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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

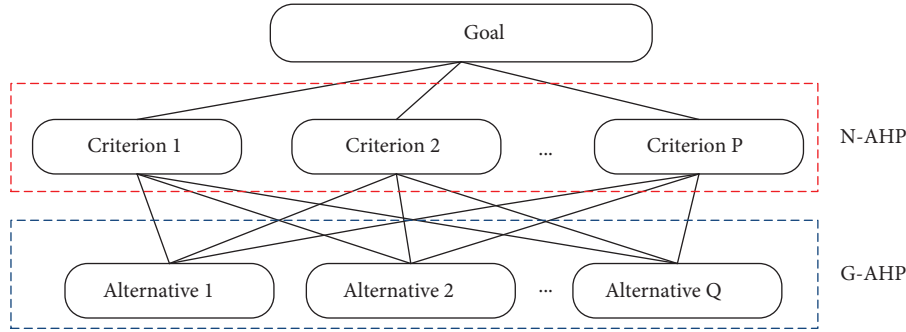


FIGURE 1: The NG-AHP decision-modelling hierarchy.

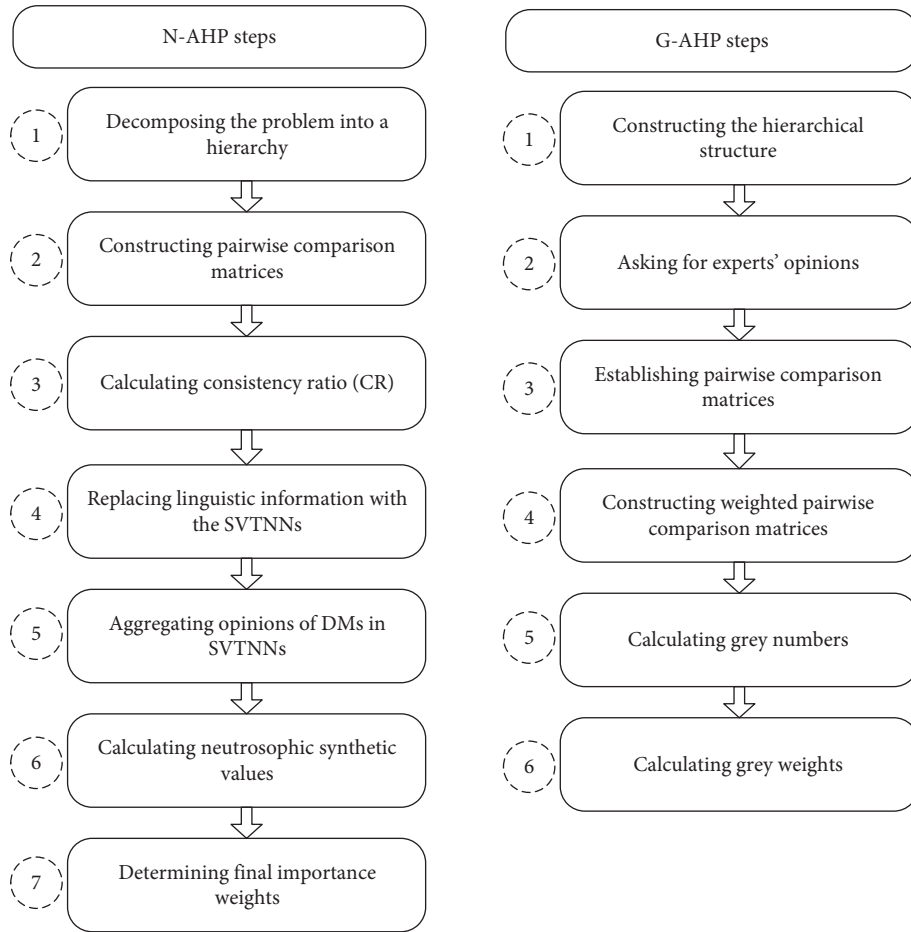


FIGURE 2: The calculation steps of the N-AHP [19] and the G-AHP.

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

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

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

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

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

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

*Definition 3* (see [71]). An SVTNN  $\tilde{a} = \langle a_1, b_1, c_1, d_1 \rangle; w_a^-, u_a^-, \gamma_a^- \rangle$ ,  $a_1, b_1, c_1, d_1 \in \mathbb{R}$ ,  $a_1 \leq b_1 \leq c_1 \leq d_1$ , and  $w_a^-, u_a^-, \gamma_a^- \in [0, 1]$  is a particular single-valued neutrosophic number (SVNN) whose  $T_a^-(x)$ ,  $I_a^-(x)$ , and  $F_a^-(x)$  are presented as the following equations, respectively:

$$T_a^-(x) = \begin{cases} \frac{(x - a_1)w_a^-}{(b_1 - a_1)}, & a_1 \leq x < b_1, \\ w_a^-, & b_1 \leq x \leq c_1, \\ \frac{(d_1 - x)w_a^-}{(d_1 - c_1)}, & c_1 < x \leq d_1, \\ 0, & \text{otherwise,} \end{cases} \quad (3)$$

$$I_a^-(x) = \begin{cases} \frac{(b_1 - x + u_a^-(x - a_1))}{(b_1 - a_1)}, & a_1 \leq x < b_1, \\ u_a^-, & b_1 \leq x \leq c_1, \\ \frac{(x - c_1 + u_a^-(d_1 - x))}{(d_1 - c_1)}, & c_1 < x \leq d_1, \\ 1, & \text{otherwise,} \end{cases} \quad (4)$$

$$F_a^-(x) = \begin{cases} \frac{(b_1 - x + \gamma_a^-(x - a_1))}{(b_1 - a_1)}, & a_1 \leq x < b_1, \\ \gamma_a^-, & b_1 \leq x \leq c_1, \\ \frac{(x - c_1 + \gamma_a^-(d_1 - x))}{(d_1 - c_1)}, & c_1 < x \leq d_1, \\ 1, & \text{otherwise.} \end{cases} \quad (5)$$

*Definition 4* (see [72]). Given  $\tilde{a} = \langle a_1, b_1, c_1, d_1 \rangle; w_a^-, u_a^-, \gamma_a^- \rangle$ , and  $\tilde{b} = \langle a_2, b_2, c_2, d_2 \rangle; w_b^-, u_b^-, \gamma_b^- \rangle$ , and  $\lambda > 0$ ,  $w_a^-, u_a^-, \gamma_a^-, w_b^-, u_b^-, \gamma_b^- \in [0, 1]$ ,  $a_1, b_1, c_1, d_1, a_2, b_2,$

$c_2, d_2 \in \mathbb{R}$ ,  $a_1 \leq b_1 \leq c_1 \leq d_1$ , and  $a_2 \leq b_2 \leq c_2 \leq d_2$ , and then equations (6) and (7) are true:

$$\tilde{a} + \tilde{b} = \langle (a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2); w_a^- w_b^-, u_a^- u_b^-, \gamma_a^- \gamma_b^- \rangle, \quad (6)$$

$$\lambda \tilde{a} = \langle (\lambda a_1, \lambda b_1, \lambda c_1, \lambda d_1); 1 - (1 - w_a^-)^\lambda, u_a^-^\lambda, \gamma_a^-^\lambda \rangle. \quad (7)$$

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:

$$\tilde{a}\tilde{b} = \langle (a_1 a_2, b_1 b_2, c_1 c_2, d_1 d_2); w_a^- w_b^-, u_a^- + u_b^-, \gamma_a^- + \gamma_b^- \rangle, \quad (8)$$

$$\tilde{a}^\lambda = \langle (a_1^\lambda, b_1^\lambda, c_1^\lambda, d_1^\lambda); w_a^-^\lambda, 1 - (1 - u_a^-)^\lambda, 1 - (1 - \gamma_a^-)^\lambda \rangle. \quad (9)$$

*Definition 5* (see [72]). Given  $\tilde{a} = \langle a, b, c, d \rangle; w_a^-, u_a^-, \gamma_a^- \rangle$  and  $a, b, c, d > 0$ . Then, the score function of  $\tilde{a}$  can be calculated in accordance with the following equation:

$$S(\tilde{a}) = \frac{1}{12} (a + b + c + d) (2 + w_a^- - u_a^- - \gamma_a^-), \quad S(\tilde{a}) \in [0, 1]. \quad (10)$$

*Definition 6* (see [72]). In order to compare two SVTNNs  $\tilde{a} = \langle a_1, b_1, c_1, d_1 \rangle; w_a^-, u_a^-, \gamma_a^- \rangle$ , and  $\tilde{b} = \langle a_2, b_2, c_2, d_2 \rangle; w_b^-, u_b^-, \gamma_b^- \rangle$  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  $\tilde{a}_j = \langle a_j, b_j, c_j, d_j \rangle; w_{a_j}^-, u_{a_j}^-, \gamma_{a_j}^- \rangle$  ( $j = 1, 2, \dots, n$ ) be a set of SVTNNs, then a trapezoidal neutrosophic weighted arithmetic averaging (TNWAA) operator is computed on the basis of [72]

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

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

**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  $\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle$ , and  $\tilde{b} = \langle (a_2, b_2, c_2, d_2); w_b^-, u_b^-, y_b^- \rangle$  be two SVTNNs, and  $w_a^-, u_a^-, y_a^-, w_b^-, u_b^-, y_b^- \in [0, 1]$  with the restrictions that  $w_b^- \neq 1, u_b^- \neq 0, y_b^- \neq 0$ , 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

$$\tilde{a} - \tilde{b} = \langle (a_1 - d_2, b_1 - c_2, c_1 - b_2, d_1 - a_2); \frac{w_a^- - w_b^-}{1 - w_b^-}, \frac{u_a^-}{u_b^-}, \frac{y_a^-}{y_b^-} \rangle. \tag{12}$$

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

$$\begin{aligned} \tilde{a} &= \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle \\ \tilde{b} &= \langle (a_2, b_2, c_2, d_2); w_b^-, u_b^-, y_b^- \rangle \\ \tilde{c} &= \langle (x, r, z, s); w_c^-, u_c^-, y_c^- \rangle \\ \tilde{a} - \tilde{b} &= \tilde{c}. \end{aligned} \tag{13}$$

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

$$\tilde{a} = \tilde{c} + \tilde{b} = \langle (x + a_2, r + b_2, z + c_2, s + d_2); w_c^- + w_b^- - w_c^- w_b^-, u_c^- u_b^-, y_c^- y_b^- \rangle. \tag{14}$$

Then,

$$\begin{aligned} \tilde{a} &= \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle = \\ &= \langle (x + a_2, r + b_2, z + c_2, s + d_2); w_c^- + w_b^- - w_c^- w_b^-, u_c^- u_b^-, y_c^- y_b^- \rangle, \end{aligned} \tag{15}$$

and

$$\begin{cases} w_a^- = w_c^- + w_b^- - w_c^- w_b^- \Rightarrow w_a^- - w_b^- = w_c^- (1 - w_b^-) \Rightarrow w_c^- = \frac{w_a^- - w_b^-}{1 - w_b^-}, \\ u_a^- = u_c^- u_b^- \Rightarrow u_c^- = \frac{u_a^-}{u_b^-}, \\ y_a^- = y_c^- y_b^- \Rightarrow y_c^- = \frac{y_a^-}{y_b^-}. \end{cases} \tag{16}$$

It is concluded that  $-\tilde{b} = \langle (-d_2, -c_2, -b_2, -a_2); (w_b^-/w_b^- - 1), (1/u_b^-), (1/y_b^-) \rangle$ , noting the remark above.  $\square$

**3.2.2. Division of SVTNNs.** Let  $\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle$  and  $\tilde{b} = \langle (a_2, b_2, c_2, d_2); w_b^-, u_b^-, y_b^- \rangle$  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  $w_a^-, u_a^-, y_a^-, w_b^-, u_b^-, y_b^- \in [0, 1]$  with the restrictions that  $w_b^- \neq 1, u_b^- \neq 0, y_b^- \neq 0$ , then the division of the two SVTNNs is shown in

$w_b^- \neq 1, u_b^- \neq 0, y_b^- \neq 0$ , then the division of the two SVTNNs is shown in

$$\tilde{a} \div \tilde{b} = \left\langle \left( \frac{a_1}{d_2}, \frac{b_1}{c_2}, \frac{c_1}{b_2}, \frac{d_1}{a_2} \right); \frac{w_a^-}{w_b^-}, \frac{u_a^- u_b^-}{1 - u_b^-}, \frac{y_a^- y_b^-}{1 - y_b^-} \right\rangle. \tag{17}$$

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

$$\begin{aligned} \tilde{a} &= \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle \\ \tilde{b} &= \langle (a_2, b_2, c_2, d_2); w_b^-, u_b^-, y_b^- \rangle \\ \tilde{c} &= \langle (x, r, z, s); w_c^-, u_c^-, y_c^- \rangle \\ \tilde{a} \div \tilde{b} &= \tilde{c}. \end{aligned} \tag{18}$$

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

$$\begin{aligned} \tilde{a} &= \tilde{c} \times \tilde{b} = \\ &= \langle (xa_2, rb_2, zc_2, sd_2); w_c^- w_b^-, u_c^- + u_b^- - u_c^- u_b^-, y_c^- + y_b^- - y_c^- y_b^- \rangle. \end{aligned} \tag{19}$$

Then,

$$\begin{aligned} \tilde{a} &= \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle = \\ &= \langle (xa_2, rb_2, zc_2, sd_2); w_c^- w_b^-, u_c^- + u_b^- - u_c^- u_b^-, y_c^- + y_b^- - y_c^- y_b^- \rangle. \end{aligned} \tag{20}$$

and

$$\begin{cases} w_a^- = w_c^- w_b^- \Rightarrow w_c^- = \frac{w_a^-}{w_b^-}, \\ u_a^- = u_c^- + u_b^- - u_c^- u_b^- \Rightarrow u_a^- - u_b^- = u_c^- (1 - u_b^-) \Rightarrow u_c^- = \frac{u_a^- - u_b^-}{1 - u_b^-}, \\ y_a^- = y_c^- + y_b^- - y_c^- y_b^- \Rightarrow y_a^- - y_b^- = y_c^- (1 - y_b^-) \Rightarrow y_c^- = \frac{y_a^- - y_b^-}{1 - y_b^-}. \end{cases} \tag{21} \square$$

**3.2.3. Inverse of an SVTNN.** Let  $\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle$  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  $w_a^-, u_a^-, y_a^- \in [0, 1]$ , then the inverse of  $\tilde{a}$  is represented in

$$\tilde{a}^{-1} = \frac{1}{\tilde{a}} = \left\langle \left( \frac{1}{d_1}, \frac{1}{c_1}, \frac{1}{b_1}, \frac{1}{a_1} \right); \frac{1}{w_a^-}, \frac{u_a^-}{u_a^- - 1}, \frac{y_a^-}{y_a^- - 1} \right\rangle. \tag{22}$$

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  $\tilde{a} = \langle (a_1, b_1, c_1, d_1); w_a^-, u_a^-, y_a^- \rangle$ , and  $\tilde{a}^{-1} = \langle (x, r, z, s); w_c^-, u_c^-, y_c^- \rangle$ ,

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

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

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

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

*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]:

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

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

$$\otimes X_1 \times \otimes X_2 = \left[ \begin{array}{l} \min(\underline{X}_1 \underline{X}_2, \underline{X}_1 \overline{X}_2, \overline{X}_1 \underline{X}_2, \overline{X}_1 \overline{X}_2) \\ \max(\underline{X}_1 \underline{X}_2, \underline{X}_1 \overline{X}_2, \overline{X}_1 \underline{X}_2, \overline{X}_1 \overline{X}_2) \end{array} \right], \quad (27)$$

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

*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  $\otimes X_1 \leq \otimes X_2$  can be defined as follows:

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

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,  $P\{\otimes X_1 \leq \otimes X_2\} = 0.5$
- (2) If  $\underline{X}_2 > \overline{X}_1$ , then  $\otimes X_2 > \otimes X_1$ . Thus,  $P\{\otimes X_1 \leq \otimes X_2\} = 1$
- (3) If  $\overline{X}_2 < \underline{X}_1$ , then  $\otimes X_2 < \otimes X_1$ . Thus,  $P\{\otimes X_1 \leq \otimes X_2\} = 0$ 
  - (i) (4-a) If  $\{\otimes X_1 \leq \otimes X_2\} > 0.5$ , then  $\otimes X_2 > \otimes X_1$
  - (ii) (4-b) If  $\{\otimes X_1 \leq \otimes X_2\} < 0.5$ , 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  $\lambda$  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:

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

*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

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

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

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

- 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  $CR \geq 0.1$ , then the DMs have to do a revision in their evaluations [88]:

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

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

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

where  $n$  is the number of elements and  $\eta_{ij}$  is the  $(i, j)$ <sup>th</sup> 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:

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

## 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

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

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  $\rho = (\rho_1, \rho_2, \dots, \rho_p)^T$  be the importance weight vector of the DMs where  $\sum_{k=1}^p \rho_k = 1, \rho_k \geq 0, k = 1, \dots, p$ . It is also given that the decision-making model includes two finite sets of alternatives and criteria which are shown by  $\{x_1, x_2, \dots, x_n\}$  and  $C = \{c_1, c_2, \dots, c_m\}$ , 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  $k^{\text{th}}$  DM:

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

(iv) Step 4 (weighted pairwise comparison matrices):  $\rho_k$  is the importance weight of the  $k^{\text{th}}$  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  $\rho_k$  and elements of matrices of equation (39), the  $\beta_{ijk}$  values can be calculated based on

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

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

(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  $\gamma_{ij} \geq \alpha_{ij}$ :

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

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

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

(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  $\mu = \min(\rho_k)$ ,  $\forall k = 1, \dots, p$ , and  $\pi = \max(\rho_k)$ ,  $\forall k = 1, \dots, p$ :

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

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

(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:

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

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

### 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  $(A_1, \dots, A_6)$ .

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

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
$A_1$	1	2	0.50	4	3
	0.50	1	0.50	4	2
	2	2	1	5	4
	0.25	0.25	0.20	1	0.50
	0.33	0.50	0.25	2	1
$A_2$	1	3	2	3	2
	0.33	1	0.50	2	2
	0.50	2	1	2	3
	0.33	0.50	0.50	1	0.33
	0.50	0.50	0.33	3	1
$A_3$	1	2	4	8	5
	0.50	1	3	6	5
	0.25	0.33	1	3	2
	0.13	0.17	0.33	1	0.50
	0.20	0.20	0.50	2	1
$A_4$	1	5	2	8	4
	0.20	1	0.50	3	2
	0.50	2	1	6	2
	0.13	0.33	0.17	1	0.25
	0.25	0.50	0.50	4	1
$A_5$	1	0.17	0.25	3	0.50
	6	1	2	4	3
	4	0.50	1	6	2
	0.33	0.25	0.17	1	0.50
	2	0.33	0.50	2	1
$A_6$	1	6	2	2	3
	0.17	1	0.20	0.20	0.17
	0.50	5	1	3	2
	0.50	5	0.33	1	2
	0.33	6	0.50	0.50	1

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  $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5,$  and  $\beta_6$  were obtained as shown in Table 12.

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

		DM1	DM2	DM3	DM4	DM5	DM6
C1	SC1	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		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	SC2	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		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	SC3	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		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	SC4	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		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)

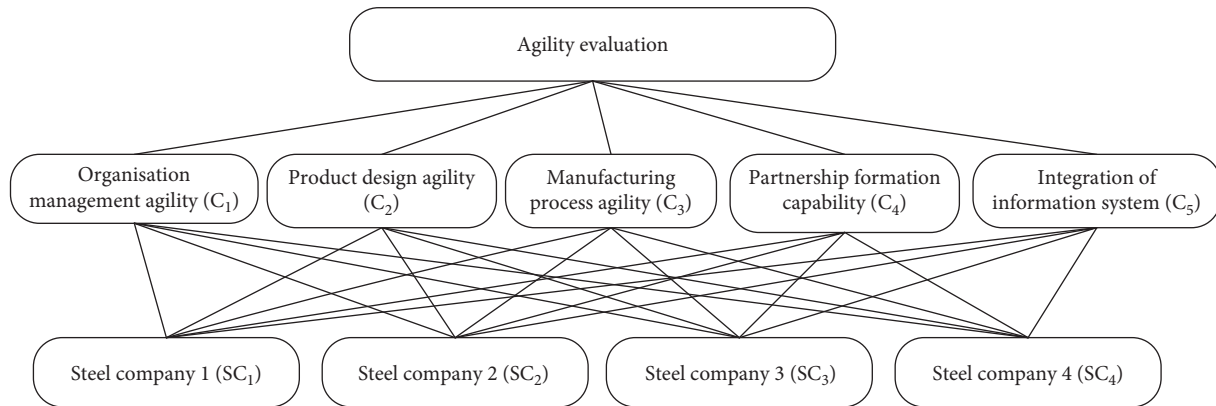


FIGURE 3: The hierarchical structure.

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 <b>0.3227</b>	C2 <b>0.2196</b>	C3 <b>0.2742</b>	C4 <b>0.0496</b>	C5 <b>0.1339</b>
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
$\beta_1$	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
$\beta_2$	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
$\beta_3$	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
$\beta_4$	SC1	0.250	0.300	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
$\beta_5$	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
$\beta_6$	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.

$\otimes Z_i$	$\otimes W_i$
$\otimes Z_1 = [0.0450, 0.3338]$	$\otimes W_1 = [0.0013, 0.0695]$
$\otimes Z_2 = [0.7219, 3.5490]$	$\otimes W_2 = [0.0202, 0.7395]$
$\otimes Z_3 = [1.8583, 13.4983]$	$\otimes W_3 = [0.0519, 2.8128]$
$\otimes Z_4 = [2.1736, 18.4083]$	$\otimes W_4 = [0.0607, 3.8360]$

TABLE 14: Final grey importance weights.

Steel companies	$\otimes W_i$
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  $\alpha$ -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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