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ORIGINAL PAPER

# Failure prioritization and control using the neutrosophic best and worst method

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**Abstract**

Failure prioritization process is described by identifying potential failures and its effects, quantifying their priorities and determining appropriate ways to mitigate or control. In the literature, many approaches are suggested to prioritize failures and associated effects quantitatively. Multicriteria decision-making (MCDM) approaches are forefront that they can express the failures verbally based on decision-makers' judgments. They explain different types of uncertainties, which are generally modeled by fuzzy sets. However, fuzzy sets focus only on one membership value in decision-making. At this point, neutrosophic sets are more suitable than classical fuzzy sets by proposing three membership values named truth-membership, indeterminacy-membership and falsity-membership. Therefore, in this study, a novel approach based on the neutrosophic best and worst method (NBWM) is proposed and a case study is also performed in the implant production. The best and worst method (BWM) is merged with neutrosophic sets since it has fewer pairwise comparisons while determining the importance weights of failures. To show the applicability of the approach, a case study in an implant manufacturing plant that produces many products, including implants in different shapes and sizes in Turkey is carried out. Besides the case study, a comparative study is performed to test the validity of the proposed NBWM approach. This approach can make the decision-making process more dynamic in real-world problems with indeterminate and inconsistent information, considering the benefits of BWM and neutrosophic sets either individually or in integration. The present study contributes to the knowledge both methodologically and in an application by proposing NBWM for failure assessment problems for the first time in the literature and creating an adaptive model for manufacturing and other industries.

**Keywords** Neutrosophic set · Best and worst method · Failure assessment · Implant industry

## 1 Introduction

A generic failure assessment process is consisted of identifying potential failures and their effects, analyzing and evaluating their priorities and determining appropriate ways to eliminate or reduce effects into an acceptable level (Gul 2018a). In the existing knowledge, many approaches are developed that are quantitative or qualitative based. Multicriteria decision-making (MCDM)-based approaches belong to the first group which they can express the failures verbally based on decision-makers' subjective judgments. Recently, these approaches are frequently applied by many scholars (Yucesan and Kahraman 2019; Ak and Gul 2019; Gul and Ak 2018; Gul et al. 2018a, b; Gul et al. 2019; Oz et al. 2018; Mete 2018). In addition to being applied singly, they can also be merged with fuzzy sets. Fuzzy sets can reflect different types of uncertainties with their extended versions (Zadeh 1965). As an example, triangular fuzzy sets (Wang et al. 2018a, b; Yazdi 2017; Gul et al. 2017a, b; Gul and Guneri 2016), trapezoidal fuzzy sets (Gul et al. 2018a), interval type-2 fuzzy sets (Ozdemir et al. 2017), hesitant fuzzy sets (Adem et al. 2018; Guo et al. 2019), intuitionistic fuzzy sets (Can 2018; Liu and Chen 2018; Liu et al. 2017, 2018; Chen et al. 2016), interval-valued intuitionistic fuzzy sets (Wang and Chen 2017; Chen et al.

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2012) and Pythagorean fuzzy sets (Gul 2018b, Gul et al. 2019; Ilbahar et al. 2018; Karasan et al. 2018) have been integrated with MCDM methods. Neutrosophic sets are more suitable in modeling the real-world problems better than classical fuzzy sets by proposing three membership values named as truth-membership, indeterminacy-membership and falsity-membership (Garg and Nancy 2019; Garg 2019; Abdel-Basset et al. 2017, 2018a, b; Biswas et al. 2016; Smarandache 2002). Therefore, in this study, a new failure assessment approach based on the neutrosophic best and worst method (NBWM) is proposed.

The best and worst method (BWM) is proposed by Rezaei (2015) for MCDM problems. The proposed method is an extension of the classical analytic hierarchy process (AHP) method. In the BWM, there is no need for full pairwise comparison as in the classical AHP method. Most and least important criteria are determined and pairwise comparisons have been done between the best/worst criterion and the other criteria. Finally, a mathematical model is built to determine the weights of criteria. Also, a new way in determination of consistency ratio is established for validation of the decision matrices. Considering the benefits of BWM and neutrosophic sets either individually or in integration, the ultimate aim of this paper is to propose a novel failure assessment approach and to demonstrate its applicability through a successful case study in the implant production industry.

The rest of the paper is organized as follows: Sect. 2 provides a literature review from the aspects both BWM and neutrosophic sets as well as the gaps and potential contributions. In Sect. 3, the novel proposed approach based on NBWM is described. In Sect. 4, the application case of the proposed approach is presented. The final section demonstrates the conclusion and future remarks.

## 2 Literature review

### 2.1 Brief literature review on BWM

In determining the weights in the BWM, in the first stage, the best criterion and the other criterion are pairwise compared. In the second stage, the other criteria are compared pairwise with the worst criteria (Rezaei 2015). BWM uses only integers. It makes this method more applicable than others (Rezaei et al. 2016). Although this method is new, it has been used mainly in energy, operation, airline industry, food and information technology. Studies conducted on BWM are summarized in Table 1.

Rezaei (2015) propose BWM to MCDM problems. First, best and worst criteria determined according to the desired conditions. Second, comparisons are made between the best and worst criteria and other criteria. Ahmad et al. (2017) aim to address the gap in the oil and gas industry by quantitatively assessing the importance of forces to supply chain management practices. They used BWM to assess the importance of these forces. Ahmadi et al. (2017) propose a framework for investigating the social sustainability of supply chains in manufacturing companies. They used BWM to evaluate social sustainability criteria. Guo and Zhao (2017) propose a comparison methodology for BWM. They used linguistic terms, which can be expressed in fuzzy triangular numbers to use in BWM. They presented the graded mean integration representation (GMIR) method to calculate the weights of criteria and alternatives to different criteria under fuzzy environment. Gupta and Barua (2016) aim at identifying important enablers of technological innovation in the context of Indian Micro-small and Medium Enterprises with the BWM method. Gupta et al. (2017) aim to address the barriers of energy efficiency in India using BWM. They determined the most prominent barriers. Gupta (2018) proposed BWM and (Vlse Kriterijuska Optimizacija I Komoromisno Resenje) VIKOR integrated method. BWM is used to rank and prioritize attributes of service quality. Then VIKOR is used to assess the best airline with respect to these attributes. van de Kaa et al. (2017) applied BWM to determine the relative importance of factors that are related to selection of biomass technologies. You et al. (2016) proposed BWM and ELECTRE III integrated model for decision-making problems. To decrease comparison and obtain consistent results, they used BWM. Then they used ELECTRE III elimination and choice translation reality with the intuitionistic environment. Salimi and Rezaei (2016) applied BWM to incorporate the inputs and outputs of the Ph.D. project and the industry’s aim. They called this measure to efficiency. Shojaei et al. (2018) aim to airport evaluation and ranking by the integration of the Taguchi loss function, the best–worst method (BWM) and VIKOR. Nawaz et al. (2018) aim to develop a cloud broker architecture for cloud service selection: first, determine architecture pattern with Markov chain; second, BWM employed to rank cloud services. Results obtained from BWM are compared with AHP. Mou et al. (2016) propose an intuitionistic fuzzy multiplicative best–worst method (IFMBWM) with intuitionistic fuzzy multiplicative preference relations (IFMPRs) for multicriteria group decision-making. Rezaei et al. (2016) proposed a methodology for supplier selection methodology using BWM in accordance with the food supply chain content. Rezaei et al. (2015) used BWM to assess the capabilities and willingness of the buying company. Rezaei (2016) offers using interval analysis for multiple optimal solutions for BWM. This methodology is extended BWM and offers a unique solution. Hafezalkotob and Hafezalkotob (2017) propose BWM based on the linguistic preferences of decision-makers about the importance of attributes with fuzzy

**Table 1** Previous studies on BWM and their contributions to the literature

| Study | Novelty | Applied area | Contributions to BWM |
|---|---|---|---|
| Rezaei (2015) | Method based | – | BWM is proposed for the first time through the literature |
| Malek and Desai (2019) | Case based | Manufacturing | BWM is applied to obtain sustainable manufacturing barriers |
| Ahmad et al. (2017) | Case based | Energy | BWM is applied to sustainable supplier selection in the oil and gas industry |
| Ahmadi et al. (2017) | Case based | Social sustainability | Social sustainability criteria are considered for this study. 'Contractual stakeholders influence' is determined as the most critical social sustainability criterion |
| Guo and Zhao (2017) | Method based | – | BWM is extended to the fuzzy environment, Graded Mean Integration (GMI) proposed for calculating the crisp ranking score of alternatives for an optimal alternative selection |
| Gupta and Barua (2016) | Case based | Micro-small and Medium Enterprises | Critical enablers of technological innovation in Micro-small and Medium Enterprises in India are weighted by BWM. Then the most important criteria are computed |
| Gupta et al. (2017) | Case based | Energy | Sensitivity analysis is carried out to check the robustness of results |
| Gupta (2018) | Method based | Airline industry | VIKOR is used to evaluate the best airline to attributes which obtain with BWM |
| van de Kaa et al. (2017) | Case based | Energy | BWM is used in order to determine the importance of biomass conversion technologies in Nederland |
| You et al. (2016) | Method based | – | BWM and ELECTRE III under intuitionistic fuzzy sets are merged in this study |
| Salimi and Rezaei (2016) | Case based | University-industry | Information is collected from 51 Ph.D. candidates and the weights are identified using BWM. |
| Shojaei et al. (2018) | Method based | Airline industry | Integration of Taguchi loss function, BWM and VIKOR techniques are studied to airport evaluation and ranking |
| Nawaz et al. (2018) | Method based | information technology | The pattern is determined by Markov chain and services are evaluated with BWM |
| Mou et al. (2016) | Method based | – | BWM is extended with intuitionistic fuzzy multiplicative preference relations |
| Rezaei et al. (2016) | Case based | Food | The proposed methodology is carried out in the food industry. BWM is used in order to determine the best suppliers among its rivals |
| Rezaei et al. (2015) | Case based | buying company | To determine supplier management strategies BWM method is used. Capabilities and willingness of the supplier are weighted with BWM |
| Rezaei (2016) | Method based | – | Interval analysis for the case of multiple optimal solutions for BWM is proposed |
| Hafezalkotob and Hafezalkotob (2017) | Method based | Politics | A fuzzy set is integrated with BWM on account of decision-makers' judgments, which are not precise |
| Kheybari et al. (2019) | Case based | Energy | The BWM method was used to find the most suitable location of the bioethanol plant |
| Khanmohammadi et al. (2019) | Case based | Management | Fuzzy BNW is used to determine the company's business strategies |
| Liao et al. (2019) | Case based | Healthcare management | Fuzzy linguistic BWM is used to evaluate hospital performance |
| Massaglia et al. (2019) | Case based | Sales and Marketing | BWM is used to determine consumer preferences in vegetable and fruit sales |

triangular numbers. Kheybari et al. (2019) aim to find the best location for bioethanol plants. Khanmohammadi et al. (2019) used fuzzy BWM to determine the business strategies of a company. Liao et al. (2019) used fuzzy linguistic BWM to hospital performance evaluation. Massaglia et al. (2019) used BWM to determine consumer preferences in fruit and vegetable sales.

## 2.2 Brief literature review on neutrosophic sets

Neutrosophic sets are proposed by Smarandache (2002) for the first time to model uncertainty and vagueness in real-world problems. These sets can reflect uncertainty better than classical fuzzy set theory, and consider three aspects of decision-making named truthiness, indeterminacy and falsity. In the initial fuzzy set theory suggested by Zadeh, there is only a membership function degree of a fuzzy set. However, in neutrosophic set theory, there exist three membership functions. Different from intuitionistic fuzzy sets, an indeterminacy degree is considered. Neutrosophic sets have some advantages compared to classical and intuitionistic fuzzy set as follows (Abdel-Basset et al. 2017, 2018a, b): (1) it recommends an indeterminacy degree. This degree aids decision-makers to explain their subjective judgments more accurately. (2) It extends decision-makers' disagreements. Considering these advantages of neutrosophic sets, in the current work, we proposed a novel NBWM approach. Since the mere BWM has failed to handle imprecise and vague information which usually exists in real-world problems, we applied NBWM in this study. To show the applicability of the novel approach, a case study in the implant production industry is provided.

Neutrosophic sets are frequently used in MCDM literature (Ye 2013, 2014; Chi and Liu 2013). However, many scholars prefer to develop theoretical extensions from neutrosophic sets. Therefore, the application aspect in neutrosophic sets is partially weaker when compared to the theoretical aspect. Few application papers in supply chain management (Abdel-Baset et al. 2019), mining (Liang et al. 2017b), healthcare (Ye 2015a; William et al. 2013), and commerce (Liang et al. 2017a) are available. Liang et al. (2017b) proposed an extended TOPSIS method with linguistic neutrosophic numbers for evaluating investment risks of metallic mines. William et al. (2013) studied neutrosophic cognitive maps in analyzing the risk factors of breast cancer. Liang et al. (2017a) developed a novel fuzzy-based approach and applied it to B2C e-commerce website evaluation. Information acquisition is conducted and transformed into single-valued trapezoidal neutrosophic numbers (SVTNNs). An innovative aggregation operator of SVTNNs is also designed. As discussed above, BWM and the neutrosophic theory have been applied, mostly separately, to MCDM problems in the previous studies. Thus, the current study aims to integrate both concepts to weigh the failures. The approach is applied to an implant manufacturing facility.

### 2.3 Research gap and contributions of this study

Based on the brief literature reviews on BWM and neutrosophic sets and as well as the concept of failure and risk assessment, it can be inferred that a growing trend is available on the MCDM in recent years. Evaluations obtained from the literature review can be summarized as follows. First, BWM is a new method and has not been fully recognized by scholars who are working in the area of failure assessment. However, it has been applied to such areas of transportation, food, information technology, health and education. Second, though researchers proposed different neutrosophic set-based approaches in theory, few of them concern with providing a real-case application. Considering the findings of the brief literature reviews, the contributions of this study can be as follows: First, the NBWM is proposed in the failure assessment problem for the first time in literature. Second, the proposed approach is tested for a real-case study. It is carried out in an implant production facility. The facility has several production processes such as CNC machining, washing, inspection, automatic cleaning, surface treatment and packaging. The approach is applied to all these processes to determine the priority weights of failures that emerged. The approach can be easily adapted to any other facility in the implant or other production industries.

## 3 Methodology

### 3.1 Preliminaries on neutrosophic sets

Neutrosophic set is a version of classical, fuzzy and intuitionistic fuzzy sets (Abdel-Basset et al. 2017). They were first proposed by Smarandache (2002). These sets reflect uncertainty, inconsistency and real-world problems better than classical and intuitionistic fuzzy sets (Abdel-Baset et al. 2019; Abdel-Basset et al. 2017, 2018a, b). Neutrosophic sets have been expanded to the current state by new concepts such as single-valued neutrosophic sets (Wang et al. 2010), trapezoidal neutrosophic sets (Deli and Subas 2017a, b; Biswas et al. 2015), triangular neutrosophic sets (Deli and Subas 2017a, b), interval neutrosophic sets (Wang et al. 2010) and so on. To see the full extensions, readers can refer to a literature review and bibliometric analysis of neutrosophic set from 1998 to 2017 by Peng and Dai (2018). Single-valued neutrosophic sets are considered as a subclass of the neutrosophic set and suitable for solving many real-world decision-making problems, especially decision-making problems related to the use of incomplete and imprecise information, uncertainties, predictions and so on (Luo et al. 2019). The single-valued neutrosophic sets are extended to present a triangular or trapezoidal neutrosophic set based on the combination of triangular/trapezoidal fuzzy numbers and a single-valued neutrosophic set and its score and accuracy functions (Deli and Şubaş 2017b; Ye 2015b). In the current study, we used single-valued triangular neutrosophic numbers to solve the failure assessment problem. In the literature, several scholars prefer triangular neutrosophic number for their problems (Deli and Subas 2014, 2017a, b; Abdel-Baset et al. 2017, 2018a, b, 2019). Since humans might feel more comfortable using linguistic terms to articulate their preferences, linguistic variables characterized by single-valued triangular neutrosophic numbers are preferred in the evaluation process of this study.

A single-valued triangular neutrosophic number is demonstrated as follows: $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$, where $n_1, n_2, n_3$ are the lower, median and upper values of neutrosophic number and $\alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}}$ are the truth-membership, indeterminacy-membership and falsity-membership functions, respectively. These three membership functions are defined as follows:

The truth-membership function $T_{\tilde{n}}(x)$

$$= \begin{cases} \alpha_{\tilde{n}}\left(\dfrac{x - n_1}{n_2 - n_1}\right) & (n_1 \le x \le n_2) \\ \alpha_{\tilde{n}} & (x = n_2) \\ \alpha_{\tilde{n}}\left(\dfrac{n_3 - x}{n_3 - n_2}\right) & (n_2 \le x \le n_3) \\ 0 & \text{otherwise} \end{cases},$$

The indeterminacy-membership $I_{\tilde{n}}\ (x)$

$$= \begin{cases} \dfrac{(n_2 - x + \beta_{\tilde{n}}(x - n_1))}{(n_2 - n_1)} & (n_1 \le x \le n_2) \\ \beta_{\tilde{n}} & (x = n_2) \\ \dfrac{(x - n_2 + \beta_{\tilde{n}}(n_3 - x))}{(n_3 - n_2)} & (n_2 \le x \le n_3) \\ 1 & \text{otherwise} \end{cases},$$

The falsity-membership function $F_{\tilde{n}}(x)$

$$= \begin{cases} \dfrac{(n_2 - x + \theta_{\tilde{n}}(x - n_1))}{(n_2 - n_1)} & (n_1 \le x \le n_2) \\ \theta_{\tilde{n}} & (x = n_2) \\ \dfrac{(x - n_2 + \theta_{\tilde{n}}(n_3 - x))}{(n_3 - n_2)} & (n_2 \le x \le n_3) \\ 1 & \text{otherwise} \end{cases},$$

where $\alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}}$ show the maximum truth-membership degree, minimum indeterminacy-membership degree and minimum falsity-membership degree, respectively. Some mathematical formulations of the neutrosophic sets are described as follows:

**Definition 1** (Abdel-Baset et al. 2017, 2018a, b, 2019): Addition of two triangular neutrosophic numbers.

Let $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ and $\tilde{s} = \langle (s_1, s_2, s_3); \alpha_{\tilde{s}}, \beta_{\tilde{s}}, \theta_{\tilde{s}} \rangle$ be two single-valued triangular neutrosophic numbers. Then addition of these two numbers can be computed as follows:

$$\tilde{n} + \tilde{s} = \langle (n_1 + s_1, n_2 + n_3 + s_1); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}} \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \rangle. \tag{1}$$

**Definition 2** (Abdel-Baset et al. 2017, 2018a, b, 2019 ): Subtraction of two triangular neutrosophic numbers. This can be computed as follows:

$$\tilde{n} - \tilde{s} = \langle (n_1 - s_3, n_2 - n_3 - s_1); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}} \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \rangle. \tag{2}$$

**Definition 3** (Abdel-Baset et al. 2017, 2018a, b, 2019): Inverse of a triangular neutrosophic number. Let $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ be a single-valued triangular neutrosophic number. Then the inverse of this number can be computed as follows:

$$\tilde{n}^{-1} = \left\langle \left(\frac{1}{n_3}, \frac{1}{n_2}, \frac{1}{n_1}\right); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \right\rangle \quad where\ \tilde{n} \ne 0. \tag{3}$$

**Definition 4** (Abdel-Baset et al. 2017, 2018a, 2019, b): Division of two triangular neutrosophic numbers.

Let $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ and $\tilde{s} = \langle (s_1, s_2, s_3); \alpha_{\tilde{s}}, \beta_{\tilde{s}}, \theta_{\tilde{s}} \rangle$ be two single-valued triangular neutrosophic numbers. Then division of these two numbers can be computed as follows:

$$\tilde{n}/\tilde{s} = \begin{cases} \left\langle \left(\dfrac{n_1}{s_3}, \dfrac{n_2}{s_2}, \dfrac{n_3}{s_1}\right); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \right\rangle & \text{if } n_3 > 0, s_3 > 0 \\ \left\langle \left(\dfrac{n_3}{s_3}, \dfrac{n_2}{s_2}, \dfrac{n1}{s_1}\right); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \right\rangle & \text{if } n_3 < 0, s_3 > 0 \\ \left\langle \left(\dfrac{n_3}{s_1}, \dfrac{n_2}{s_2}, \dfrac{n_1}{s_3}\right); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \right\rangle & \text{if } n_3 < 0, s_3 < 0 \end{cases}. \tag{4}$$

**Definition 5** (Abdel-Baset et al. 2019; Abdel-Basset et al. 2017, 2018a, b): Multiplication of two triangular neutrosophic numbers.

Let $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ and $\tilde{s} = \langle (s_1, s_2, s_3); \alpha_{\tilde{s}}, \beta_{\tilde{s}}, \theta_{\tilde{s}} \rangle$ be two single-valued triangular neutrosophic numbers. Then multiplication of these two numbers can be computed as follows:

$$\tilde{n} * \tilde{s} = \begin{cases} \langle (n_1 * s_1, n_2 * s_2, n_3 * s_3); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \rangle & \text{if } n_3 > 0, s_3 > 0 \\ \langle (n_1 * s_3, n_2 * s_2, n_3 * s_1); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \rangle & \text{if } n_3 < 0, s_3 > 0 \\ \langle (n_3 * s_3, n_2 * s_2, n_1 * s_1); \alpha_{\tilde{n}} \Lambda \alpha_{\tilde{s}}, \beta_{\tilde{n}} \vee \beta_{\tilde{s}}, \theta_{\tilde{n}} \vee \theta_{\tilde{s}} \rangle & \text{if } n_3 < 0, s_3 < 0 \end{cases}. \tag{5}$$

## 3.2 The neutrosophic best and worst method

BWM is one of the essential MCDM methods (Rezaei 2015). Some unique aspects of BWM separated it from other methods, such as (1) consistent and reliable results can be obtained with the pairwise comparisons used in this method; (2) two vectors are used instead of a full pairwise comparison matrix. Thus, calculations can be performed in less time and with fewer data. Surprisingly, the two vectors are more structured than the full matrix, resulting in more consistent results with less data; (3) only integer values are used in this method. This allows the BWM method to be practical and easy to understand than other methods (Rezaei et al. 2016).

**Step 1:** The first step concerns the determination of the expert who is responsible for and experienced in enterprise failure assessment and management.

**Step 2:** The second step covers the identification and determination of failures in each section of the implant facility (e.g. CNC processing, quality control, heat processing, washing and labeling).

**Step 3:** This step is regarding the pairwise comparison of each failure using the style of the best–worst method under the triangular neutrosophic environment. In this step, we first determine the best and the worst failures. In assessing the failures in pairwise manner, the neutrosophic scale given in Table 2 is used. In the literature, there exists a new BWM method based on the single-valued neutrosophic sets proposed by Luo et al. (2019). In that study, an algorithm is designed to identify the best and the worst criteria through computing the out-degrees and in-degrees of the collective single-valued neutrosophic preference relation-directed network, and then calculate the optimal weight vector of criteria (Luo et al. 2019) which contains tangent similarity.

**Step 4:** In this step, the preference of the best criterion (failure) over all the other criteria using a neutrosophic number from Table 2 is determined. The resulting Best-to-Others vector would be $\widetilde{A_{\mathrm{B}}} = (\widetilde{a_{\mathrm{B}1}}, \widetilde{a_{\mathrm{B}2}}, \ldots \widetilde{a_{\mathrm{B}3}})$, where $\tilde{a}_{\mathrm{B}j}$ indicates the preference of the best criterion B over criterion $j$. It is clear that $\tilde{a}_{\mathrm{BB}} = 1$.

**Step 5:** After Step 4, the preference of all the criteria over the worst criterion using a neutrosophic number from Table 2 is determined. The resulting Others-to-Worst vector would be $A_{\mathrm{B}} = (a_{1\mathrm{W}}, a_{2\mathrm{W}}, \ldots, a_{n\mathrm{W}})^T$, where $a_{j\mathrm{W}}$ indicates the preference of the criterion $j$ over the worst criterion W. It is clear that $\tilde{a}_{\mathrm{ww}} = 1$.

**Step 6:** This step transforms the evaluation of the expert opinion in the neutrosophic set into the deterministic value using Eqs. (6–7) (Abdel-Basset et al. 2017, 2018a, b). Let $\tilde{n} = \langle (n_1, n_2, n_3); \alpha_{\tilde{n}}, \beta_{\tilde{n}}, \theta_{\tilde{n}} \rangle$ be a single-valued triangular neutrosophic number, then

$$S(\tilde{n}_{ij}) = \frac{1}{8}[n_1 + n_2 + n_3]x(2 + \alpha_{\tilde{n}} - \beta_{\tilde{n}} - \theta_{\tilde{n}}), \quad (6)$$

$$A(\tilde{n}_{ij}) = \frac{1}{8}[n_1 + n_2 + n_3]x(2 + \alpha_{\tilde{n}} - \beta_{\tilde{n}} - \theta_{\tilde{n}}). \quad (7)$$

These two terms are score and accuracy degrees of $\tilde{n}_{ij}$, respectively. After this transformation, the evaluation of the expert about the corresponding failures is turned into a deterministic decision platform. Following the deterministic values in this step, the classical calculations of BWM by Rezaei (2015) are continued as well as the consistency checking.

**Step 7:** This step is about finding the transformed and deterministic optimal weights of failures $(w_1^*, w_2^*, \ldots, w_n^*)$. The optimal weight for the criteria shows as $w_j/w_w = a_{jw}$ and $w_{\mathrm{B}}/w_j = a_{\mathrm{B}j}$. To satisfy these for a $j$, we should find a solution where the maximum absolute differences $\left|\frac{w_{\mathrm{B}}}{w_j} - a_{\mathrm{B}j}\right|$ and $\left|\frac{w_j}{w_{\mathrm{W}}} - a_{j\mathrm{W}}\right|$ or all $j$ is minimized. Considering the non-negativity and sum condition for the weights, the following problem has resulted in

$$\min_j \max \left\{ \left| \frac{w_{\mathrm{B}}}{w_j} - a_{\mathrm{B}j} \right|, \left| \frac{w_j}{w_{\mathrm{W}}} - a_{j\mathrm{W}} \right| \right\},$$

s.t

$$\Sigma w_j = 1$$

$w_j \geq 0$ for all $j$.

The model is transformed as follows:

$$\min \xi,$$

$$\left| \frac{w_{\mathrm{B}}}{w_j} - a_{\mathrm{B}j} \right| \leq \xi \text{ for all} j,$$

$$\left| \frac{w_j}{w_{\mathrm{W}}} - a_{j\mathrm{W}} \right| \leq \xi \text{ for all} j,$$

$$\Sigma w_j = 1,$$

$$w_j \geq 0, \text{ for all} j.$$

Solving problem, the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and $\xi^*$ are calculated. Using $\xi^*$, consistency ratio is calculated (Rezaei 2015). No doubt, the bigger the $\xi^*$, the higher the consistency ratio, and the less consistent the comparisons become.

## 4 Case study: failure analysis in implant manufacturing

### 4.1 The implant industry and the observed production facility

A dental implant replaces the jawbone and restores the function of the missing teeth. In other words, the dental implant is an artificial tooth root made of titanium. According to the reports of international research agencies, the demand for dental implants will increase. In 2020, the total market size is expected to exceed 13 billion dollars (Meticulous research center 2017). The figures of a research in Turkey shows 350,000 implants were sold and

**Table 2** Linguistic terms and corresponding triangular neutrosophic numbers

| Saaty scale | Corresponding linguistic term | Neutrosophic triangular scale | Reciprocal neutrosophic triangular scale |
|---|---|---|---|
| 1 | Equally influential (EI) | {(1, 1, 1);0.5, 0.5, 0.5} | {(1, 1, 1);0.5, 0.5, 0.5} |
| 2 | Sporadic values between EI and SI | {(1, 2, 3);0.4, 0.65, 0.6} | {(0.33, 0.5, 1);0.4, 0.65, 0.6} |
| 3 | Slightly influential (SI) | {(2, 3, 4);0.3, 0.75, 0.7} | {(0.25, 0.33, 0.5);0.3, 0.75, 0.7} |
| 4 | Sporadic values between SI and STI | {(3, 4, 5);0.6, 0.35, 0.4} | {(0.2, 0.25, 0.33);0.6, 0.35, 0.4} |
| 5 | Strongly influential (STI) | {(4, 5, 6);0.8, 0.15, 0.2} | {(0.17, 0.2, 0.25);0.8, 0.15, 0.2} |
| 6 | Sporadic values between STI and VSI | {(5, 6, 7);0.7, 0.25, 0.3} | {(0.14, 0.17, 0.2);0.7, 0.25, 0.3} |
| 7 | Very strongly influential (VSI) | {(6, 7, 8);0.9, 0.1, 0.1} | {(0.13, 0.14, 0.17);0.9, 0.1, 0.1} |
| 8 | Sporadic values between VSI and AI | {(7, 8, 9);0.85, 0.1, 0.15} | {(0.11, 0.13, 0.14);0.85, 0.1, 0.15} |
| 9 | Absolutely influential (AI) | {(9, 9, 9);1, 0, 0} | {(0.11, 0.11, 0.11);1, 0, 0} |

it is estimated that 56% of these numbers were used by private dental hospitals and private polyclinics, 29% by freelance dentists, 14% by university dentistry faculties and 1% by public hospitals for the year of 2014 (Implantder 2014). Given this development in the sector, it is expected that the improvement of the production processes will be a trigger for the use and sales of the implant. As well as it becomes essential to uncover the frequently encountered failures in the whole process of the implant industry.

Therefore, we carried out a failure priority analysis for each process of an implant production facility in Turkey. The process at the implant manufacturing plant starts with receiving orders for four product types of implant: abutment, fixture, screw and measure equipment. Then they are sent to be processed at CNC machines. CNC machining process is mandatory for each of the four product types. As soon as they are processed at the CNC machining area, three of them (abutment, fixture and screw) proceed for first washing, first inspection and second washing, respectively. Measure equipment goes for the heat-treating process before first washing. Abutment and screw are inspected second and then labeled. By the labeling process, the production process for abutment and screw is finalized. For fixture products, there is a resorbable blast media (RBM) process before third washing. After third washing, if the product type is the fixture, the production flow is continued by second inspection and labeling. If not, it proceeds to quality control followed by drying. The process flowchart is shown in Fig. 1. Each process in this flow has its specific failure modes and associated risks. They are described in the following subsections in detail.

## 4.2 Identification of failures

The director of the implant factory, which has been in service since the foundation of the implant factory and has been in charge of all of the production processes and having 10 years of business experience, has been selected to evaluate the failures. In this case study, twenty-four failures of the observed implant facility are evaluated by the director of the implant factory. The descriptions of failures are as follows:

### 4.2.1 CNC processing (Group A failures)

Titanium or steel rods are machined on CNC machines and brought to the form of fixture, abutment and measuring parts. Three factors cause errors in this section. These factors are materials, cutting tools and coolant. The deformations of cutting tools due to machining cause the products to exceed their specified tolerances. Failure of the coolant to perform its task leads to deformations of the cutting tool and material. Material failure breaks the tool.

### 4.2.2 The quality control section (Group B failures)

Dental implants are subject to full quality control as they are directly related to human life. In this section, quality control specialists control the products dimensionally and visually. The failure models in this section are all due to the human factor.

### 4.2.3 Heat treatment section (Group C failures)

Dental implants are intended to function for many years. To achieve the desired mechanical properties, implants are subjected to heat treatment. The temperature at which the products are heated and how long they remain at these temperatures is directly proportional to the success of the heat treatment.

### 4.2.4 Washing section (Group D failures)

Dental implants used in the mouth should be decontaminated. The primary objective of this process is to purify the chemicals remaining from the coolant in the CNC section. For this purpose, cleaning is carried out by means of soldering and washing with special equipment.

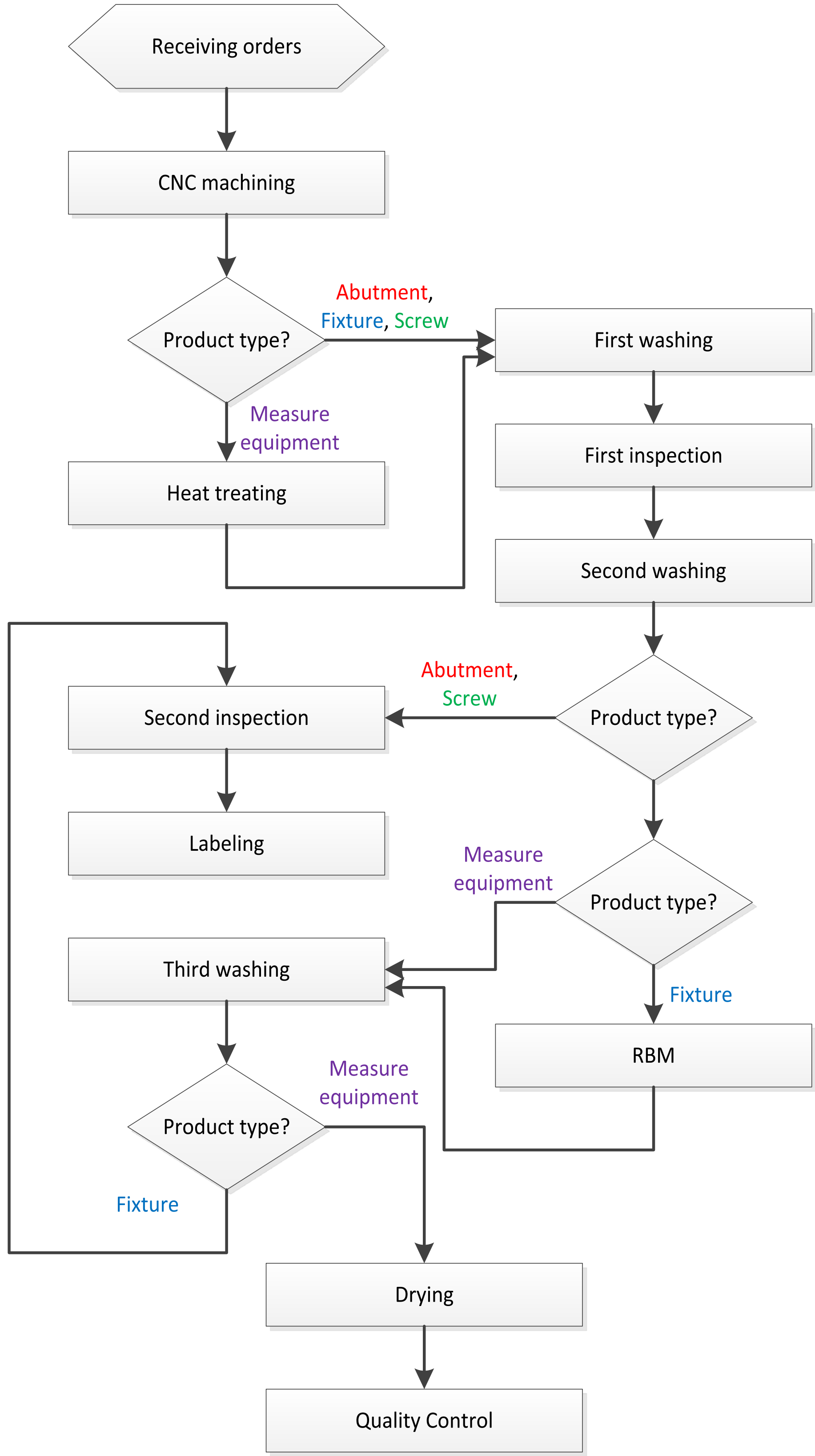


**Fig. 1** The production process in the observed implant production plant (Gul et al. 2018d)

#### 4.2.5 Labeling section (Group E failures)

Products are labeled in this section. We pay utmost attention to not mix the products. The serial numbers, production dates and batch numbers of the products must be correct and legible on the product. Otherwise, the product cannot be used.

### 4.3 Application of the proposed NBWM approach

When executing a pairwise comparison $\tilde{a}_{ij}$, the decision-maker expresses both the direction and the strength of the preference $i$ over $j$. The importance of $j$ to $i$ is shown $\tilde{a}_{ji}$ (Fig. 2). The A, B, C, D and E refer to the failures that emerged in the following sections of the observed implant facility: CNC processing, quality control, heat treatment, washing and labeling. To obtain the importance weight of these main failure modes and the sub-failures in each of the five sections, we utilized our proposed NBWM approach.

The mathematical computations for each main failure mode using NBWM are performed as follows:

$$\min \xi$$
$$\text{s.t.}$$
$$\left|\frac{w_{\mathrm{E}}}{w_{\mathrm{D}}}-\tilde{8}\right|\le\xi,\ \left|\frac{w_{\mathrm{E}}}{w_{\mathrm{C}}}-\tilde{4}\right|\le\xi,\ \left|\frac{w_{\mathrm{E}}}{w_{\mathrm{B}}}-\tilde{7}\right|\le\xi,\ \left|\frac{w_{\mathrm{E}}}{w_{\mathrm{A}}}-\tilde{9}\right|\le\xi,$$
$$\left|\frac{w_{\mathrm{B}}}{w_{\mathrm{A}}}-\tilde{2}\right|\le\xi,\ \left|\frac{w_{\mathrm{C}}}{w_{\mathrm{A}}}-\tilde{3}\right|\le\xi,\ \left|\frac{w_{\mathrm{D}}}{w_{\mathrm{A}}}-\tilde{1}\right|\le\xi,$$
$$w_{\mathrm{A}}+w_{\mathrm{B}}+w_{\mathrm{C}}+w_{\mathrm{D}}+w_{\mathrm{E}}=1,$$
$$w_{\mathrm{A}},w_{\mathrm{B}},w_{\mathrm{C}},w_{\mathrm{D}},w_{\mathrm{E}}\ge 0,$$

where $w_A, w_B, w_C, w_D, w_E$ stand for the importance weight of main failures. After demonstrating the NBWM calculation procedure as above, the transformations of the expert opinion from neutrosophic number into the deterministic value using Eqs. (6–7) have been performed. Thus, the problem has turned into classical BWM.

To solve this classical BWM problem, the procedure of Rezaei (2015) is followed. The transformed version of the problem regarding the main failures (referring to A, B, C, D and E) is arranged in mathematical programming as follows:

$$\min \xi$$
$$\text{s.t.}$$
$$\left|\frac{w_E}{w_D}-7.800\right|\le\xi,\ \left|\frac{w_E}{w_C}-2.775\right|\le\xi,\ \left|\frac{w_E}{w_B}-7.088\right|\le\xi,\ \left|\frac{w_E}{w_A}-10.125\right|\le\xi,$$
$$\left|\frac{w_B}{w_A}-0.863\right|\le\xi,\ \left|\frac{w_C}{w_A}-0.956\right|\le\xi,\ \left|\frac{w_D}{w_A}-0.563\right|\le\xi,$$
$$w_A+w_B+w_C+w_D+w_E=1,$$
$$w_A,w_B,w_C,w_D,w_E\ge 0.$$

We recommend the CI calculation procedure to determine how consistent the evaluation is. In classical BWM, evaluations are made using 1–9 numbers. The highest value of $a_{\mathrm{BW}}$ = 9. A different consistency table is required since it uses transformed neutrosophic numbers. The NBWM, the value of 10.125, is used instead of the value of 9. Therefore, we propose a consistency ratio for the NBWM.

$a_{ij}\in\{1,\ldots,a_{\mathrm{BW}}\}$. Where the highest possible value of $a_{\mathrm{BW}}$ is $\tilde{9}$. As for the minimum consistency $a_{\mathrm{B}j}=a_{j\mathrm{w}}=a_{\mathrm{BW}}$, we have $(a_{\mathrm{BW}}-\xi)(a_{\mathrm{BW}}-\xi)=(a_{\mathrm{BW}}+\xi)$.

$$\xi^2-(1+2a_{\mathrm{BW}})\xi+(a_{\mathrm{BW}}^2-a_{\mathrm{BW}})=0.$$

Solving for different values of $a_{\mathrm{BW}}\in\{\tilde{1},\tilde{2},\ldots\tilde{9}\}$ we can find the maximum possible ξ (max ξ). We use these maximum values as the consistency index (Table 3).

For the consistency ratio, the consistency index for this problem is 15.153 (see Table 3) and the consistency ratio is 1.2492/15.153 = 0.082 which implies a very good consistency.

The mathematical programming models created for failure models in each section are given in the following.

$$\min \xi$$
$$\text{st.}$$
$$\left|\frac{w_{\mathrm{A3}}}{w_{\mathrm{A1}}}-\tilde{9}\right|\le\xi,\ \left|\frac{w_{\mathrm{A3}}}{w_{\mathrm{A2}}}-\tilde{3}\right|\le\xi,\ \left|\frac{w_{\mathrm{A3}}}{w_{\mathrm{A4}}}-\tilde{5}\right|\le\xi,\ \left|\frac{w_{\mathrm{A3}}}{w_{\mathrm{A5}}}-\tilde{6}\right|\le\xi,$$
$$\left|\frac{w_{\mathrm{A2}}}{w_{\mathrm{A1}}}-\tilde{1}\right|\le\xi,\ \left|\frac{w_{\mathrm{A4}}}{w_{\mathrm{A1}}}-\tilde{3}\right|\le\xi,\ \left|\frac{w_{\mathrm{A5}}}{w_{\mathrm{A1}}}-\tilde{3}\right|\le\xi,$$
$$w_{\mathrm{A1}}+w_{\mathrm{A2}}+w_{\mathrm{A3}}+w_{\mathrm{A4}}+w_{\mathrm{A5}}=1,$$
$$w_{\mathrm{A1}},w_{\mathrm{A2}},w_{\mathrm{A3}},w_{\mathrm{A4}},w_{\mathrm{A5}}\ge 0,$$

$$\min \xi$$
$$\text{st.}$$
$$\left|\frac{w_{\mathrm{B2}}}{w_{\mathrm{B1}}}-\tilde{9}\right|\le\xi,\ \left|\frac{w_{\mathrm{B2}}}{w_{\mathrm{B3}}}-\tilde{2}\right|\le\xi,\ \left|\frac{w_{\mathrm{B2}}}{w_{\mathrm{B4}}}-\tilde{4}\right|\le\xi,$$
$$\left|\frac{w_{\mathrm{B3}}}{w_{\mathrm{B1}}}-\tilde{3}\right|\le\xi,\ \left|\frac{w_{\mathrm{B4}}}{w_{\mathrm{B1}}}-\tilde{3}\right|\le\xi,$$
$$w_{\mathrm{B1}}+w_{\mathrm{B2}}+w_{\mathrm{B3}}+w_{\mathrm{B4}}=1,$$
$$w_{\mathrm{B1}},w_{\mathrm{B2}},w_{\mathrm{B3}},w_{\mathrm{B4}}\ge 0,$$

$$\min \xi$$
$$st.$$
$$\left|\frac{w_{\mathrm{C3}}}{w_{\mathrm{C4}}}-\tilde{9}\right|\le\xi,\ \left|\frac{w_{\mathrm{C3}}}{w_{\mathrm{C2}}}-\tilde{2}\right|\le\xi,\ \left|\frac{w_{\mathrm{C3}}}{w_{\mathrm{C1}}}-\tilde{3}\right|\le\xi,$$
$$\left|\frac{w_{\mathrm{C2}}}{w_{\mathrm{C4}}}-\tilde{3}\right|\le\xi,\ \left|\frac{w_{\mathrm{C1}}}{w_{\mathrm{C4}}}-\tilde{2}\right|\le\xi,$$
$$w_{\mathrm{C1}}+w_{\mathrm{C2}}+w_{\mathrm{C3}}+w_{\mathrm{C4}}=1,$$
$$w_{\mathrm{C1}},w_{\mathrm{C2}},w_{\mathrm{C3}},w_{\mathrm{C4}}\ge 0,$$

**Fig. 2** Pairwise comparison in BWM

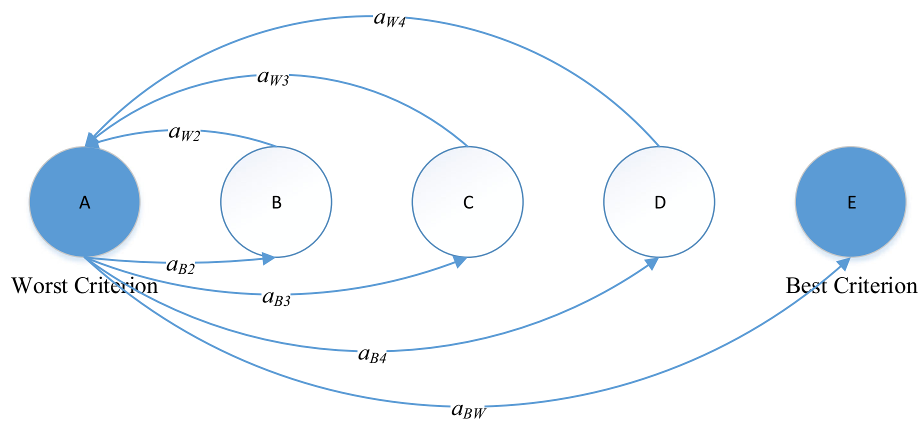


**Table 3** Consistency index calculation

| $a_{BW}$(Neutrosophic) | $\tilde{1}$ | $\tilde{2}$ | $\tilde{3}$ | $\tilde{4}$ | $\tilde{5}$ | $\tilde{6}$ | $\tilde{7}$ | $\tilde{8}$ | $\tilde{9}$ |
|---|---|---|---|---|---|---|---|---|---|
| $a_{BW}$(Deterministic) | 0.563 | 0.863 | 0.956 | 2.775 | 4.594 | 4.838 | 7.088 | 7.800 | 10.125 |
| Consistency index | 2.235 | 2.768 | 2.927 | 5.683 | 8.166 | 8.488 | 11.386 | 12.281 | 15.153 |

$$\begin{aligned} &\min \xi \\ &st. \\ &\left|\frac{w_{D1}}{w_{D2}} - \tilde{9}\right| \le \xi, \left|\frac{w_{D1}}{w_{D3}} - \tilde{4}\right| \le \xi, \\ &\left|\frac{w_{D3}}{w_{D2}} - \tilde{3}\right| \le \xi, \\ &w_{D1} + w_{D2} + w_{D3} = 1, \\ &w_{D1}, w_{D2}, w_{D3} \ge 0, \end{aligned}$$

$$\begin{aligned} &\min \xi \\ &st. \\ &\left|\frac{w_{E2}}{w_{E3}} - \tilde{9}\right| \le \xi, \left|\frac{w_{E2}}{w_{E1}} - \tilde{5}\right| \le \xi, \\ &\left|\frac{w_{E1}}{w_{E3}} - \tilde{3}\right| \le \xi, \\ &w_{E1} + w_{E2} + w_{E3} = 1, \\ &w_{E1}, w_{E2}, w_{E3} \ge 0. \end{aligned}$$

After solving the mathematical models for each section where each failure emerged (A–E) and each failure (A1,…A5, B1,.. B4, C1,…, C4, D1,…, D3, E1,…E3) by Lindo 16.0, the weights are calculated as in Table 4. The consistency index values for each failure group are provided in Table 5. According to these results, the most severe section in this implant manufacturing plant is the labeling section with a weight value of 0.6121. It is followed by the sections of the heat treatment section (a weight value of 0.1521), quality control section (a weight value of 0.0734), washing section (a weight value of 0.0934) and CNC processing section (a weight value of 0.0690). When the failures are investigated in terms of prioritization, disorder labeling of products (E2), incorrect labeling (E1) and product blackout error (C3) are determined to be the most critical failure modes.

Due to the health procedures in the country, the production dates and serial numbers of the dental implants should be clearly and comprehensively present in the product. Otherwise, these products will not be sold. Therefore, "*disorder labeling of products*" has been determined as the most important failure by the decision-maker. The second most important failure is "*Incorrect labeling*." This failure is very similar to "*disorder labeling of products*." Titanium alloys are relatively soft, so they are subjected to heat treatment to improve their mechanical properties. The most important parameters of the heat treatment are temperature and time. If these parameters are set above the reference values, "*Products blackout error*" failure may occur. Another way to prevent this error is to calibrate the heat treatment thermocouple and change it at the end of its life. During the CNC operation, coolant is used to protect the cutting tool and reduce the processing temperature. If these refrigerant chemicals are not cleaned, it may cause harm to human health. "*Incorrect washing error*" occurs because the washing parameters cannot be determined correctly.

## 4.4 Comparative study

To strengthen the results of the current study, a comparative study is performed. In this follow-up study, two different versions of BWM are utilized. The applied comparison methods are classical BWM and fuzzy BWM (FBWM). The overall results of the comparisons are

**Table 4** Results of NBWM: weights of failures

| Code | Failure mode | Local weights | Global weights | Ranking order |
|---|---|---|---|---|
| A | CNC processing section | | 0.0690 | |
| A1 | Size error | 0.0712 | 0.0049 | 19 |
| A2 | Diameter error | 0.1883 | 0.0130 | 12 |
| A3 | Internal hole diameter error | 0.5722 | 0.0395 | 7 |
| A4 | Errors due to cutting tools break | 0.0857 | 0.0059 | 16 |
| A5 | Errors caused by cooling fluid | 0.0827 | 0.0057 | 17 |
| B | Quality Control section | | 0.0734 | |
| B1 | Blasting error due to product contact | 0.0724 | 0.0053 | 18 |
| B2 | Incorrect measurement error | 0.5919 | 0.0435 | 6 |
| B3 | Lost or accidentally mixing of product | 0.2104 | 0.0155 | 11 |
| B4 | Failure to detect surface defects during the visual inspection | 0.1253 | 0.0092 | 14 |
| C | Heat Treatment section | | 0.1521 | |
| C1 | Failure to reach undesired hardness | 0.1888 | 0.0287 | 9 |
| C2 | Oxidation error | 0.1951 | 0.0297 | 8 |
| C3 | Products blackout error | 0.5489 | 0.0835 | 3 |
| C4 | Disorder of products in the heat treatment process | 0.0671 | 0.0102 | 14 |
| D | Washing section | | 0.0934 | |
| D1 | Incorrect washing error | 0.7347 | 0.0686 | 4 |
| D2 | Failure to dry | 0.0828 | 0.0077 | 15 |
| D3 | Incorrect determination of the detergent amount | 0.1826 | 0.0171 | 10 |
| E | Labeling section | | 0.6121 | |
| E1 | Incorrect labeling | 0.1439 | 0.0881 | 2 |
| E2 | Disorder labeling of products | 0.7734 | 0.4734 | 1 |
| E3 | Missing or over-labeling | 0.0828 | 0.0507 | 5 |

**Table 5** Results of the consistency values

| Failure mode groups | Consistency value |
|---|---|
| General evaluation of failure groups | 0.082 |
| Failures of group A | 0.137 |
| Failures of group B | 0.129 |
| Failures of group C | 0.129 |
| Failures of group D | 0.040 |
| Failures of group E | 0.052 |

provided in Table 6. When comparing the results of NBWM and BWM, it is easily observed that the priority rankings of the first three failures remain the same. Moreover, the least important failure is the same for both methods. The second comparison is performed between NBWM and FBWM methods. The failures of E2 and E1 that emerged in the labeling process have the highest priority ranking orders in both methods. The results of both classical BWM and FBWM are seen to be consistent with the proposed NBWM method. The authors conclude that the property of neutrosophy in considering failures can provide as good results as the other two methods. It is obvious that a straightforward comparison can be misleading. To discuss the usefulness of the ranking found by the NBWM approach, a correlation analysis is applied to measure the correlation coefficients between the final values of NBWM, classical BWM and FBWM. The results of the correlation analysis are given in Table 7.

Various applications of correlation analysis have been performed by some authors in the literature (Büyüközkan and Göçer 2019; Pamucar et al. 2018). This analysis aims to find the relationship among rankings obtained by the NBWM and the other two methodologies. The strength of the correlation can be described verbally by the following values: the values "0.00–0.19," "0.20–0.39," "0.40–059," "0.60–0.79" and "0.80–1.00" indicate "Very Weak," "Weak," "Moderate," "Strong" and "Very Strong" statistical significance, respectively (Büyüközkan and Göçer 2019; Pamucar et al. 2018). From Table 7, it is seen that there is a very strong and positive correlation (with a correlation coefficient of 99.8% and 92.9%, respectively) between the proposed NBWM method and the other two compared methods (classical BWM and FBWM).

**Table 6** Results of the comparative study

| Failure no. | NBWM | | | BWM | | | FBWM | | |
|---|---|---|---|---|---|---|---|---|---|
| | Local weight | Global weight | Rank | Local weight | Global weight | Rank | Local weight | Global weight | Rank |
| Section A failures | | 0.0690 | | | 0.0641 | | | 0.1640 | |
| A1 | 0.0712 | 0.0049 | 19 | 0.0633 | 0.0041 | 19 | 0.1032 | 0.0169 | 19 |
| A2 | 0.1883 | 0.0130 | 12 | 0.1364 | 0.0087 | 14 | 0.2207 | 0.0362 | 11 |
| A3 | 0.5722 | 0.0395 | 7 | 0.5665 | 0.0363 | 7 | 0.3347 | 0.0549 | 6 |
| A4 | 0.0857 | 0.0059 | 16 | 0.1169 | 0.0075 | 15 | 0.1787 | 0.0293 | 14 |
| A5 | 0.0827 | 0.0057 | 17 | 0.1169 | 0.0075 | 16 | 0.1626 | 0.0267 | 15 |
| Section B failures | | 0.0734 | | | 0.0944 | | | 0.1337 | |
| B1 | 0.0724 | 0.0053 | 18 | 0.0635 | 0.0060 | 17 | 0.1292 | 0.0173 | 18 |
| B2 | 0.5919 | 0.0435 | 6 | 0.5556 | 0.0525 | 4 | 0.4050 | 0.0542 | 7 |
| B3 | 0.2104 | 0.0155 | 11 | 0.2222 | 0.0210 | 10 | 0.2392 | 0.0320 | 12 |
| B4 | 0.1253 | 0.0092 | 14 | 0.1587 | 0.0150 | 11 | 0.2265 | 0.0303 | 13 |
| Section C failures | | 0.1521 | | | 0.1586 | | | 0.1762 | |
| C1 | 0.1888 | 0.0287 | 9 | 0.1593 | 0.0253 | 9 | 0.2300 | 0.0405 | 9 |
| C2 | 0.1951 | 0.0297 | 8 | 0.2240 | 0.0355 | 8 | 0.2375 | 0.0419 | 8 |
| C3 | **0.5489** | **0.0835** | **3** | **0.5520** | **0.0875** | **3** | 0.4022 | 0.0709 | 4 |
| C4 | 0.0671 | 0.0102 | 13 | 0.0647 | 0.0103 | 13 | 0.1302 | 0.0229 | 16 |
| Section D failures | | 0.0934 | | | 0.0717 | | | 0.1320 | |
| D1 | 0.7347 | 0.0686 | 4 | 0.7281 | 0.0522 | 5 | **0.5495** | **0.0725** | **3** |
| D2 | 0.0828 | 0.0077 | 15 | 0.0789 | 0.0057 | 18 | 0.1646 | 0.0217 | 17 |
| D3 | 0.1826 | 0.0171 | 10 | 0.1930 | 0.0138 | 12 | 0.2859 | 0.0377 | 10 |
| Section E failures | | 0.6121 | | | 0.6112 | | | 0.3941 | |
| E1 | **0.1439** | **0.0881** | **2** | **0.1439** | **0.0879** | **2** | **0.2508** | **0.0988** | **2** |
| E2 | **0.7734** | **0.4734** | **1** | **0.7734** | **0.4727** | **1** | **0.5860** | **0.2310** | **1** |
| E3 | 0.0828 | 0.0507 | 5 | 0.0828 | 0.0506 | 6 | 0.1632 | 0.0643 | 5 |

The bold fonts show the priority rankings of the first three failures according to three methods

### 4.5 Sustainable packaging and eco-labeling system suggestion for the observed facility

In light of the results obtained from the study, the most critical failure modes are determined as E1 (incorrect labeling) and E2 (disorder labeling of products). New and sustainable packaging and labeling automation system has been proposed to minimize the impact of these failure modes. With this proposed automation system, the size of the product, the material, the lot, the factory must be written in Turkish and English with a legible form on the label as required by the legal requirement. The necessary information will be obtained from the Enterprise Resource Planning (ERP) program. Therefore, this machine should be integrated with the ERP system. Also, the label used in products must be made of recyclable material. To maintain its activities healthily, the company needs to pack approximately 3000 implants a day. Sterilization is very important in the manufacturing process. The materials to be used in a sustainable packaging system must be antibacterial and resistant to corrosive effects.

## 5 Conclusion

The failure assessment process includes three important pillars of safety described as (1) identifying potential failures and its effects, (2) quantifying their priorities and (3) determining appropriate ways to reduce its negative effects into acceptable levels. Several approaches are proposed to prioritize failures and associated effects qualitatively, quantitatively or semi-quantitatively. MCDM approaches are forefront that they have the ability to express the failures verbally based on decision-makers' subjective judgments. Different types of uncertainties are explained by MCDM approaches using fuzzy sets in general. Since fuzzy sets focus only on membership value in decision-making, neutrosophic sets are more suitable in modeling

**Table 7** Results of correlation analysis

| | NBWM | BWM | FBWM |
|---|---|---|---|
| NBWM | 1.000 | | |
| BWM | 0.998 | 1.000 | |
| FBWM | 0.929 | 0.928 | 1.000 |

the real-world problems better than classical fuzzy sets by proposing three membership values named as truth-membership, indeterminacy-membership and falsity-membership. Therefore, in this study, a new failure assessment approach based on NBWM is proposed and a case study is also performed in the implant production industry.

The BWM proposed a promising vector-based MCDM method using less data and provides reliable results. However, BWM only uses integer values. The pairwise comparison can be done using only two vectors. This requires fewer data and less time. Surprisingly, the structure constructed with two vectors yields more consistent results than the full pair comparison matrix. In this respect, it is more practical than other MCDM methods. Since the single BWM has failed to handle imprecise and vague information which usually exists in real-world problems, we integrated neutrosophic set and BWM. Thus, the proposed model can reflect uncertainty and ambiguity in real-world problems better than BWM. This approach can make the decision-making process more dynamic, considering the benefits of BWM and neutrosophic sets either individually or in integration. This study contributes to the literature in some aspects as follows:

- Although the BWM method is used in many areas, it is not used for failure assessment before.
- Neutrosophic sets and BWM are merged for the first time in the literature. As well as it has been proposed for the first time, it has been applied to failure assessment problem.
- A real-case study is provided for the implant industry, which has not been previously studied.
- A comparative study with classical BWM and FBWM is also carried out to test the validity of the proposed NBWM.
- A new inconsistency index table for NBWM has been attached.
- An essential managerial implication to set up a new sustainable packaging and eco-labeling system for the observed facility is suggested regarding NBWM results.

In the future study, we will also apply this proposed methodology to some other areas, such as plastic injection and pistol production. Also, this methodology can be integrated with other methods such as neutrosophic AHP and applied for any other case studies.

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