when the time factor approaches infinity, E_{RSS}^C is the stable value of the product's green level.

Then, we can obtain the long-term profit of the whole green supply chain under the centralized decision-making situations, as shown in Theorem 2 (3). □

3.3. Comparison and Analysis. Combining Theorems 1 and 2, we can draw the following corollaries.

Corollary 1. *Compared to the decentralized decision-making situations, the product's green level and its stable value under the centralized decision-making situations are relatively higher.*

Proof. According to equations (8) and (20), we can obtain $c_1^* = m_1^*$ and $c_2^* = m_2^* + s_1^*$. Because $E_{RSS}^C - E_{RSS}^D = ((2c_2^*(\Delta_1 + \Delta_2) - 2m_2^*(\Delta_1 + \Delta_2) - s_1^*(\Delta_1 + 2\Delta_2))/(2[\sigma - 2c_1^*(\Delta_1 + \Delta_2)]))$, $E_{RSS}^C - E_{RSS}^D > 0$ can be obtained. In addition, $E^C(t) - E^D(t) = (E_{RSS}^C - E_{RSS}^D)(1 - e^{-(\sigma - 2c_1^*(\Delta_1 + \Delta_2))t})$, then $E^C(t) - E^D(t) > 0$ is obtained. □

Corollary 2. *Compared to the decentralized decision-making situations, the green innovation efforts of the supply chain members under the centralized decision-making situations are relatively higher.*

Proof. A simple comparison of equations (19) and (7) can prove this. □

Corollary 3. *Compared to the decentralized decision-making situations, the long-term profit of the whole green supply chain under the centralized decision-making situations is relatively higher. However, the amount of the profits obtained by the supply chain members, related to the profit-distribution agreement, is uncertain and variable.*

Proof. $J_C^{C*} - J_C^{D*} > 0$ can be simply obtained according to formulas (10) and (22). However, under the centralized decision-making situation, the supplier and the manufacturer are regarded as a system, and they distribute their profits according to a pre-established mutual agreement. As emphasized by Liu and Papageorgiou [40], distributed profits of supply chain members may be higher or lower than those under the decentralized decision-making situation. □

4. Profit-Distribution Contract Design

According to the previous analysis, the green innovation efforts of the supply chain members and the long-term profit of the whole supply chain under the centralized decision-making situations are higher relatively than those under the decentralized decision-making situations. A scientifically and reasonably designed profit-distribution agreement can effectively guarantee that the profits obtained by the supplier and the manufacturer are higher than their optimal profits under the decentralized decision-making situations. Moreover, it can also encourage the supply chain members to put more effort toward green innovation, improve the product's green level, and achieve the "Dual Pareto Improvements" in both economic and environmental performance [34, 39, 41]. Therefore, this section will focus on the design of the supply chain's profit-distribution agreement under the centralized decision-making situations.

Obviously, a profit-distribution agreement can be reached if and only if the supplier's and manufacturer's distributed profits under the centralized situations are not lower than their optimal profits under the decentralized situations. We assume that, under the centralized situations, the proportion of the profit distributed to the manufacturer in the whole supply chain is $\Phi\,(0 \leq \Phi \leq 1)$, and that of the supplier is $1 - \Phi$. Thus, the profit-distribution ratio (Φ) satisfies the following equation:

$$\begin{aligned} \Phi J_C^{C*} &\geq J_M^{D*}, \\ (1 - \Phi) J_C^{C*} &\geq J_S^{D*}. \end{aligned} \quad (28)$$

$\Phi \in [(J_M^{D*}/J_C^{C*}), ((J_C^{C*} - J_S^{D*})/J_C^{C*})]$ is obtained. For the sake of simplicity, note that $\Phi_{\min} = (J_M^{D*}/J_C^{C*})$ and $\Phi_{\max} = ((J_C^{C*} - J_S^{D*})/J_C^{C*})$.

Therefore, when $\Phi \in [\Phi_{\min}, \Phi_{\max}]$, the profit-distribution agreement can be reached; however, both the supplier and the manufacturer expect to obtain more profits, where the manufacturer expects a larger Φ while the supplier expects a smaller Φ. A reasonable profit-distribution plan can be designed based on the discount factor in the Rubinstein bargaining model [42]. It should be noted that the discount factor here is different from the discount rate in finance. It represents the "patience" or "bargaining power" of the participants and is generally related to the competitiveness, negotiation ability, and risk preference of the participants [43, 44]. We assume that the discount factors of the supplier and the manufacturer are σ_S and

σ_M $(0 \le \sigma_S \le 1, 0 \le \sigma_M \le 1)$. Drawing from Binmore et al. [45] and Zhang and Wang [46], we adopt the Rubinstein bargaining model by considering the manufacturer's dominant position to obtain the only subgame Nash equilibrium as follows:

$$K = \frac{1-\sigma_S}{1-\sigma_S\sigma_M}. \tag{29}$$

Therefore, the optimal profit-distribution ratio (Φ^*) under the centralized decision-making situation is

$$\begin{aligned}\Phi^* &= K\left(\Phi_{\max} - \Phi_{\min}\right) + \Phi_{\min} \\ &= \frac{1-\sigma_S}{1-\sigma_S\sigma_M}\Phi_{\max} + \frac{\sigma_S\left(1-\sigma_M\right)}{1-\sigma_S\sigma_M}\Phi_{\min}.\end{aligned} \tag{30}$$

Theorem 3. *Under the centralized decision-making situations, the optimal profits distributed to the supplier and the manufacturer are*

$$\begin{cases} J_S^{C*} = \left(1-\Phi^*\right)J_C^{C*} = \dfrac{\sigma_S\left(1-\sigma_M\right)}{1-\sigma_S\sigma_M}\left(J_C^{C*} - J_C^{D*}\right) + J_S^{D*}, \\ J_M^{C*} = \Phi^* J_C^{C*} = \dfrac{1-\sigma_S}{1-\sigma_S\sigma_M}\left(J_C^{C*} - J_C^{D*}\right) + J_M^{D*}. \end{cases} \tag{31}$$

From formula (31), we can see that, under the centralized situation, using the Rubinstein bargaining model to formulate a scientific and reasonable profit-distribution plan can effectively ensure that the profits distributed to the supplier and the manufacturer are higher than their optimal profits under the decentralized situations.

5. Simulations and Sensitivity Analysis

Using exogenous variable assignment, this section will further analyze the impacts of the driving factors including the environmental regulations' intensity and the consumers' green preference, on the long-term dynamic equilibrium strategies of the green supply chain under the two different situations. We will also verify the scientificity and validity of the profit-distribution agreement. The following parameter value of simulations are set as benchmarks: $\alpha = 0.6$, $\beta = 0.7$, $\eta_S = 4$, $\eta_M = 3$, $\sigma = 0.8$, $\theta = 0.6$, $\overline{D} = 10$, $\varphi = 0.2$, $E_h = 3$, $E(0) = 0$, $\rho = 0.3$, $\pi_s = 0.8$, $\pi_m = 1$, $\sigma_s = 0.5$, and $\sigma_m = 0.7$. They are chosen form previous studies in green supply chain, such as Zhou and Ye [25], Wang et al. [26], Zu and Zeng [30], and Zu et al. [34].

5.1. Integrity Analysis. Under the case of benchmark parameters, we set $t \in [0, 10]$ and plot the change of the supply chain members' green innovation efforts and their equilibrium (distributed) profits and the profits of the whole supply chain under the two situations, as shown in Figures 2–3. In addition, when $t \in [0, 10]$ and increases by 1, the proportion of the green innovation investment borne by the manufacturer for the supplier under the decentralized situations is continuously increasing and then tends to be stable with the passage of time. The values of λ^* are 0.8076, 0.8121, 0.8142, 0.8151, 0.8155, 0.8157, 0.8158, 0.8159, 0.8159, 0.8159, and 0.8159, respectively. Because of limited space, the changes of λ^* are expressed by numerical values instead of a separate drawing.

From Figure 2, it can be seen that the supply chain members' green innovation efforts under the centralized situations, including the supplier and manufacturer, are higher than the values of the relative variables under the decentralized situations. Because of the direct influence of the supply chain members' green innovation efforts, the products' green level under centralized situations is also higher than that under decentralized situations. This strongly verifies Corollaries 1 and 2. It shows that cooperation mechanism can motivate supply chain members to carry out green innovation and thus significantly improve the environmental performance of supply chain [47].

Similarly, from Figure 3(a), it can be seen that the dynamic equilibrium profit of the whole supply chain under the centralized situations is higher than that under decentralized situations. This indicates that green innovation cooperation among supply chain members can not only improve the environmental performance of supply chain but also increase the economic performance. However, whether the economic performance of supply chain members can be improved depends on the profit-distribution agreement. Furthermore, Figure 3(b) shows that the distributed profits of the supplier and the manufacturer under the centralized situations are higher than their equilibrium profits under the decentralized situations. In other words, a reasonable profit-distribution agreement designed by using the Rubinstein bargaining model can effectively promote both the economic performance and environmental performance of the supply chain members, i.e., $J_S^{C*} > J_S^{D*}$, $J_M^{C*} > J_M^{D*}$, and $E^C(t) > E^D(t)$. This strongly verifies Corollary 3. Therefore, in order to reduce pollutant emission and effectively improve the environment, the government should pay attention to the whole supply chain, including upstream and downstream enterprises. Moreover, the supply chain members should develop scientific and reasonable cooperation mechanism to improve the product's green level and obtain more economic profits, so as to achieve double Pareto improvement [34].

5.2. Sensitivity Analysis

5.2.1. The Impact of the Consumer's Green Preference. In order to analyze the market driving effect, we keep the other parameters fixed and let the consumer's green preference θ take a random value in the range of [0, 1]. The relationship among S, M, J_S, J_M, and θ in different decision models is shown in Figure 4. Since the changes of relevant variables at different moments have been analyzed, for the sake of convenience, this section only analyzes the stability of relevant variables $(t \longrightarrow \infty)$.

Figures 4(a) and 4(b) show that, with the increase of the consumer's green preference θ, suppliers and manufacturers are increasing their investment in green innovation under

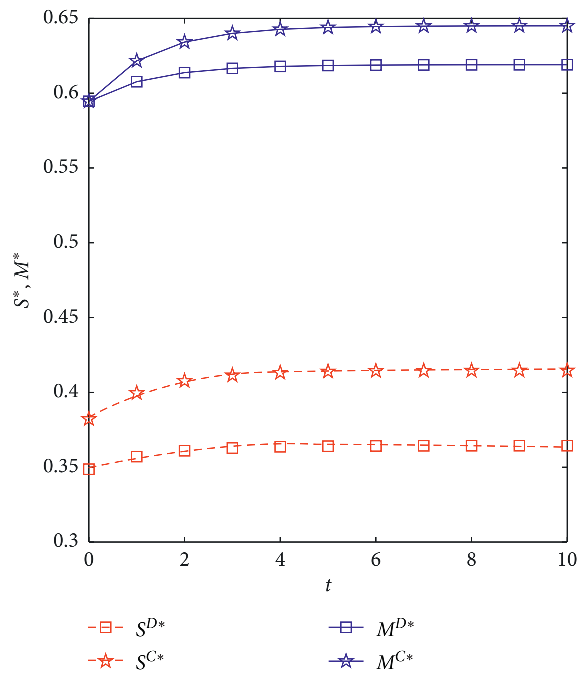


FIGURE 2: Comparison of green innovation efforts under different situations.

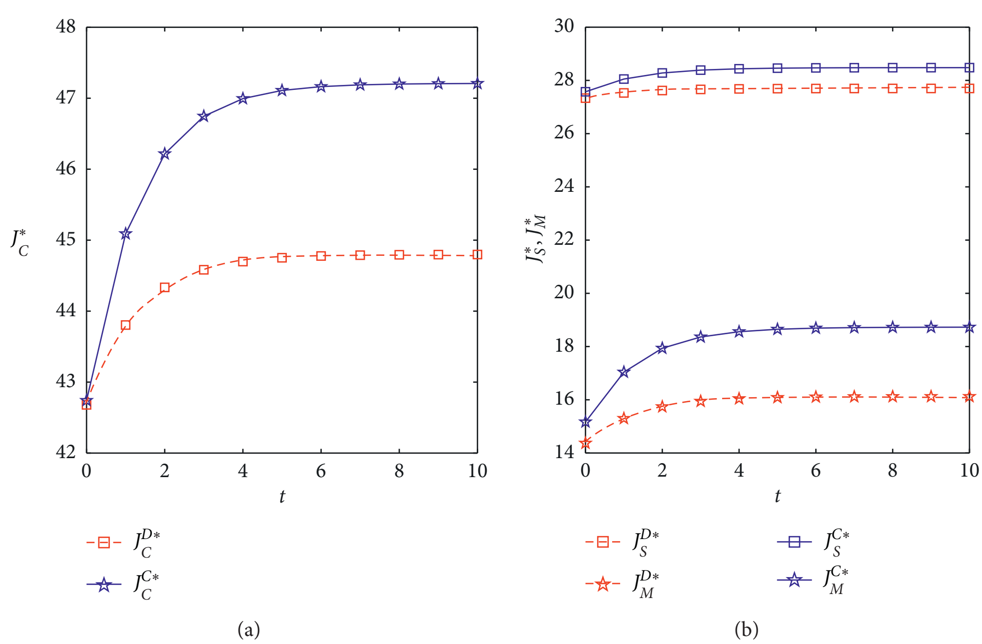
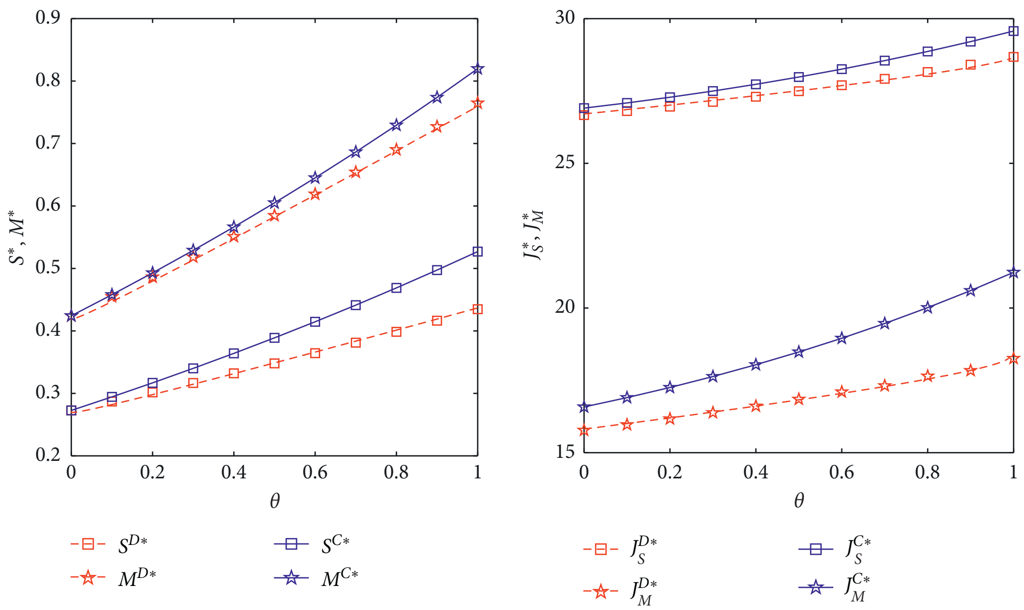


FIGURE 3: Comparison of the equilibrium (distributed) profits under different situations. (a) The equilibrium profit of the whole supply chain. (b) The equilibrium (distributed) profits of the supply chain members.

both the decentralized and centralized situations. Meanwhile, the benefits of the members' green innovation exceed the R&D costs with consumers' preference for green products. Moreover, the more consumers prefer green products, the more profits they will earn. However, under the decentralized situations, the proportion of the green innovation costs borne by the manufacturer for the supplier is decreasing. Specifically, when $\theta \in [0, 1]$ and increases by 0.1, the values of λ^* are 1.0000, 0.9618, 0.9271, 0.8954, 0.8665, 0.8400, 0.8159, 0.7938, 0.7736, 0.7552, and 0.7383, in turn.

This is because with the increasing preference of the consumer for green product, both the manufacturer and supplier are willing to actively increase their investment in green innovation and expand the market demands by increasing the product's green level to obtain more profits.



(a) (b)

Figure 4: The impact of θ on the members' green innovation efforts and profits. (a) The changes of the green innovation efforts. (b) The changes of the members' profits.

Considering the direct driving effect of the consumer's green preference, the manufacturer will gradually reduce the proportion of innovation costs borne for the supplier to maximize its own profits. Particularly, when the consumers have no preference for green products (i.e., $\theta = 0$)—only the government driving effect is considered—the supplier is willing to invest in the green innovation only if the manufacturer bears all the innovation costs under the decentralized decision situations. Therefore, the government should—by making full use of the Internet, new media, and other platforms—strengthen the publicity of low-carbon technology and environmental protection and actively carry out public opinion guidance to raise the public's green consumption awareness and positively encourage enterprises to conduct green innovation.

5.2.2. The Impact of the Environmental Regulation Intensity. Similarly, we keep the other parameters fixed and let environmental regulation intensity φ take a random value in the range of [0, 1] to analyze the government driving effect. The relationship among S, M, J_S, J_M, and φ in different decision models is shown in Figure 5. For the sake of convenience, this section only analyzes the stability of relevant variables $(t \longrightarrow \infty)$.

From Figure 5(a), we can see that, with the continuous increase of φ, the manufacturer faces increasing pressure of emission reduction but is willing to bear a larger proportion of the green innovation costs for the supplier while increasing its own green innovation investment. Specifically, when $\varphi \in [0, 1]$ and increases by 0.1, the values of λ^* are 0.4286, 0.7181, 0.8159, 0.8651, 0.8947, 0.9146, 0.9288, 0.9395, 0.9479, 0.9546, and 0.9601, in turn. Although the environmental regulation has no direct effect on the supplier's green innovation, the supplier, under the indirect drive of the manufacturer's innovation participation and consumer's green preference, is also willing to continuously increase its green innovation investment. With the joint efforts of the manufacturer and the supplier in green innovation, the product's green level has been greatly improved. As we notice, this finding is consistent to the research of Yang and Lin [4] and Liao and Tsai [48]. The results show that the increase of customer's environmental pressure captivates firms to increase the enthusiasm to carry out green innovation; namely, effective supply chain management has a significant driving effect on green innovation performance.

Furthermore, from Figure 5(b), we can see that, with the continuous increase in the intensity of the environmental regulation (φ), both the supplier and manufacturer have increased their investment in green innovation; however, the equilibrium profit of the supplier only shows a slight increase, while the equilibrium profit of the manufacturer shows the U-shaped dynamic characteristic, i.e., decreasing and then increasing. This finding is different with the research of Deng and Li [49] and Pan et al. [50]. This is because this study integrates green innovation into the supply chain context, which leads to a different perspective from the previous two studies. When the intensity of the environmental regulation is relatively low, the manufacturer and supplier will make a low investment in green innovation and produce a large number of pollutant emissions, even exceeding the emission limits set by the government, thus incurring emission costs. With the gradual increase in the intensity of the environmental regulations, the manufacturer

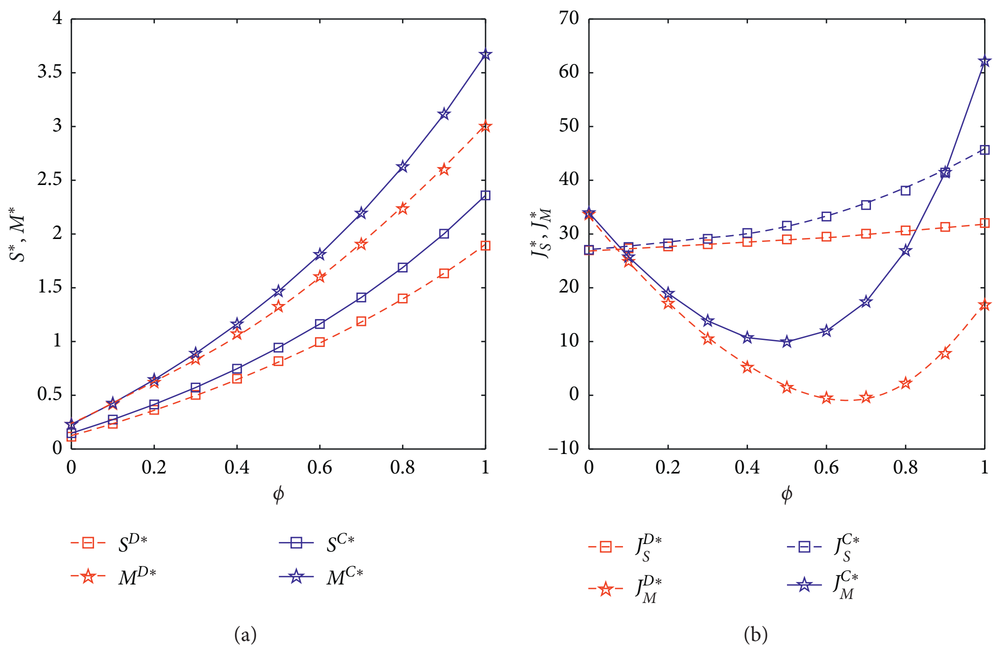


Figure 5: The impact of φ on the members' green innovation efforts and profits. (a) The changes of the green innovation efforts. (b) The changes of the members' profits.

needs to pay more and more emission costs while bearing increasing green innovation costs for the supplier, so the profit declines continuously. However, when the intensity of environmental regulation exceeds a given threshold, both the manufacturer and the supplier increase their investment in green innovation, the product's green level increases greatly, and the pollutant emission amount drops below the limit set by the government. The original emission cost then turns into benefits. In this case, with the gradual increase in the intensity of environmental regulation, the manufacturer obtains more and more benefits from emission reduction.

5.3. Managerial Implications. Through the above analysis, we can also obtain some managerial implications:

(1) The government cannot blindly increase the intensity of the environmental regulations; rather, it should comprehensively consider the environmental performance and economic performance of the enterprises and the social welfare in a unified framework and then formulate scientific and reasonable environmental policies.

(2) Considering the direct driving effect of market demand, while formulating environmental policies, the government should also actively carry out public opinion guidance to improve the public's awareness of green consumption.

(3) Under the background of low-carbon economy, managers should transform their single-handed strategy into cooperation with the upstream and downstream firms for green innovation, so as to achieve the "Dual Pareto Improvements" in both economic and environmental performance.

6. Conclusions

Comprehensively considering the dual-driving effect of the environmental regulation and the consumer's green preference, this research studies the long-term dynamic equilibrium strategies of the green innovation cooperation in a supply chain by using differential game models. The green supply chain includes a manufacturer and a supplier, in which the members' green innovation positively affects the dynamic changes of the products' green level. A scientifical and rational profit-distribution agreement under the centralized decision situations is designed to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance. The research results are as follows:

(1) Compared with the decentralized decision situations, the green innovation efforts of the supply chain members, the optimal trajectory and stable value of the product's green level, and the long-term profit of the whole supply chain under the centralized situations are relatively higher. However, the amount of the profits obtained by the supply chain members is uncertain and related to the profit-distribution agreement.

(2) Under the centralized situations, using the Rubinstein bargaining model to design a scientific and rational profit-distribution agreement can effectively ensure that the profits distributed to the supplier and the manufacturer achieve the "Dual Pareto Improvements".

(3) With the increase of the environmental regulation's intensity, the optimal green innovation efforts of the

supply members continuously increase and the product's green level continues to rise and then tends to stabilize, but the equilibrium profit of the whole supply chain shows the U-shaped fluctuation characteristic, i.e., decreasing and then increasing.

(4) With the increase of the consumer's green preference, the product's green level, the supply chain members' green innovation efforts and their equilibrium\distributed profits, and the equilibrium profits of the whole supply chain all keep increasing.

Nevertheless, this paper has some limitations. For example, this study does not consider the supply chain members' behavioral factors, including the risk preference, fair preference, and altruistic preference. In addition, this paper does not consider the competition between supply chains. In the future, the research can be further extended to the dynamic decision-making of the green innovation cooperation in multilevel green supply chains with competitive relationships and the influences of the fairness preference, risk preference, and other behavioral factors of the supply chain members.

Data Availability

The data are only based on an assumption of general market reality to verify the correctness of the model establishment and verification analysis.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Research Article

Customized Preventive Maintenance Strategies for Products Sold with Two-Dimensional Warranty

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Two-dimensional warranty has played a significant role in improving product quality and competitiveness. However, two-dimensional basic warranty (BW) and extended warranty (EW) have not yet been combined effectively, and the customized maintenance strategies based on the consumers' heterogeneity have been quite limited, which result in high maintenance costs. In this paper, the possibility of reducing warranty cost over BW and EW is explored by classifying customers based on their usage rates and then offering them with customized preventive maintenance (PM) strategies. By considering the purchasing ratio of EW contracts, the PM strategies for BW and EW are closely combined by the bi-level programming model. Numerical analysis is given to show the application of the proposed warranty strategy, and the significant findings and sensitivity of the main parameters are analyzed in the end. The findings demonstrate that the customized PM strategies combining BW and EW can effectively reduce warranty costs within the warranty period and provide a scientific guidance for manufacturers to design a more reasonable PM strategy.

1. Introduction

In an increasingly fierce competitive market environment, many manufacturers begin to offer attractive warranty service for capturing more market share and customer loyalty. A warranty is a contractual agreement between the customer and the manufacturer, which provides a detailed description of the manufacturer's responsibilities in the event that the product cannot operate satisfactorily when used correctly [1]. According to the number of parameters defining warranty coverage, warranty policies can be generally classified into one-dimensional warranty and two-dimensional warranty [2, 3]. One-dimensional warranty is often characterized by age limit or usage limit, while two-dimensional warranty considers both age limit and usage limit or the internal relation between them. Actually, the product failures of consumer durable goods like engineering machinery and autos are indexed by both age and usage. Moreover, in order to attract consumers and improve competitive advantages, manufacturers often make an effective two-dimensional warranty policy, in which the product's age and usage are considered simultaneously. Generally, two-dimensional warranties can be extended to apply in the durable goods mentioned above. For instance, a car is generally sold with a two-dimensional warranty, providing free repair for 60000 km or 3 years, whichever comes up first.

Within the warranty coverage, corrective maintenance (CM) and preventive maintenance (PM) are usually implemented for warranty service [4]. A CM action is generally unscheduled to bring a failed product back to its operating status, and it would be minimal, which restores the failed product to the original state, or imperfect, which repairs the failed product back to a status between as good as the original state and as same as failed. In addition, a CM action could be perfect as a replacement by bringing the product to a state akin to the original version [4]. Compared with a CM action, a PM action, the level of which can be decided and governed by the manufacturers, is planned action either to lower the failure probability or to lengthen the lifetime while the product is still in the operational status, which can also be either perfect or imperfect [2]. At the price of additional PM costs, the warranty cost can be effectively decreased by performing PM actions, which can be enforced by slowing down the degradation process of the product, when the decrement in the warranty cost surpasses the expense of PM activities [5].

Usually, manufacturers offer a free BW service for those customers buying a new product. In product sales, customers are often offered an option of purchasing an EW contract that offers protection for an extended period after the BW period expires, which can offer considerable profit margins for manufacturers and contribute to keep in contact with customers beyond the period of BW [6]. Due to the growing complexity of consumer durable goods in both functions and structures, the repair of such products is more sophisticated and expensive. Therefore, a reasonable maintenance policy has a remarkable influence on reducing the warranty cost covered by the manufacturer [2]. In recent years, how to apply the right PM strategies for products covered by two-dimensional BW or EW contract is a great challenge for the manufacturers, which has attracted significant attention among practitioners and academics [7–10].

The related work of PM strategies for two-dimensional warranty can be grouped into three main types based on warranty coverage, such as BW, EW, and both BW and EW [11–15]. For products covered by BW, Wang and Su [10] prove that compared to periodic PM programs, two-dimensional PM based on both the age and usage of products can effectively reduce the warranty servicing cost. For a dump truck sold with different two-dimensional BW contracts, Nasrum et al. [13] suggest that preventive maintenance with different time intervals can effectively reduce warranty servicing cost, which is examined by a numerical example. Considering both product availability and warranty cost, a warranty service combining minimal repair and the imperfect preventive maintenance is presented by Cheng et al. [5] to minimize the product's cost-efficiency per unit time. As is well known, the maintenance strategies for products under BW have an important influence on the maintenance followed by EW. Under the assumption that minimal repair is executed when the product failed during the BW, the optimal PM strategies for two-dimensional EW have been studied by Shahanaghi [14], for which the optimal PM time interval and maintenance degree are obtained by computational analysis.

Most of the abovementioned researches mainly focus on the optimization of schedule intervals or the maintenance degree of the unitary PM strategy. However, due to the heterogeneity of customers' usage rates or risk preference, the unitary PM strategy cannot meet the different demands of all the customers. Thus, the concept of customized PM strategy is proposed by SU [16], who suggests that the PM strategies with different time intervals or maintenance degrees can be provided to the customers over the EW coverage according to their usage rates, which can significantly lower the maintenance cost as a whole. Then, Huang et al. [17] propose a customized PM strategy for products during the EW period analogously, in which customers are divided into three groups on the basis of their maintenance records during the BW period, and customers in the different groups are offered different PM schedules. The results show that providing customers with customized PM can not only lower the warranty costs but also be a tangible competitive strategy for manufacturers. For all we know, the customized PM programs with two-dimensional warranty are quite limited, which cannot meet the demand of practitioners and academics.

The above researches for the optimal PM strategies have not incorporated BW and EW as a whole; therefore, it is practically impossible to get optimal warranty under either BW or EW coverage, when considering the whole warranty service. In the manufacturer's view, it is absolutely essential to combine the BW and EW contracts, and calculate the entire expected warranty cost to the manufacturer, for the purpose of deriving the optimal PM strategy within the whole warranty period [2, 16]. By applying different PM strategies for products over the BW and EW periods, Bouguerra et al. [18] obtained the highest two-dimensional EW cost acceptable to the consumers, and the lowest two-dimensional EW price acceptable to the manufacturers, which provide convenience for pricing of the two-dimensional EW service. Subsequently, BW and EW are combined into a whole warranty period by Wang et al. [2], and the optimal PM strategy under the whole two-dimensional warranty is obtained, for which the PM intervals and maintenance degrees during BW and EW are different, and the total warranty cost is the minimum.

In the researches mentioned above, the maintenance strategies combining the BW and EW take no account of the EW purchasing ratio, which may have a significant influence on the maintenance strategies for both BW and EW, since not everyone will purchase the EW contracts when the BW period expires. Furthermore, customers in the market are different in usage rates, which would have a major impact on the optimization of maintenance strategies [17, 19]. Motivated by this, the study designs a customized periodic PM strategy for the customers with different usage rates, and then combines the maintenance strategies between BW and EW with the bi-level programming model, for which the warranty servicing cost of the manufacturers is minimum as a whole.

The remaining study is arranged as follows. In Section 2, the modeling assumption and notations used in this paper are described. In Section 3, the model analysis is presented to estimate the expected warranty cost under the periodic and imperfect PM schedule. In Section 4, the optimal PM strategies model that combines BW and EW is created based on the bi-level programming model. In Section 5, an illustrative numerical example is adopted to evaluate the performance of the proposed strategy and the sensitivity analysis of the main parameters. Finally, the major conclusions and some topics for future research are discussed in Section 6.

2. Model Assumptions and Notations

The model assumptions and main mathematical notations used in this study are given in this section.

2.1. Model Assumptions

(1) For a given customer, the usage rate over the BW and EW is constant, but it varies from customer to customer. The distribution of usage rates for all customers is obtained by summarizing the sales records of products from the dealers or surveying the customers.

(2) When the BW period expires, the customer can purchase an EW contract at a fixed price. All the product failures are statistically independent, and the manufacturer is responsible for minimally repairing and bearing the total maintenance cost during the warranty coverage.

(3) The periodic PM is designed and performed to slow down the degradation process of the product during the whole warranty period, and it is assumed that the level of preventive repair is adjustable.

(4) The time interval and maintenance degree of the PM can be different between BW and EW but must be the same for the same warranty period. The PM cost during the whole warranty period is undertaken by the manufacturer. Compared to the time to product failure, the time to minimal repair and PM is very short and negligible.

2.2. Model Notations. The mathematical notations and descriptions applied in the study are given in Table 1.

3. Product Failure and Periodic PM Strategy Model

3.1. Product Failure Model. At present, marginal (univariate) method, bivariate failures distribution method, and composite scale method have been proposed for modeling product failures under two-dimensional warranty [20–22]. In this paper, the marginal method is used to model the process of product failure. Set x and u as the product's age and usage, respectively, and $(t, u) = (0, 0)$ corresponds to the point of product purchase. In the marginal method, the usage rate R is assumed as a random variable varying with the customer population; however, a specific customer's usage rate R is constant over time. Hence, distribution function $G(r) = P(R < r)$ and cumulative distribution function $g(r)$ can be adopted to model R. Conational on $R = r$, the product's overall usage u at age t can be calculated by $u = rt$.

Assuming that manufacturers minimally repair all failures with negligible duration and do not implement any PM strategy, the failures over time follow a nonhomogeneous Poisson process (NHPP), in which the conditional failure intensity function is $\lambda(t|r) = \varphi(t, u)$, where $\varphi(t, u)$ denotes nondecreasing function of both t and u. Therefore, a point process with an intensity function can be adopted to model product failure, which is dependent on both t and u. As described by Murthy et al. [23], this paper models the conditional intensity function as a polynomial function, which can be expressed as

$$\lambda_0(t|r) = \theta_0 + \theta_1 r + (\theta_2 + \theta_3 r)t, \quad \theta_0, \theta_1, \theta_2, \theta_3 > 0, \tag{1}$$

where θ_0, θ_1, θ_2, θ_3, which are positive constants, can be calculated through the manufacturer's database of warranty claims and maintenance records. The two-dimensional failure model can be simplified to a one-dimensional model by using the marginal approach. It is noteworthy that the two-dimensional warranty usually uses the polynomial intensity function in the literature [2, 8, 15, 16, 24] for reference.

As can be seen, customer usage rate r is a critical factor influencing the degradation process of the product, so as to optimize the maintenance strategy for the product during the whole warranty period. In this paper, the customers are divided into different categories based on their usage rates; then, customized PM strategy can be provided for customers in the different categories. For the given $G(r)$ and $g(r)$, set $r_{\min}, r_{\max}$ as the minimum usage rate and maximum usage rate, respectively, then the i^{th} usage rate interval $[r_{i-1}, r_i), i = 1, \ldots, N$ can be calculated by

$$\begin{aligned} r_0 &= r_{\min}, \\ r_i &= r_{\min} + i * \frac{r_{\max} - r_{\min}}{N}, \quad i = 1, 2, \ldots, N, \end{aligned} \tag{2}$$

where N denotes the number of usage rate scenarios; for any given customer, the probability of his usage rate r dropping into the i^{th} usage rate interval is

$$P_{ri} = G(r_i) - G(r_{i-1}), \quad i = 1, \ldots, N. \tag{3}$$

In this paper, the distribution $G(r)$ is assumed to be known, either through the historical data of similar products or from customer investigation.

3.2. Imperfect and Periodic PM Strategy Model. A PM action generally corresponds to a series of repair activities, including systematic cleaning, inspection, lubricating, and renewing components. [10, 25]. 2An imperfect PM does not repair the failed item to a good-as-new state; instead, it repairs the failed item to a state of better-than-now. In order to measure the maintenance level of imperfect PM, experts and scholars usually model it with two approaches: virtual life decline and failure rate reduction [26, 27]. As is well known, the periodic PM strategy is always implemented on the basis of a predetermined PM scheme, with which age decline could occur between the actual age and virtual age. This study uses virtual life reduction to model the maintenance degree of PM, and applies the model framework used by Kim et al. [28] to illustrate the age decline effort of imperfect PM strategy.

Assume that a set of PM activities of a product are planned at actual age $\tau_1, \tau_2, \ldots, \tau_j$. The effort of PM is supposed to result in the restoration of the product, so as to decline the system's virtual age significantly. This paper assumes that the damage accumulated during the time between the $j - 1^{\text{th}}$ and the j^{th} PM tasks only can be compensated by the j^{th} PM effectively, which results in an arithmetic decline of virtual age. The relationship between the effort of PM and the age reduction of the product can be

Table 1: Mathematical notations and description.

Notation	Description
W^0, U^0	Basic warranty's covered length and usage
W^1, U^1	Extended warranty's covered length and usage
R	Usage rate (random variables)
t, u	Product age and total usage, respectively
$\lambda_0(x\|r)$	Conditional failure intensity of the product with no PM actions
N	Number of usage of rare scenarios
$G(r), g(r)$	Cumulative distribution function (CDF) and probability density function (PDF) of the customer's usage rate
$r_{\min}, r_{\max}$	The minimum and maximum usage rates of the product
$[r_{i-1}, r_i)$	The i^{th} usage rate interval, $i = 1, \ldots, N$
P_{ri}	The probability of usage rate r belonging to the i^{th} usage rate scenarios
m	PM level $[0 \leq m \leq M]$. $M = 0$ corresponds to no PM and M is the prespecified upper PM level, which is a constant
$\delta(m)$	The age reduction factor of PM with level m $[0 \leq m \leq M]$
τ_j	Actual age of the j^{th} PM actions scheduled, with $\tau_0 = 0$
v_j	Virtual age of the product following the j^{th} PM action
T_i^B, m_i^B	Time interval and maintenance degree of PM during the BW period for the i^{th} usage rate interval
T_i^E, m_i^E	Time interval and maintenance degree of PM during the EW period for the i^{th} usage rate interval
n_i^B, n_i^E	The expected number of PM scheduled in the BW and EW or customers with the i^{th} usage rate scenarios
W_i^B, W_i^E	Actual age limit of the BW and EW for customers with the i^{th} usage rate scenarios
$C_{\min}$	Expected cost of each minimal repair
$C_{\text{PM}}(m)$	Expected cost of each imperfect PM with maintenance level m
EB_{PM}^r, EB_C^r	The expected PM cost and minimal repair cost for product with usage rate r during the BW
EE_{PM}^r, EE_C^r	The expected PM cost and minimal repair cost for product with usage rate r during the EW
E_i^B, E_i^E	The expected total warranty cost for customers belonging to the i^{th} usage rate scenarios
P_i^E	The purchasing ratio of PM contract for customers belonging to the i^{th} usage rate scenarios

characterized by the age reduction factor $\delta(m)$, Where m is the maintenance level of PM task. Then, v_j right after implementing the j^{th} PM task is delivered by

$$v_j = v_{j-1} + \delta(m)\left(\tau_j - \tau_{j-1}\right), \quad m = 1, 2, \ldots, M. \tag{4}$$

In this study, a large value of m means greater PM effect; therefore, $\delta(m)$ is a decreasing function of m with $\delta(0) = 1$ and $\delta(M) = 0$. The level of PM effect m is supposed to remain unchanged throughout the BW or EW period, which is usually used in the existing PM models. This paper defines the functional relationship between m and $\delta(m)$ by an exponentially decreasing function, $\delta(m) = (1+m)e^{-m}$. By iterative calculation, it can be obtained

$$v_j = v_0 + \delta(m)\left(\tau_j - \tau_0\right). \tag{5}$$

This formula will be applied to explore the expected number of failures when a periodic and imperfect PM strategy is adopted in the next section.

4. Mathematical Model of Two-Dimensional Warranty Cost

In this section, a mathematical optimization model for a product sold with two-dimensional warranty is obtained to minimize the whole expected warranty cost of BW and EW from the manufacturer's view. For this purpose, the first section estimates the expected costs of PM and CM for the product in the BW and EW period, respectively. In the next section, considering the impact of the purchasing ratio of EW contract P_i^E, the optimization model based on bi-level programming is presented.

4.1. Warranty Cost Model of BW and EW. Product warranty costs mainly include four different categories: PM cost in BW period, CM cost in BW period, PM cost in EW period, and CM cost in EW period. As mentioned above, the time interval and maintenance degree of PM can be different between BW and EW but must be consistent during the same warranty period. Generally speaking, the usage rate of a customer has an important impact on the degradation process of a product, with regard to the optimal maintenance strategy for the product during the BW or EW period. As shown in Figure 1, the warranty period this study assumes often varies with the usage rates of customers. This study has classified the customers based on their usage rates and then provided them with customized PM strategies, which are chartered by different schedule time intervals and maintenance degree.

Suppose (W^0, U^0) and (W^1, U^1) are the age and usage limit of the two-dimensional BW and EW period, respectively. Taking the i^{th} usage rate scenarios as an example, T_i^B, m_i^B represent the time interval and maintenance level of PM in the BW period, respectively; T_i^E, m_i^E represent the schedule time interval and maintenance level of PM in the EW period, respectively; and n_i^B, n_i^E are the number of PM in the BW and EW periods, respectively. P_i^E is the purchasing ratio of EW contracts for customers belonging to the i^{th} usage rate scenarios; $C_{\text{PM}}(m)$ represents the expected PM costs of maintenance level m; $C_{\min}$ is the expected cost of each minimal repair, conditional on usage rate $R \in [r_{i-1}, r_i)$; and the actual age limits of the BW and EW periods are:

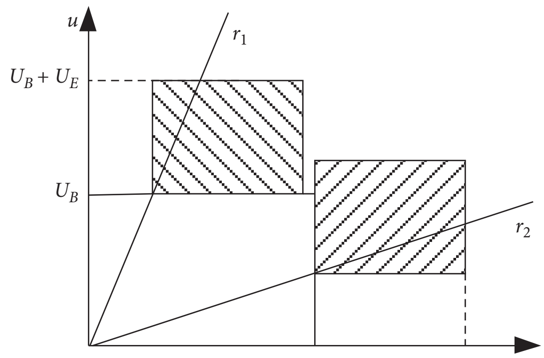

Figure 1: Two-dimensional warranty period.

$$W_i^B = \min\left(W_0, \frac{U_0}{r_i}\right) = \begin{cases} W_0, & \text{if } r_i \le \dfrac{U_0}{W_0}, \\ \dfrac{U_0}{r_i}, & \text{if } r_i > \dfrac{U_0}{W_0}, \end{cases}$$
$$W_i^E = \min\left(W_1, \frac{U_1}{r_i}\right) = \begin{cases} W_1, & \text{if } r_i \le \dfrac{U_1}{W_1}, \\ \dfrac{U_1}{r_i}, & \text{if } r_i > \dfrac{U_1}{W_1}. \end{cases} \quad (6)$$

Then, the number of PM carried out during the BW and EW for the i^{th} usage rate scenario is given by

$$n_i^B = \left\lceil \frac{W_i^B}{T_i^B} \right\rceil,$$
$$n_i^E = \left\lceil \frac{W_i^E}{T_i^E} \right\rceil. \quad (7)$$

For the i^{th} usage rate scenario, the values of these four types of warranty cost $EB_{\text{PM}}^r(T_i^B, m_i^B)$, $EB_C^r(T_i^B, m_i^B)$, $EE_{\text{PM}}^r(T_i^B, m_i^B, T_i^E, m_i^E)$, and $EE_C^r(T_i^B, m_i^B, T_i^E, m_i^E)$ are as follows:

(1) The expected PM cost in the BW period is

$$EB_{\text{PM}}^r\left(T_i^B, m_i^B\right) = n_i^B * C_{\text{PM}}\left(m_i^B\right). \quad (8)$$

(2) The expected CM cost in the BW period is

$$EB_C^r\left(T_i^B, m_i^B\right) = C_{\min} * \left(\sum_{j=0}^{n_i^B-1} \int_{j*\delta(m_i^B)*T_i^B}^{j*\delta(m_i^B)*T_i^B+T_i^B} \lambda_0(t|r)\mathrm{d}t + \int_{\delta(m_i^B)*n_i^B*T_i^B}^{\delta(m_i^B)*n_i^B*T_i^B+W_r^B-n_i^B*T_i^B} \lambda_0(t|r)\mathrm{d}t\right). \quad (9)$$

(3) Set $\tau_i^E = \delta(m_i^B) * n_i^B * T_i^B + W_r^B - n_i^B * T_i^B$ as the virtual life of products whose usage rate is $R \in [r_{i-1}, r_i]$ when they enter the EW period; thus, the expected PM cost in the EW period is

$$EE_{\text{PM}}^r\left(T_i^B, m_i^B, T_i^E, m_i^E\right) = n_i^E * C_{\text{PM}}\left(m_i^E\right). \quad (10)$$

(4) The expected CM cost in the EW period is

$$EE_C^r\left(T_i^B, m_i^B, T_i^E, m_i^E\right) = C_{\min} * \left(\sum_{j=0}^{n_i^E-1} \int_{j*\delta(m_i^E)*T_i^E+\tau_i^E}^{j*\delta(m_i^E)*T_i^E+T_i^E+\tau_i^E} \lambda_0(t|r)\mathrm{d}t + \int_{\delta(m_i^E)*n_i^E*T_i^E+\tau_i^E}^{\delta(m_i^E)*n_i^E*T_i^E+W_r^E-n_i^E*T_i^E+\tau_i^E} \lambda_0(t|r)\mathrm{d}t\right). \quad (11)$$

Based on these four types of warranty cost, the total expected cost for the i^{th} usage rate scenario can be calculated by

$$E_i^B\left(T_i^B, m_i^B\right) + P_i^E * E_i^E\left(T_i^B, m_i^B, T_i^E, m_i^E\right) = \int_{r_{i-1}}^{r_i} \left(EB_{\text{PM}}^r + EE_{\text{PM}}^r + P_i^E * \left(EE_{\text{PM}}^r + EE_C^r\right)\right) * \left(\frac{g(r)}{P_{ri}}\right)\mathrm{d}r. \quad (12)$$

4.2. Warranty Cost Optimal Model Based on Bi-Level Programming. As mentioned above, the maintenance strategy analysis for a product during BW or EW are mostly studied independently (IND) or are totally combined to be a unified warranty study (UND) as modeled by Wu [22] and Wang et al. [2]. However, in actual life, the purchasing ratio of the EW contract P_i^E is less than 1, meaning that not everyone will purchase EW contract after BW ceases. Both IND and UND methods are unreal and cannot deliver the optimal PM strategy within the total warranty period.

It is well known that the maintenance strategy of the BW and the purchasing ratio of EW contracts will influence the optimal maintenance strategy for products during the EW period; in turn, the optimal maintenance strategy for products during the EW period will affect the maintenance strategy during the BW period. Referring to [29, 30], the bi-level programming can solve exactly the mutual influence between BW and EW. Therefore, this study applies the bi-level programming method to combine the maintenance strategies between BW and EW tightly, with the aim of minimizing the warranty costs as a whole.

In this study, based on the purchasing ratio of the EW contract for different usage rate scenarios P_i^E, the optimal and imperfect PM strategy of combined BW and EW by bi-level programming method (COD) is proposed, which is different from IND and UND models, as shown in Figure 2.

In the upper-level programming, the decision variables are $(T_i^B, m_i^B), i = 1, \ldots, N$, and the aim is to minimize the overall expected warranty cost for all customers in the BW and EW periods. In the lower-level programming, the decision variables are $(T_i^E, m_i^E), i = 1, \ldots, N$, and the aim is to minimize the expected warranty cost in the EW period for customers who purchase the EW contract, on condition that the value of $(T_i^B, m_i^B), i = 1, \ldots, N$ is known. As the upper-level decision variables, the maintenance strategies in the BW period determine the reliability of products when they enter the EW period. Then, they have a very important influence on the maintenance strategies in the EW period, which are the critical variables of the lower level. The objective function of the lower-level is a part of the objective function of the upper-level programming. Therefore, this model is a typical bi-level programming model, and the detailed model structure is as follows:

$$
\begin{aligned}
\text{upper level: } & \min_{T_i^B, m_i^B} E_T\left(T_i^B, m_i^B, T_i^E, m_i^E\right) = \sum_{i=1}^{N} P_{ri} * \left(E_i^B\left(T_i^B, m_i^B\right) + P_i^E * E_i^E\left(T_i^B, m_i^B, T_i^E, m_i^E\right)\right), \\
& \text{s.t. } 0 < T_i^B \le W_0, \quad i = 1, \ldots, N, \\
& 0 \le m_i^B \le M, \quad i = 1, 2, \ldots, N, \\
\text{lower level: } & \min_{T_i^E, m_i^E} E_E\left(T_i^B, m_i^B, T_i^E, m_i^E\right), \\
& \text{s.t. } 0 < T_i^E \le W_1, \quad i = 1, \ldots, N, \\
& 0 \le m_i^E \le M, \quad i = 1, 2, \ldots, N, \\
& \tau_i^E = \delta\left(m_i^B\right) * n_i^B * T_i^B + W_r^B - n_i^B * T_i^B, \quad i = 1, 2, \ldots, N.
\end{aligned} \tag{13}
$$

In this model, when the purchasing ratio of the EW contract $P_i^E, \forall i \in [1{:}\ N]$ is set to be 0, the bi-level programming model will turn into two independent optimal models, of which the PM strategies for the BW and EW are studied independently (IND). On the contrary, when the purchasing ratio of EW contract $P_i^E, \forall i \in [1{:}\ N]$ is set to be 1, it implies that all consumers will purchase EW services before the end of the BW period, and then the optimal maintenance researches for BW and EW can be modeled by a unified warranty period (UND), as studied by Wang et al. [2]. Therefore, the model proposed by this paper also can be perfectly applied to both IND and UND.

Generally speaking, if the values of T_i^B, T_i^E are continuous variables in this model, the resolving process for this bi-level programming model will be an NP-hard problem, and it is quite hard to obtain the precise analytic solution. However, in fact, the time schedule and maintenance degree of PM are always treated as discrete variables for easily execution in practice. Therefore, the values of T_i^B, T_i^E are treated as discrete variables. Then, the optimal time schedule T_i^B, T_i^E and the corresponding maintenance degree m_i^B, m_i^E are obtained by the global traversal method, which will be illustrated in more detail in the numerical analysis.

5. Numerical Analysis

As highlighted in the introduction, automobiles are one of the commonest industries for which two-dimensional warranties are applied successfully, so this paper uses a numerical example from the automotive industry to test and verify the effectiveness of the model. Firstly, by comparing the expected warranty costs of BW and EW for the different third optimal methods, IND, UND, and the method proposed by this paper, the model validity has been proven in Section 5.1. Secondly, through the warranty cost comparison of the unitary PM policy and customized PM policy proposed by this paper, the necessity of implementing customized PM strategies during the warranty period has been proven in Section 5.2. Finally, the sensitivity analysis of the main parameters, such as the purchasing ratio P_i^E and the expected cost of minimal repair $C_{\min}$ are shown in Section 5.3.

Referring to [2, 16], the main parameters are set as follows. Assume that an automobile component covered by a two-dimensional FRW policy is the product under consideration in this study. The BW period is 3 years and 60 thousand km, that is $[W_0, U_0] = [3, 6]$. Three EW regions

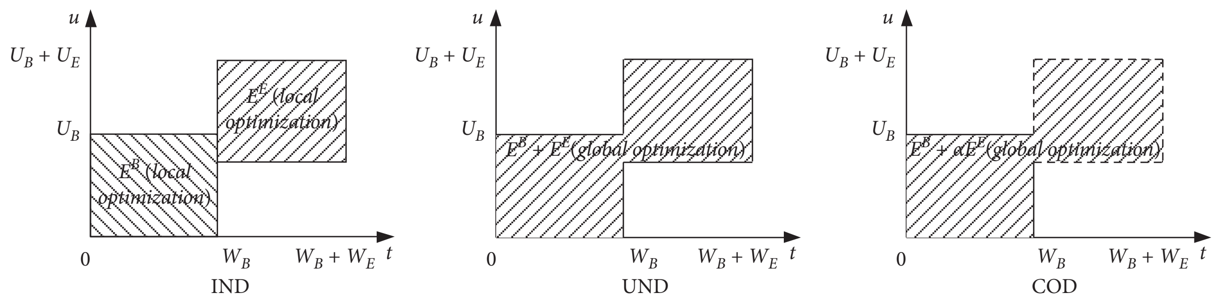

Figure 2: Comparison of IND, UND, and COD models.

are considered, $[3, 3]$, $[3, 6]$, $[6, 6]$, respectively. The polynomial intensity function of the product failure given by (1) is used and taken to be

$$\lambda_0 (t|r) = \theta_0 + \theta_1 r + (\theta_2 + \theta_3 r)t = 0.1 + 0.2r + (0.7 + 0.7r)t. \tag{14}$$

with the parameter values $\theta_0 = 0.1$, $\theta_1 = 0.2$, $\theta_2 = 0.7, \theta_3 = 0.7$.

Besides, R is supposed to be uniformly distributed over $[0.5, 3.5]$, the value range of which is then equally divided into 4 usage rate scenarios as $[0.5, 1.25]$, $[1.25, 2]$, $[2, 2.75]$, $[2.75, 3.5]$. What should be noted is that the distribution patterns of customer product usage rate have no or little impact on the study of optimal customized PM strategy proposed by this paper, and uniform distribution has been extensively applied to model the product usage rate, such as [2, 16, 17].

Moreover, this study considers $\delta(m) = (1 + m)e^{-m}$ for $m = 0, 1, \ldots, 5$, and the corresponding expected PM cost is $C_{\text{PM}}(0) = 0$ $C_{\text{PM}}(1) = 10$ $C_{\text{PM}}(2) = 30$ $C_{\text{PM}}(3) = 60$, $C_{\text{PM}}(4) = 100$, and $C_{\text{PM}}(5) = 160$. The expected minimal repair cost is $C_{\min} = 250$, which is consistent with that of [28], and the purchasing ratio of the EW contract is $P^E = [\, 0.4 \;\; 0.5 \;\; 0.6 \;\; 0.6 \,]$ correspondingly.

It is noteworthy that time intervals and maintenance degree of periodic preventive maintenance are usually discrete in practice; however, most of the researches rarely consider this question by giving an oversimplified assumption of continuity. For the purpose of efficient maintenance management, this paper searches for the best, not necessarily optimal, maintenance degree and time interval over a coarse grid with m and t varying within $(0, 5]$ and $(0, W^0]$. The expected costs of different maintenance degrees and time intervals in BW and EW are calculated by the method of global traversal, and the optimal maintenance interval and maintenance degree are obtained as described below, of which the basic unit of time schedule for PM is one month.

5.1. Model Validity Analysis. In this section, no matter what kind of decision scheme is to be adopted, the customized PM strategy will always be provided for customers according to their usage rate scenarios. Through numerical analysis, the optimal PM strategies under IND, COD, and UND are obtained, and the expected warranty costs for different usage rate scenarios during BW, EW, and both BW and EW are all calculated simultaneously, as presented in Tables 2 and 3.

The meanings of symbols in Tables 2 and 3 are all listed after Table 3. By comparing the optimal PM strategies and expected warranty cost of these three kinds of decision schemes for different EW regions (as shown in Figure 3), the following main findings can be obtained:

(1) By comparing the expected warranty cost of these three kinds of decision schemes for different warranty periods, it can be concluded that, for products covered by two-dimensional BW and EW, the maintenance strategies of BW and EW combining with bi-level programming model (COD) can effectively reduce the totally expected warranty cost, when compared to IND and UND, which is of great significance to the profit of the manufacturer.

(2) By comparing the optimal PM strategies for BW and EW under three kinds of decision schemes, it can be found that no matter what kind of EW regions are adopted, the optimal PM strategies for EW under different decision schemes always stay consistent, while the PM strategies for BW are changed obviously. Then, it can be summarized that the maintenance strategies for BW are the variables that can be adjusted to minimize the expected warranty cost for the whole warranty period. Therefore, it is worthwhile to consider the EW contract when taking decisions about the maintenance strategies for products during the BW period.

(3) By comparing the expected warranty cost of BW and EW under IND, UND, and COD, it can be found that when the purchasing ratio of EW is less than 1, the warranty cost of EW under COD is less than that under IND but more than that under UND, while the warranty cost of BW under COD is more than that under IND but less than that under UND. On the whole, the expected cost of the whole warranty period under COD is minimal among these decision schemes, and the degree of reduction depends on the parameters such as product failure intensity, the purchasing ratio of EW, and so on.

(4) By comparing the optimal PM strategies between different usage ratio scenarios, it can be concluded that with the usage rate increasing, the schedule time interval of PM strategies will become shorter while

Table 2: Preventive maintenance strategy and warranty cost of IND and COD.

W	Z	IND					COD				
		T^B	M^B	T^E	M^E	$C_I(10\hat{}3)$	T^B	M^B	T^E	M^E	$C_C(10\hat{}3)$
3, 3	1	10	3	10	3	1.4656	10	4	10	3	1.3663
	2	10	4	7	3	1.6535	10	4	7	3	1.6535
	3	7	3	7	3	1.484	7	4	7	3	1.4004
	4	7	3	6	2	1.2765	7	4	6	2	1.212
		C_B	4.266	C_E	1.613	**5.8797**	C_B	4.28	C_E	1.353	**5.6322**
3, 6	1	10	3	10	3	1.6169	10	4	10	3	1.4922
	2	10	4	10	4	2.1317	13	5	10	4	2.1237
	3	7	3	7	3	2.0305	9	5	7	3	1.8447
	4	7	3	7	3	1.7341	7	4	7	3	1.6011
		C_B	4.266	C_E	3.247	**7.5131**	C_B	4.45	C_E	2.609	**7.0617**
6, 6	1	10	3	10	3	2.0646	13	5	10	4	1.8426
	2	10	4	10	4	2.1317	13	5	10	4	2.1237
	3	7	3	7	3	2.0305	9	5	7	3	1.8447
	4	7	3	7	3	1.7341	7	4	7	3	1.6011
		C_B	4.266	C_E	3.695	**7.9609**	C_B	4.53	C_E	2.884	**7.4121**

Table 3: Preventive maintenance strategy and warranty cost of UND and COD.

W	Z	UND							COD
		T^B	M^B	$C_B(10\hat{}3)$	T^E	M^E	$C_E(10\hat{}3)$	$C_U(10\hat{}3)$	$C_C(10\hat{}3)$
3, 3	1	13	5	1.0648	10	3	0.3287	1.3935	1.3663
	2	13	5	1.3927	7	3	0.3058	1.6985	1.6535
	3	7	4	1.0663	7	3	0.3341	1.4004	1.4004
	4	7	4	0.9293	6	2	0.2827	1.2120	1.212
			C_B	4.4531		C_E	1.2513	**5.7044**	**5.6322**
3, 6	1	13	5	1.0648	10	3	0.4425	1.5073	1.4922
	2	13	5	1.3927	10	4	0.7311	2.1238	2.1237
	3	9	5	1.141	7	3	0.7037	1.8447	1.8447
	4	7	5	1.0132	7	3	0.6067	1.6199	1.6011
			C_B	4.6117		C_E	2.4839	**7.0956**	**7.0617**
6, 6	1	13	5	1.0648	10	4	0.7778	1.8426	1.8426
	2	13	5	1.3927	10	4	0.7310	2.1237	2.1237
	3	9	5	1.141	7	3	0.7037	1.8447	1.8447
	4	7	5	1.0132	7	3	0.6067	1.6199	1.6011
			C_B	4.6117		C_E	2.8191	**7.4308**	**7.4121**

W: extended warranty; Z: different usage rate scenarios; C_I: expected cost for IND; C_C: expected cost for COD; C_U: expected cost for UND; C_B: expected cost of BW; C_E: expected cost of BW.

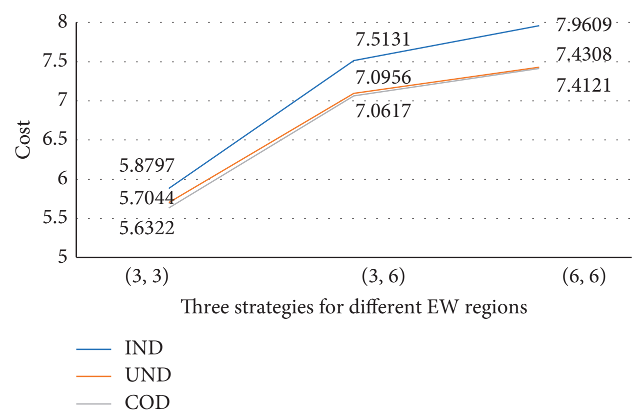

Figure 3: The expected warranty cost of different strategies.

the maintenance levels remain unchanged or change a little, meaning that the manufacturer should carry out more PM actions to slow down the degradation process of products caused by the high product usage rate. A reasonable PM scheme is a trade-off between PM cost and CM cost.

5.2. Model Validity Analysis of Customized PM Strategy. As mentioned above, the customers are divided into four different types based on their usage rate, and customized PM strategies are provided for each of them. In order to test the effectiveness of these customized PM strategies, this study has compared the expected warranty cost between the customized PM strategies and uniform PM strategies during both BW and EW periods; it is supposed that the bi-level programming model is also used to combine the maintenance strategies between BW and EW, and all the other parameters remain unchanged, then the optimal maintenance strategies and expected warranty cost of the uniform PM strategies are obtained, as shown in Table 4.

As shown above, for products sold with two-dimensional BW and different optional EW contracts, the optimal unitary PM strategies for each of them are obtained and the expected warranty costs for different usage rate scenarios are also calculated simultaneously. By comparing the expected warranty costs between unitary PM strategies and customized PM strategies for different usage rate scenarios, it can be found that the customized PM strategies for customers with different usage rates can lower warranty cost covered by the manufacturer availability, thus the total warranty cost will decrease obviously.

5.3. Sensitivity Analysis of Main Parameters. In this section, the sensitivity analysis of main parameters such as the purchasing ratio P_i^E and the expected cost of minimal repair

Table 4: Maintenance strategy and warranty cost of unitary PM and customized PM.

W	(T^B M^B T^E M^E)	Z	C_B (10ˆ3)	C_E (10ˆ3)	C_U (10ˆ3)	C_C (10ˆ3)
		1	1.0961	0.3992	1.4953	1.3663
		2	1.3645	0.3754	1.7399	1.6535
3 3	7 4 6 2	3	1.0663	0.3464	1.4127	1.4004
		4	0.9293	0.2827	1.2120	1.212
		TOTAL	4.4562	1.4037	**5.8599**	**5.6322**
		1	1.0961	0.5181	1.6142	1.4922
		2	1.3645	0.8617	2.2262	2.1237
3 6	7 4 7 3	3	1.0663	0.7900	1.8563	1.8447
		4	0.9293	0.6718	1.6011	1.6011
		TOTAL	4.4562	2.8415	**7.2977**	**7.0617**
		1	1.0961	0.9422	2.0383	1.8426
		2	1.3645	0.8617	2.2262	2.1237
6 6	7 4 7 3	3	1.0663	0.7900	1.8563	1.8447
		4	0.9293	0.6718	1.6011	1.6011
		TOTAL	4.4562	3.2656	**7.7218**	**7.4121**

Table 5: Sensitivity analysis of purchasing ratio P^E.

P^E	1				2				3				4			
	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E
0.1	10	4	10	4	10	4	10	4	7	4	7	3	7	4	7	3
0.3	10	4	10	4	10	4	10	4	7	4	7	3	7	4	7	3
0.5	13	5	10	4	13	5	10	4	7	4	7	3	7	4	7	3
0.7	13	5	10	4	13	5	10	4	8	5	7	3	7	4	7	3
0.9	13	5	10	5	13	5	10	4	9	5	7	3	7	5	7	3

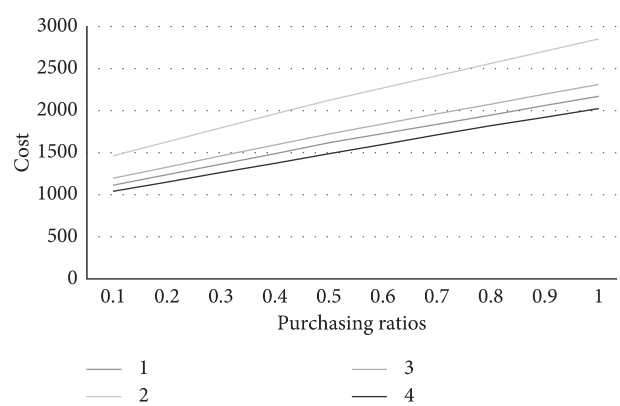

Figure 4: The expected warranty cost of different usage rate scenarios.

$C_{\min}$ are discussed in detail. Generally speaking, the bi-level programming model proposed by this paper is mainly based on the purchasing ratio of EW contract P_i^E. For testing the effect of P_i^E on the maintenance strategies of BW and EW, this study has calculated all the optimal PM strategies of the four different usage rate scenarios when their purchasing ratio changed from 0.1 to 0.9, with the EW region of [3, 6], while all the other model parameters remain unchanged. The result is listed in Table 5.

As shown in Table 5, with the purchasing ratio of the PM contract increasing, the schedule time of PM strategies for BW becomes longer or the maintenance level of PM becomes bigger. However, the optimal PM strategies for the EW period remain unchanged, and it can be summarized that the adjustment of maintenance strategies during the BW period can effectively reduce the total warranty cost when the value of P_i^E is changed.

At the same time, this study has also compared the expected warranty cost between different usage rate scenarios for purchasing ratios ranging from 0.1 to 1, with the purchasing ratio of PM contract for different usage rate scenarios staying the same, as is shown in Figure 4.

By comparing the expected warranty cost during the whole warranty period between different usage rate scenarios, it is obvious that the expected warranty cost does not follow up with the growth of the usage rate, and the expected warranty cost for the second usage rate scenarios is always the highest among all usage rate scenarios, for any circumstance. This phenomenon means that the expected warranty costs are not positively correlated with the product usage rate, and it may be caused by the fact that customers belonging to the second usage rate scenarios have a longer warranty period than the higher usage rate scenarios, while they have more expected product failures than the lower usage rate scenarios.

Except the purchasing ratio P_i^E, the expected cost of each minimal repair $C_{\min}$ or PM cost with different maintenance levels $C_{\mathrm{PM}}(m)$ are the main parameters impacting the optimal PM strategies during the whole warranty period. Or more precisely, the ratio of the expected cost of minimal repair to preventive maintenance for different levels is the main parameter affecting the optimal maintenance strategies. Suppose that the expected cost of PM with different maintenance level m remains

Table 6: Sensitivity analysis of the expected cost of minimal repair $C_{\min}$.

$C_{\min}$	1				2				3				4			
	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E	T^B	M^B	T^E	M^E
50	13	3	13	2	13	3	13	2	14	4	14	2	11	3	11	2
100	13	4	13	3	13	4	13	3	14	4	9	3	11	4	11	3
150	13	4	13	3	13	4	10	3	9	4	9	3	11	4	7	3
200	13	4	10	3	13	5	10	4	9	4	7	3	7	4	7	3
250	10	4	10	3	13	5	10	4	9	5	7	3	7	4	7	3
300	10	4	10	4	10	5	8	4	9	5	7	4	7	5	7	4
350	10	4	10	4	10	5	8	4	9	5	7	4	7	5	7	4
400	10	5	8	4	10	5	8	4	7	5	7	4	7	5	7	4
450	10	5	8	4	8	5	8	4	7	5	7	4	7	5	6	4
500	10	5	8	4	8	5	8	4	7	5	7	4	7	5	6	4

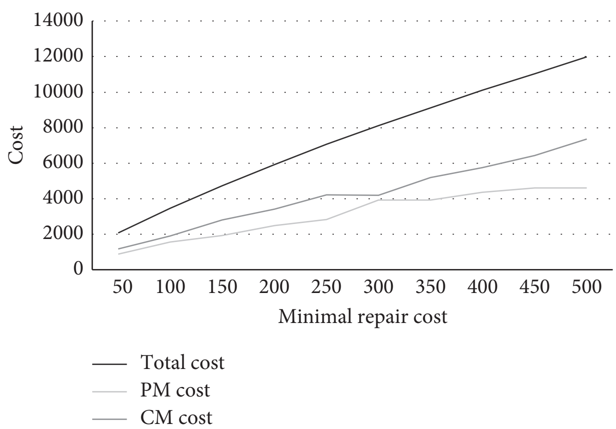

Figure 5: The expected cost for different $C_{\min}$.

unchanged, this paper has calculated the optimal PM strategies under all circumstances, when the expected cost of each minimal repair changes from 50 to 500, adding 50 each time.

Table 6 shows that with the increase in the expected minimal repair cost, the schedule time interval of PM becomes shorter and the maintenance level of PM becomes bigger; this means that the manufacturer has to implement more PM actions to reduce the expected failure of products during the whole warranty period, for the sake of avoiding expensive maintenance costs.

What is more, this study has also compared the expected PM cost, the expected CM cost, and the total cost when the expected minimal repair cost changes from 50 to 500, as shown in Figure 5.

It is obvious to find that all the expected warranty costs, such as PM cost, CM cost, and total cost, will increase when the expected minimal repair cost changes to bigger values, which is very easy to understand. However, what needs to be pointed out is that the expected PM cost is invariably less than the expected CM cost, which is very close when the minimal repair cost is 300. The reason for this is that the optimal PM strategies for products during the whole warranty period are a balance of PM cost and CM cost, with the aim of minimizing the full warranty cost, which is always obtained when the cost of PM and CM is the same or thereabouts.

6. Conclusions

Two-dimensional warranty has played a significant role in improving product quality and competitiveness. Two-dimensional basic warranty (BW) and extended warranty (EW) are not incorporated in an integrated manner, which could potentially result in additional warranty costs for manufacturers. Due to the heterogeneity of customers' usage rates, the unitary PM strategy cannot meet the different demands of all the customers. In the manufacturer's view, it is absolutely essential to combine the BW and EW contracts, and consider the heterogeneity of customers' usage rates [2,16]. Since studies on two-dimensional warranties combining BW with EW and customized PM strategies are fairly limited, this paper provides a customized PM strategy combining BW with EW for products sold with two-dimensional warranty.

The main innovation of this study is twofold. First, this study applies the bi-level programming technique for combining the maintenance strategies between BW and EW effectively. Generally, the maintenance strategies of BW would influence the maintenance cost of EW. When the manufacturer makes the maintenance strategies within the BW period, the warranty cost of EW would be considered simultaneously in the bi-level programming model. Hence, the perfection of the BW strategies in the early stage would reduce the warranty cost within the EW period, thereby reducing the total warranty cost. Second, this study sets up an optimal customized PM strategy model by considering the heterogeneity of customers' usage rates. Manufacturers can make optimal PM strategies based on the customers' usage rates, which would contribute to improve the satisfaction of customers with different usage rates. Compared with IND and UND, the proposed model can significantly decline the warranty cost covered by the manufacturer during the whole warranty period. Therefore, this paper establishes a perfect research framework for the optimization of the maintenance strategy during the whole warranty period, which can provide scientific guidance for manufacturers to optimize the PM strategy during the BW and EW periods, thereby helping manufacturers to form more reasonable PM strategies for different customers.

PM strategies during the BW and EW period have been optimized in this paper. In practice, the EW period often varies for customers with different usage rates. Therefore, it is worth studying the PM strategies and the design of the EW period for customers with different usage rates as a whole under the constraint of maintenance cost, thereby providing a customized maintenance strategy based on the situation of the customers' usage rates in the future.

In addition, the interactions among the cost of EW, the purchasing ratio of the two-dimensional warranty service, and the optimization of predictive maintenance strategies are not taken into account in this paper. Since the objective of manufacturers is to maximize profits, the optimal maintenance strategies within the whole warranty period are required by considering two-dimensional extended warranty price and this is also an interesting topic for future research.

Last but not least, the expected cost of minimal maintenance and PM are supposed to be constant during the whole warranty in this paper. However, in practice, the cost of corrective repair and PM could add to the product's age or usage; thus, it is meaningful to explore the cost of minimal repair or PM as a function of the age and usage of the product when making decisions on maintenance strategies during the warranty period.

Data Availability

The warranty data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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