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An approach to maintenance sustainability level assessment integrated with Industry 4.0 technologies using Fuzzy-TOPSIS: A real case study

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A B S T R A C T

Sustainable development (SD) activities within a manufacturing should be integrated with the Industry 4.0 (I4.0) technologies implementation due to ensure the continuous evaluation and even prediction the SD level. Such integration should be provided cross all company areas but must be strictly defined for each core process realised within a company. Therefore, the main purpose of the study is to build the new approach to assess the maintenance sustainability (MS) level in a manufacturing company, as a good example of integrating I4.0 technologies and SD activities within a company, using Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS). The major contributions of the work are as follows: 1) to the existing literature by identification the key objectives of MS, in the context of Industry 4.0 2) using the F-TOPSIS method and based on the empirical data received from 125 Polish manufacturing enterprises, 3) the establishment of the integrated approach, which allow continuous monitor the level of the MS within a manufacturing, 4) demonstrating the usefulness of the fresh framework in managerial practice through its verification in the five Polish manufacturing companies. Managers of manufacturing enterprises, thanks to the use of the proposed approach, may assess and constant monitor the MS level, while application of the I4.0 technologies.

A R T I C L E I N F O

Keywords:
Maintenance sustainability (MS);
Assessment;
Manufacturing;
Industry 4.0;
Multi-criteria decision making (MCDM);
Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS);
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1. Introduction

Production and industrial systems consume a huge amount of resources and energy, constituting a sector with a large percentage of emissions to the environment. That is why the modern industry is directed in its activities to support the three pillars of Sustainable Development (SD): social, economic and environmental. In that way, industrial enterprises and more precisely manufacturing ones seek to integrate the environment into their strategy by conducting an innovative rationalization of production as promoted by industrial ecology and circular economy paradigms [1]. Maintenance plays a key role in this regard, as a possibility for the prolong the life of manufacturing [2]. Standard maintenance is an integration of technical, administrative and managerial aspects of production [3]. Usually, the view of maintenance activities is narrowed down to the economic dimension. However, the increasing complexity of production systems indicates the need to broaden the horizons related to the effects of maintenance activities with an environmental and social dimension. It seems necessary to the implementation of the process approach to the design and operations of a company, an integrated management system based on the application of certain standards (quality, environment, safety at work, etc.) and elements of business excellence of a company [4].

The growing interest in the field of maintenance management is indicated by numerous publications in this area [5-8] indicating the possibility of including SD objectives in the maintenance management strategy. The literature on the subject indicates attempts to imply the assumptions of Sustainable Development (SD) in the assessment of maintenance results [9-12]. The Global Reporting Initiative - GRI [13] provides guidance on SD reporting for organizations where "the G4 Guidelines provide global guidance for a standardized approach to reporting, promoting clarity and consistency of information that is necessary to acquire useful and reliable content for the market and the public" [13]. SD reporting in accordance with the standards set by GRI is used by, among others, such companies as Orlen, Allegro, and PGNiG. SD, within manufacturing, should also be seen in the three areas: (1) production processes, (2) production durability and (3) product development. In the article, based on the literature (e.g., 14-16) the objectives of maintenance sustainability (MS) were defined.

The contemporary challenge of society is, therefore, the implementation of SD goals in the era of Industry 4.0. Zhou *et al*. [17] indicate that it is a futuristic and multifaceted process with many opportunities and challenges. Industry 4.0 can be started as the industrial transformation that provides new technological solutions by integrating information technologies and automation that communicate among themselves to achieve better results [18]. However, the growing importance of industry requires extensive measures to protect the well-being of m.in stocks, the environment, and dignified life. There is growing interest in sustainability practices for organisations [19]. Industry 4.0 can be used to increase SD's ability to achieve its goals by enabling organizations to diagnose in real-time and to optimize and improve the system's ability to adapt to a dynamically changing environment [20]. Thus, the organization is able to capture data from the actual implementation of production and quickly analyse the state of individual process parameters. Active data collection helps managers track, monitor, and then make sustainable decisions about their processes. Another important aspect is the use of the latest technologies in production systems to increase efficiency. This solution, in turn, provides a competitive advantage to the organization by producing high-quality products at a lower cost [21].

Therefore, the main idea of this paper is to evaluate the maintenance sustainability level in manufacturing companies integrated with Industry 4.0 technologies using one of the Decision Making (MCDM) methods. In the research process, two methods of multi-criteria analysis were considered to evaluate the maintenance sustainability level in manufacturing companies integrated with Industry 4.0 technologies: Analytic Hierarchy Process (AHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS). The choice of the AHP method was considered due to the ability to capture quantitative and qualitative attributes in a simple way, as well as the ability to handle rare or low-quality data. The use of the AHP method also allows for simple verification of the quality of expert judgments by performing a consistency test. The next step in the research process was the use of the F-TOPSIS method due to the complete autonomy of individual experts in making assessments. The IFWA operator was used to aggregate expert assessments. In the process of verification of selected MCDM methods, the F-TOPSIS method was used in the further part of the work due to the uncertainty and imprecision of the assessment of decision options in relation to the adopted criteria in the context of multifacetedness: evaluate the maintenance sustainability level in manufacturing companies.

MCDM methods are designed to solve such manufacturing problems [22]. It is indicated that the MCDM constitutes an excellent decision-making tool for evaluating and ranking/prioritizing the alternatives even when the criteria involved are complex [23]. The literature indicates the effective application of MCDM in the field of manufacturing enterprises, including flow control in a manufacturing system with three production lines is described [24], selection of the lean six sigma project [25], identifying key performance factors for sustainability development [26], materials selection [27]. To build the new approach to assess the maintenance sustainability level in manufacturing companies, using F-TOPSIS and IFWA operator the Decision Makers (DMs) opinions are needed. Therefore 125 Polish manufacturing companies from western Poland in the automotive industries were researched to assess the activities of the organization for the benefit of MS. Next, the research results obtained using the F-TOPSIS method represent the key objectives of MS in production enterprises. The values of the key MS objectives set should be determined based on the data included in applied I4.0 technologies within manufacturing. Finally, the universality of the proposed approach and its adaptability to the specificity of a given company was demonstrated and employed in five different types of Polish manufacturing enterprises.

2. Materials and methods

In the industrial scope, one of the key areas that directly influence the manufacturing sustainability of each company is maintenance [15].

The Decision Making (MCDM) methods refer to the methods of utilizing different data sources comprehensively to select optimization alternatives [28]. The MCDM methods focus on decision problems in which the set of all permissible decisions is a discrete set containing a finite, predetermined number of possible solution variants. MCDM tool can handle concurrently the various criteria which may be dimensional or non-dimensional in nature [23]. It is indicated that the MCDM constitutes an excellent decision-making tool for evaluating and ranking/prioritizing the alternatives even when the criteria involved are complex [23]. The literature indicates the effective application of MCDM methods in the field of a manufacturing company, including flow control in a manufacturing system with three production lines is described [24], selection of the lean six sigma project [25], identifying key performance factors for sustainability development [26], materials selection [27].

For the purpose of the assessment of the MS level, the F-TOPSIS and IFWA methods seem to be appropriate for this research. The F-TOPSIS method was presented by [29].

Fuzzy TOPSIS method and IFWA operator to rank the adopted alternatives and criteria. Along with the TOPSIS method, Intuitionistic Fuzzy Sets (IFS) were used. IFS A in the finite set X can be defined as follows [30]:

$$A = \{< x, \mu_A(x), v_A(x) > | x \in X\}, \text{where:} \tag{1}$$

$$\mu_A : x \to [0,1], v_A : x \to [0,1] \text{ and } 0 \leq \mu_A(x) + v_A(x) \leq 1 \; \forall \, x \in X \tag{2}$$

$\mu_A(x)$ and $v_A(x)$ determine the degree of membership and non-membership of x to A. For each IFS A of X there is also a third parameter called the degree of fluctuation, defined as:

$$\pi_A(x) = 1 - \mu_A(x) - v_A(x) \tag{3}$$

therefore, it is obvious that:

$$0 \leq \pi_A(x) \leq 1 \tag{4}$$

When the value of $\pi_A(x)$ is small, then the information about x is more certain, whereas when the value of $\pi_A(x)$ has a larger range, the information becomes uncertain.
The multiplication operator for intuitionistic fuzzy numbers (IFNs), where A and B belong to the set F is as follows:

$$A \otimes B = \{\mu_A(x). \mu_B(x), v_A(x) + v_B(x) - v_A(x). v_B(x) | \, x \in X \tag{5}$$

Multiplication of matrix components is calculated by the formula:

$$A \circ B = [< min\{\mu_A(x), \mu_B(x)\}, max\{\mu_A(x), \mu_B(x)\} >] \tag{6}$$

In order to establish the integrated approach, which allows continuous monitor the level of the MS within manufacturing the F-TOPSIS and IFWA methods were employed according to the following steps:

Step I. Calculation of weights for selected DMs

The group was assumed to include l decision-makers. The importance of individual decision-makers is represented by intuitionistic fuzzy numbers. Assuming that $D_k = [\mu_A, v_A, \pi_A]$, then IFN is showing the overall importance of Decision Maker k-th in the ranking. The k-th DM weight is calculated using the following formula:

$$\lambda_k = \frac{(\mu k + \pi_k(\frac{\mu k}{(\mu k + \ vk\ )})}{\Sigma_{k=1}^{l}(\mu k + \pi_k(\frac{\mu k}{\mu k + v_k})},\tag{7}$$

where assuming that:

$$\sum_{k=1}^{l} \lambda k = 1$$

Step II. Create the aggregated intuitionistic fuzzy decision matrix according to the DMs opinions

It was assumed that intuitionistic fuzzy decision matrix for each DM takes the form of $R^k = \left(r_{ij}^{(k)}\right)_{mnx} = \{1,2,\dots,l\}$, then weights of individual $DM\ \sum_{k=1}^{l} k = 1 \in [0,1]$. Opinions of all members should be combined into a group decision. For this purpose, the operator Intuitionistic Fuzzy Weighted Averaging (IFWA) proposed by [19] was used, assuming that:

$$r_{ij} = IFWA_\lambda\ \left(r_{ij}^{(1)}, r_{ij}^{(2)}, \dots, r_{ij}^{(l)}\right) = \ \lambda_1 r_{ij}^{(1)} \oplus \lambda_2 r_{ij}^{(2)} \oplus\ \dots\ \oplus\ \lambda_l r_{ij}^{(l)} = \tag{8}$$
$$= \left[1 - \prod_{k=1}^{l}\left(1 - \mu_{ij}^{(k)}\right)\lambda_k\ , \prod_{k=1}^{l}\ \left(\nu_{ij}^{(k)}\right)\lambda_k\ , \prod_{k=1}^{l}\left(1 - \mu_{ij}^{(k)}\right)\lambda\text{k}\ \ - \prod_{k=1}^{l}\ \left(\nu_{ij}^{(k)}\right)\lambda_k\right]$$

and

$$r_{ij}\ = (\mu_{Ai}(xj), \nu_{Ai}\ (x_j), \pi_{Ai}(x_j))\ \ (\ i\ =\ (1,2,\dots,m;\ \ j\ = 1,2,\dots,n)$$

Then, the aggregated IF decision matrix can be presented as:

$$\text{R} = \begin{bmatrix} \mu_{A1}(x1), \nu_{A1}(x1), \pi_{A1}(x1) & \mu_{A1}(x2), \nu_{A1}(x2), \pi_{A1}(x2) & \cdots & \mu_{A1}(x3), \nu_{A1}(x3), \pi_{A1}(x3) \\ \mu_{A2}(x1), \nu_{A2}(x1), \pi_{A2}(x1) & \mu_{A2}(x2), \nu_{A2}(x2), \pi_{A2}(x2) & \cdots & \mu_{A2}(x3), \nu_{A2}(x3), \pi_{A2}(x3) \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{Am}(x1), \nu_{Am}(x1), \pi_{Am}(x1) & \mu_{Am}(x2), \nu_{Am}(x2), \pi_{Am}(x2) & \cdots & \mu_{Am}(xn), \nu_{Am}(xn), \pi_{Am}(xn) \end{bmatrix} \tag{9}$$

$$\text{R} = \begin{bmatrix} \mu_{A1}(x1), \nu_{A1}(x1), \pi_{A1}(x1) & \mu_{A1}(x2), \nu_{A1}(x2), \pi_{A1}(x2) & \cdots & \mu_{A1}(x3), \nu_{A1}(x3), \pi_{A1}(x3) \\ \mu_{A2}(x1), \nu_{A2}(x1), \pi_{A2}(x1) & \mu_{A2}(x2), \nu_{A2}(x2), \pi_{A2}(x2) & \cdots & \mu_{A2}(x3), \nu_{A2}(x3), \pi_{A2}(x3) \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{Am}(x1), \nu_{Am}(x1), \pi_{Am}(x1) & \mu_{Am}(x2), \nu_{Am}(x2), \pi_{Am}(x2) & \cdots & \mu_{Am}(xn), \nu_{Am}(xn), \pi_{Am}(xn) \end{bmatrix} \tag{10}$$

$$\text{R}= \begin{bmatrix} r_{11} & r_{12} \cdots & r_{1m} \\ r_{21} & r_{22} \cdots & r_{2m} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{nm} \end{bmatrix} \tag{11}$$

To create the aggregated intuitionistic fuzzy decision matrix, a set of alternatives and also the Decision Makers (DMs) opinions are needed. Therefore, at the end of 2020, we researched 125 Polish manufacturing companies from western Poland (from the Lubuskie Voivodeship, Lower Silesia, Opole, Greater Poland and West Pomeranian Voivodeship) in the automotive industries to assess the activities of the organization for the benefit of SM. The tests were carried out using the survey method. The survey questionnaire included multi-choice, closed questions. The research group represents 1 % of manufacturing companies from the automotive industry, in western Poland [31] based on data from the Central Statistical Office of Poland, Warsaw. 61 % of the companies surveyed carry out an analysis in the area of energy consumption, although it is an essential tool for energy efficiency measures in the plant. Improving energy efficiency can have measurable effects in the form of energy savings, thereby reducing costs and reducing negative environmental impacts. It should be emphasised that energy efficiency protects land resources and is an important element of sustainable development. The survey data shows that 67 % of the companies surveyed carry out an analysis. So, based on the research results the set of decision-makers were defined:

DMs = {DM1, DM2}.

DM1 (an Owner) and DM2 (a Maintenance Manager) were selected based on the survey results, where the responses received in the positions of an owner and a maintenance manager accounted for the largest number of responses. The percentage for each position that was responsible for completing the survey is as follows: an owner 34 %, a co-owner 6.7 %, a board chairman 3.5 %, a board member 1.6 %, an administrative director 2.4 %, a sales director 0.8 %, a managing director 0.8 %, a director 0.8 %, a manager 3.2 %, a production manager 7.1 %, a maintenance manager 20 %, an assistance maintenance manager 0.8 %, a workshop manager 1.6 %, a service manager 0.8 %, a process engineer 4%, an engineer 0.8 %, a superintendent/caretaker 2.4 %, a chief accountant 0.8 %, an accountant 0.8 %, a technical specialist 0.8%, a maintenance specialist 1.7 %, a financial controller 0.8 %, a specialist 3.2 %.

Step III. Determine the weights of criteria and sub-criteria

Since it cannot be assumed that all criteria and sub-criteria are equally important, a W degree of importance should be set for them. To obtain the W parameter, opinions of individual DMs on the validity of criteria and sub-criteria must be combined into one assessment.

Suppose that $w_j^{(k)} = \left[\mu_j^{(k)}, v_j^{(k)}, \pi_j^{(k)}\right]$, then IFN is assigned to criterion Xj by k-th decision maker. Next, the weight for a particular criterion and sub-criterion is determined using the IFWA operator:

$$w_{ij} = IFWA_\lambda \left(w_j^{(1)}, w_j^{(2)}, \dots, w_j^{(l)}\right) = \lambda_1 w_j^{(1)} \oplus \lambda_2 w_j^{(2)} \oplus \dots \oplus \lambda_l w_j^{(l)} =$$

$$= \left[1 - \prod_{k=1}^{l}\left(1-\mu_{ij}^{(k)}\right)\lambda_k, \prod_{k=1}^{l}\left(v_{ij}^{(k)}\right)\lambda_k, \prod_{k=1}^{l}\left(1-\mu_{ij}^{(k)}\right)\lambda_k - \prod_{k=1}^{l}\left(v_{ij}^{(k)}\right)\lambda_k\right] \tag{12}$$

$$W = \left[w_1, w_2, \dots, w_j\right],$$

where

$$w_j = (\mu_j, v_j, \pi_j) \quad (j = 1,2, \dots, n) \tag{13}$$

Then a multiplication of the matrix components is used to combine the weights of each criterion with the corresponding sub-criteria (Eq. 6).

Step IV. Create the aggregated weighted intuitionistic fuzzy decision matrix

Calculation of criteria and sub-criteria weights (W) allows to create the aggregated weighted IF decision matrix. The aggregated weighted IF decision matrix based on [32]:

$$R \otimes W = \{x, \mu_{Ai}(x) \bullet \mu_W(x), \nu_{Ai}(x) + \nu_W(x) - \nu_{Ai}(x) + \nu_W(x) | x \in X \tag{14}$$

and

$$\pi_{Ai\bullet W} = 1 - \nu_{Ai}(x) - \nu_W(x) - \mu_{Ai}(\mathrm{x}) \bullet \mu_W(x) + \nu_{Ai}(x) + \nu_W(x) \tag{15}$$

Step V. Appoint the intuitionistic fuzzy positive-ideal solution and intuitionistic fuzzy negative-ideal solution

Suppose that $J1$ is a benefit criterion, while $J2$ is a cost criterion. A^+ is intuitionistic fuzzy positive ideal solution and A^- is intuitionistic fuzzy negative ideal solution. Eqs. 16 and 17 determine A^+ and A^-:

$$A^+ = (\mu_{A^+W}(x_j), \nu_{A^+W}(x_j) \text{ and } A^- = (\mu_{A^-W}(x_j), \nu_{A^-W}(x_j) \tag{16}$$

where:

$$\mu_{A^+W}(x_j) = ((max_i\ \mu_{AiW}(x_j) | j \in J1), (min_i\ \mu_{AiW}(x_j) | j \in J2) \tag{17}$$

$$\nu_{A^+W}(x_j) = ((min_i\ \nu_{AiW}(x_j) | j \in J1), (max_i\ \nu_{AiW}(x_j) | j \in J2) \tag{18}$$

$$\mu_{A^+W}(x_j) = ((min_i\ \mu_{AiW}(x_j) | j \in J1), (max_i\ \mu_{AiW}(x_j) | j \in J2) \tag{19}$$

$$\nu_{A^-W}(x_j) = ((max_i\ \nu_{AiW}(x_j) | j \in J1), (min_i\ \nu_{AiW}(x_j) | j \in J2) \tag{20}$$

Step VI. Calculate the separation measures and closeness coefficient

Measuring the separations between alternatives in Intuitionistic fuzzy set can be done by using a number of distance measures proposed by [33] or [32] including Hamming distance, Euclidean distance and their normalized distance measures [1]. After selecting the distance measure, the separation measures (S_{i^+} and S_{i^-}) for each alternative from intuitionistic fuzzy positive ideal and negative ideal solutions the selection is made. The article uses normalized Euclidean distance:

$$S^+ = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}[(\mu_{AiW}(x_j) - \mu_{A^+W}(x_j))^2 + (\nu_{AiW}(x_j)^2 - \nu_{A^+W}(x_j))^2 + (\pi_{AiW}(x_j)^2 - \pi_{A^+W}(x_j))^2]} \quad (21)$$

$$S^- = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}[(\mu_{AiW}(x_j) - \mu_{A^-W}(x_j))^2 + (\nu_{AiW}(x_j)^2 - \nu_{A^-W}(x_j))^2 + (\pi_{AiW}(x_j)^2 - \pi_{A^-W}(x_j))^2]} \quad (22)$$

Then the relative closeness coefficient to the ideal solution is:

$$C_i = \frac{S_{i-}}{S_{i-} + S_{i+}}, \text{where } 0 \leq C_i \leq 1 \quad (23)$$

Step VII. Rank the alternatives

After calculating the relative closeness coefficients of each alternatives, a ranking of the alternative has been made, based on C_i's decreasing value.

3. Research results

In order to create a framework for assessing the maintenance sustainability level in manufacturing companies, integrated with I4.0 technologies, the following elements should be defined: Element 1: a set of criteria: C = {C1, C2,…., C12}, Element 2: a set of sub-criteria: I = {I1, I2,…, I14}, Element 3: a set of alternatives: Av = {Av1, Av2, Av3}.

Based on the analysis of our previous works and based on the literature, e.g. [14-16, 34], the set of criteria: C = {C1, C2,…, C7} and a set of sub-criteria: I = {I1, I2,…, I14} were determined. It should be noted that the selected criteria and sub-criteria for maintenance sustainability are related to the industry concerned (manufacturing) to meet the unique needs of the manufacturing sector. A set of alternatives: Av = {Av1, Av2, Av3} was determined as the management levels within an enterprise: the operational (Av1), as well as tactical (Av2) and strategic level (Av3). The adopted criteria (Table 1) were also divided into a benefit (criteria for which the higher value then better) and cost (criteria for which the lower value then better). Benefit and cost criteria are presented in Table 2.

Table 1 Selected criteria and sub-criteria

Criteria		Sub-criteria	
Staff education	C1	Cost of training for maintenance Preventive maintenance time causing downtime	I1 I2
Timeliness	C2	Timeliness of order	I2
Reduction of downtime costs	C3	Total number of downtime related to maintenance	I4
Environmental protection	C4	Number of failures causing potential damage to the environment	I5
Reduction of production costs	C5	Reduction costs of losses related to production stoppages resulting from breakdowns	I6
Safety	C6	Reduction costs connected with potentially accidental events and accidents of maintenance workers, operators and third parties during maintenance works	I7
Investment profitability	C7	Return on eco-friendly maintenance investment and innovation	I8
Resources saving	C8	Total of spare parts used/ Original spare parts used Recycled spare parts used/ Re-purposed spare parts used	I9 I10
Good practices	C9	Skill improvement related to sustainable maintenance practices	I11
Innovation and modernization	C10	Modernization carried out in the last six months related to sustainable maintenance	I12
Use of renewable energy	C11	Renewable energy consumption	I13
Reduction of non-renewable energy consumption	C12	Non-renewable energy consumption	I14

Table 2 Benefit and cost criteria

Action	Criteria	Benefit	Cost
MS (maintenance sustainability)	C1	x	
	C2	x	
	C3		x
	C4		x
	C5		x
	C6	x	
	C7	x	
	C8	x	
	C9	x	
	C10	x	
	C11	x	
	C12		x

Selected DMs (section 2) was assigned the importance of weights based on their involvement in the adopted action (maintenance sustainability). To determine the importance of weights for DM, the following formula was used Eq. 7.

The results of the studies allowed to assess the involvement of the selected DMs in the activities of the organization for the benefit of SD. The assessment of involvement in the implementation of particular DMs criteria was carried out on the basis of the adopted linguistic terms and Intuitionistic Fuzzy Numbers. Linguistic terms for ranking the importance of the DMs, criteria and sub-criteria: little consequence (LC) – IFN ∈ (0.10, 0.90); medium consequence (MC) – IFN ∈ (0.25, 0.70); important (I) – IFN ∈ (0.45, 0.50; very important (VI) – IFN ∈ (0.75, 0.20); crucial (C) –IFN ∈ (0.90, 0.10). The importance of DMs and their weights: DM1 – Crucial; Weight 0.539, and DM2 – Very Important; Weight 0.461**.**

Table 3 The ratings of the alternatives

Action	SD objective	Level of management in company	DMs			
			DM1	DM2	DM1	DM2
MS	C1	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	SL	HL	(0.55, 0.35)	(0.75, 0.25)
		OP	IL	ML	(0.20, 0.65)	(0.40, 0.50)
	C2	ST	SL	HL	(0.55, 0.35)	(0.75, 0.25)
		TA	HL	VHL	(0.75, 0.25)	(1.00, 0.00)
		OP	ML	ML	(0.40, 0.50)	(0.40, 0.50)
	C3	ST	HL	HL	(0.75, 0.25)	(0.75, 0.25)
		TA	VHL	VHL	(1.00, 0.00)	(1.00 , 0.00)
		OP	IL	ML	(0.20, 0.65)	(0.40, 0.50)
	C4	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	HL	SL	(0.75, 0.25)	(0.55, 0.35)
		OP	IL	NL	(0.20, 0.65)	(0.00, 1.00)
	C5	ST	VHL	HL	(1.00, 0.00)	(0.75, 0.25)
		TA	HL	ML	(0.75, 0.25)	(0.40, 0.50)
		OP	IL	IL	(0.20, 0.65)	(0.20, 0.65)
	C6	ST	HL	HL	(0.75, 0.25)	(0.75, 0.25)
		TA	VHL	VHL	(1.00, 0.00)	(1.00 , 0.00)
		OP	IL	IL	(0.20, 0.65)	(0.20, 0.65)
	C7	ST	SL	HL	(0.55, 0.35)	(0.75, 0.25)
		TA	HL	VHL	(0.75, 0.25)	(1.00, 0.00)
		OP	ML	SL	(0.40, 0.50)	(0.55, 0.35)
	C8	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	HL	HL	(0.75, 0.25)	(0.75, 0.25)
		OP	IL	NL	(0.20, 0.65)	(0.00, 1.00)
	C9	ST	HL	HL	(0.75, 0.25)	(0.75, 0.25)
		TA	SL	SL	(0.55, 0.35)	(0.55, 0.35)
		OP	NL	NL	(0.00, 1.00)	(0.00, 1.00)
	C10	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		OP	IL	ML	(0.20, 0.65)	(0.40, 0.50)
	C11	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	HL	HL	(0.75, 0.25)	(0.75, 0.25)
		OP	ML	SL	(0.40, 0.50)	(0.55, 0.35)
	C12	ST	VHL	VHL	(1.00, 0.00)	(1.00, 0.00)
		TA	VHL	HL	(1.00, 0.00)	(0.75, 0.25)
		OP	IL	NL	(0.20, 0.65)	(0.00, 1.00)

The linguistic terms (LT) and IFNs for the adopted alternatives were then determined:

- LT: Very high level (VHL) – IFN ∈ [1.00;0.00]
- LT: High level (HL) – IFN ∈ [0.75;0.25]
- LT: Significant level (SL) – IFN ∈ [0.55;0.35]
- LT: Medium level (ML) – IFN ∈ [0.40;0.50]
- LT: Insignificant level(IL) – IFN ∈ [0.20;0.65]
- LT: Nonsignificant level (NL) – IFN ∈ [0.00;1.00]

Based on Table 1, the experts assessed the criteria in terms of the alternatives adopted (Table 3).

The aggregated Intuitionistic Fuzzy Decision Matrix according to the DMs opinions presented on Table 4 (Eq. 8).

Table 4 Aggregated Intuitionistic Fuzzy Decision Matrix

		ST	TA	OP
	C1	(1.000, 0.000, 0.000)	(0.656, 0.210, 0.043)	(0.299, 0.576, 0.124)
	C2	(0.657, 0.299, 0.043)	(1.000, 0.000, 0.000)	(0.400, 0.500, 0.100)
	C3	(0,750. 0.250, 0.000)	(1.000, 0.000, 0.000)	(0.299, 0.576, 0.125)
	C4	(1.000, 0.000, 0.000)	(0.672, 0.291, 0.036)	(0.113, 0.792, 0.093)
	C5	(1.000, 0.000, 0.000)	(0.625, 0.344, 0.030)	(0.200, 0.650, 0.150)
R =	C6	(0,750. 0.250, 0.000)	(1.000, 0.000, 0.000)	(0.200, 0.650, 0.150)
	C7	(0.656, 0.210, 0.043)	(1.000, 0.000, 0.000)	(0.475, 0.424, 0.101)
	C8	(1.000, 0.000, 0.000)	(0,750, 0.250, 0.000)	(0.113, 0.792, 0.093)
	C9	(0,750. 0.250, 0.000)	(0.550, 0.350, 0.150)	(0.000, 1.000, 0.000)
	C10	(1.000, 0.000, 0.000)	(1.000, 0.000, 0.000)	(0.299, 0.576, 0.125)
	C11	(1.000, 0.000, 0.000)	(0,750. 0.250, 0.000)	(0.475, 0.424, 0.101)
	C12	(1.000, 0.000, 0.000)	(1.000, 0.000, 0.000)	(0.133, 0.793, 0.094)

DMs evaluated selected criteria and sub-criteria using linguistic terms (Table 5, Table 6). The opinions received in form of linguistic terms were then translated into intuitionistic fuzzy numbers (Table 7, Table 8).

Table 5 The criteria importance weight

Action	Criteria	DMs	
		DM1	DM2
	C1	C	VI
	C2	VI	C
	C3	VI	VI
	C4	I	VI
	C5	C	VI
MS	C6	I	MC
	C7	MC	I
	C8	VI	VI
	C9	I	I
	C10	VI	VI
	C11	C	C
	C13	C	C

Table 6 The sub-criteria importance weight

Action	Sub-criteria	DMs	
		DM1	DM2
	I1	C	VI
	I2	VI	C
	I3	I	VI
	I4	VI	I
	I5	C	VI
	I6	MC	LC
MS	I7	I	I
	I8	I	VI
	I9	VI	VI
	I10	MC	I
	I11	C	VI
	I12	VI	VI
	I13	VI	I
	I14	C	C

Table 7 The rating of criteria based on intuitionistic fuzzy numbers

Action	Criteria	DMs	
		DM1	DM2
MS	I1	(0.90, 0.10)	(0.75, 0.25)
	I2	(0.75, 0.25)	(0.90, 0.10)
	I3	(0.75, 0.25)	(0.75, 0.25)
	I4	(0.45, 0.55)	(0.75, 0.25)
	I5	(0.90, 0.10)	(0.75, 0.25)
	I6	(0.45, 0.55)	(0.25, 0.75)
	I7	(0.25, 0.75)	(0.45, 0.55)
	I8	(0.75, 0.25)	(0.75, 0.25)
	I9	(0.45, 0.55)	(0.45, 0.55)
	I10	(0.75, 0.25)	(0.75, 0.25)
	I11	(0.90, 0.10)	(0.90, 0.10)
	I12	(0.90, 0.10)	(0.90, 0.10)

Table 8 The rating of sub-criteria based on intuitionistic fuzzy numbers

Action	Sub-criteria	DMs	
		DM1	DM2
MS	I1	(0.90, 0.10)	(0.75, 0.25)
	I2	(0.75, 0.25)	(0.90, 0.10)
	I3	(0.45, 0.55)	(0.75, 0.25)
	I4	(0.75, 0.25)	(0.45, 0.55)
	I5	(0.90, 0.10)	(0.75, 0.25)
	I6	(0.25, 0.75)	(0.10, 0.90)
	I7	(0.45, 0.55)	(0.45, 0.55)
	I8	(0.45, 0.55)	(0.75, 0.25)
	I9	(0.75, 0.25)	(0.75, 0.25)
	I10	(0.25, 0.75)	(0.45, 0.55)
	I11	(0.90, 0.10)	(0.75, 0.25)
	I12	(0.75, 0.25)	(0.75, 0.25)
	I13	(0.75, 0.25)	(0.45, 0.55)
	I14	(0.90, 0.10)	(0.90, 0.10)

Aggregation of criteria and sub-criteria importance according to DMs opinions is presented in Table 9 (Eq. 6). The final weights for aggregated criteria and sub-criteria (ACI) are presented in Table 10 (Eq. 11).

Table 9 The aggregated importance of criteria and sub-criteria

Action	Combination	DMs	
		DM1	DM2
MS	I1	(0.90, 0.10)	(0.75, 0.20)
	I2	(0.75, 0.20)	(0.90, 0.10)
	I3	(0.45, 0.50)	(0.75, 0.20)
	I4	(0.45, 0.50)	(0.45, 0.50)
	I5	(0.90, 0.10)	(0.75, 0.20)
	I6	(0.25, 0.70)	(0.10, 0.90)
	I7	(0.25, 0.70)	(0.45, 0.55)
	I8	(0.75, 0.20)	(0.75, 0.20)
	I9	(0.25, 0.70)	(0.45, 0.50)
	I10	(0.75, 0.20)	(0.75, 0.20)
	I11	(0.75, 0.20)	(0.45, 0.50)
	I12	(0.90, 0.10)	(0.90, 0.10)

Table 10 The final weight of Aggregated Criteria and Sub-criteria (ACI)

W =	ACI1	(0.8474, 0.1525, 0.0001)
	ACI2	(0.8361, 0.1638, 0.0001)
	ACI3	(0.6176, 0.3823, 0.0391)
	ACI4	(0.6176, 0.3823, 0.0001)
	ACI5	(0.8474, 0.1525, 0.0001)
	ACI6	(0.1842, 0.8157, 0.0001)
	ACI7	(0.3499, 0.6501, 0.0000)
	ACI8	(0.7500, 0.2500, 0.0000)
	ACI9	(0.3499, 0.6501, 0.0000)
	ACI10	(0.7500, 0.2500, 0.0000)
	ACI11	(0.6404, 0.3596, 0.0000)
	ACI12	(0.9000, 0.1000, 0.0000)

Based on Aggregated Intuitionistic Fuzzy Decsion Matrix (Table 4) and the weightings of criteria and sub-criteria (W) the aggregated weighted intuitionistic fuzzy decision matrix was created, where Eq. 14 and Eq. 15 were used.

Table 11 The aggregated weighted intuitionistic fuzzy decision matrix

		ST	TA	OP
	C1	(0.874,0.153,0.001)	(0.556, 0.330,0.114)	(0.253, 0.641,0.106)
	C2	(0.549,0.414,0.037)	(0.836,0.164,0.000)	(0.334,0.582,0.084)
	C3	(0.493,0.519,0.042)	(0.618,0.382,0.000)	(0.131,0.728,0.141)
	C4	(0.617,0.382,0.001)	(0.415,0.562,0.023)	(0.082,0.871,0.047)
	C5	(0.847,0.153,0.000)	(0.529,0.444,0.027)	(0.169,0.703,0.128)
R' =	C6	(0.138,0.862,0.000)	(0.184,0.816,0.002)	(0.037,0.935,0.028)
	C7	(0.229,0.724,0.047)	(0.349,0.650,0.001)	(0.166,0.798,0.036)
	C8	(0.750,0.250,0.000)	(0.563,0.437,0.000)	(0.085,0.844,0.071)
	C9	(0.262,0.737,0.001)	(0.192,0.773,0.035)	(0.000,1.000,0.000)
	C10	(0.750,0.250,0.000)	(0.750,0.250,0.000)	(0.224,0.682,0.094)
	C11	(0.640,0.359,0.001)	(0.480,0.519,0.001)	(0.304,0.631,0.065)
	C12	(0.900,0.100,0.000)	(0.900,0.100,0.000)	(0.119,0.814,0.067)

In accordance with the division presented in Table 2 the selected criteria belong respectively to the following: J1 = { C1,C2,C6,C7,C8,C9,C10,C11} and J2 = {C3,C5,C12}.

T he intuitionistic fuzzy positive-ideal solution and intuitionistic fuzzy negative-ideal solution made by using Eqs. 16 to 20.

$$A^{+} = \begin{pmatrix} (0.253,0.641,0.106) & (0.836,0.164,0.000) & (0.131,0,780,0.089\ ) & (0.617,0.382,0.001) \\ (0.847,0.153,0.000) & (0.184,\ 0.816,0.000) & (0.166,0.650,0.184\ ) & (0.750,0.000,0.250) \\ (0.480,0.250,0.270) & 0.847,0.153,0.000 & 0.640,0.359,0.001) & 0.900,0.100,0.000 \end{pmatrix}$$

$$A^{-} = \begin{pmatrix} (0.847,0.\ 153,0.000) & (0.334,0.582,0.084) & (0.618,0.382,0.000) & (0.082,0.872,0.046) \\ (0.169,0.703,0.128\ ) & (0.037,0.935,0.028) & (0.349,0.650,0.001) & (0.085,0.844,0.071) \\ (0.311,0.623,\ 0.066) & (0.253,0.641,\ 0.106) & (0.024,0.962,0.014) & (0.403,0.512,0.085) \end{pmatrix}$$

Measurement of separation between alternatives in the Intuitionistic fuzzy set was made by using normalized Euclidean distance (Eqs. 21 and 22). Then, the relative closeness coefficient to the ideal solution (Eq. 23) was set. The results are presented in Table 12.

Table 12 The relative closeness coefficient and separation measures of each level

Level of management in company	S^{+}	S^{-}	Ci^{*}	Rank
ST	0.219	0.238	0.520	2nd
TA	0.206	0.227	0.523	1st
OP	0.305	0.251	0.451	3rd

In order to rank the alternatives, the Ci* factor was first calculated and then the alternatives were ranked in decreasing order of Ci*. In the adopted case study, three levels were adopted, which were arranged as follows TA < ST < OP. As a result of calculations, the ST level was accepted as crucial for the examined company. Then, based on the results of the aggregated weighted intuitionistic fuzzy decision matrix (Table 11) key indicators were selected for the SD level by descending order of the μ parameter (Table 13).

Table 13 Key SD objectives for the defined MS level in the context I4.0

Rank	Criteria	Sub-criteria
1	C12	I14
2	C2	I3
3	C10	I12
4	C3	I4
5	C8	I9
		I10
6	C1	I1
7	C5	I6
8	C11	I13
9	C7	I8
10	C4	I5
11	C9	I11
12	C6	I7

The results obtained using the F-TOPSIS method represent the key objectives of MS in production enterprises. These objectives should be pursued first, as they form the basis for further activities carried out in the organisation for the benefit of the MS in the context of I4.0. Therefore the values of the key SD objectives set should be determined based on the data included in IT in the I4.0 context (Table 14).

Table 14 Data source in IT in I4.0 context for the values of the key SD objectives set

Rank	Criteria	Data source
1	C12	ERP
2	C2	ERP
3	C10	MANUALLY
4	C3	ERP
5	C8	ERP
6	C1	ERP
7	C5	ERP
8	C11	ERP
9	C7	MANUALLY
10	C4	MANUALLY
11	C9	MANUALLY
12	C6	MANUALLY

4. Verification and discussion

The proposed approach was verified and implemented in five Polish metal companies from the SME sector, in order to verify the usability of applying our model to select SD objectives and to define the needed corrective actions to increase the level of SD in the company.

The following company's activities that are supported by an IT in I4.0 (an ERP system) and its functionality were indicated, namely: Production planning (F1), Cost accounting (F2), Manufacturing execution system (F3), Production technology management (F4), Customer relationship management (F5), Service and repair planning (F6), Personnel management (F7), Warehouse Management (F8), Transport improvement (F9).

The following SD indicator values in the analysed company were obtained (Table 15).

Table 15 The base of SD indicator values in the analysed companies

C	S-C	Data source	Functionality of the ERP system	Value				
				I	II	III	IV	V
C12	I14	ERP	F2	640000 kWh	38128 kWh	25000 kWh	26141 kWh	41344 kWh
C2	I3	ERP	F1	over 90 %	over 90 %	less than 80 %	between 80-90 %	less than 80 %
C10	I12	MANUALLY	-	YES	YES	NO	YES	YES
C3	I4	EPP	F6	10	20	0	0	16

To determine the reference SD indicators values for a given class of enterprises in a given area the statistical data on a given country, which should be averaged out for a given industry of enterprises should be adopted. Therefore the reference MS indicators values for a given class of enterprises were obtained based on the statistical data in Poland [35] and REACH; ISO 14001; ISO50001; OHSAS 18001 were obtained (Table 16).

Table 16 The reference values

SD objective	SD Indicators	Reference values I
C12	I14	-5 %
C2	I3	over 90 %
C10	I12	YES
C3	I4	0

However, to apply our approach to enterprises in other countries, the reference MS indicators values for a given class of enterprises based on the statistical data in the country of the surveyed enterprise should be adopted.

Finally, the setting of SD recommendations for the analysed company is possible based on the comparison of the obtained key SD indicator values with the reference values for the SD indicators (Table 17, Table 18).

Table 17 Range of values for determining the level of SD

MS level	Compartment
Good	< 90-100 % references values
Medium	< 85-60 % references values
Low	> 60 % references values

Table 18 The base of the obtained SD indicators values in the company compared with the reference values

Enterprise	Criteria	Sub-Criteria	Reference values	Obtained values	SD level
I	C12	I14	-5 %	640000	Check after implementing changes
	C2	I3	over 90 %	over 90 %	Good
	C10	I12	YES	YES	Good
	C3	I4	0	10	Low
II	C12	I14	-5 %	38128	Check after implementing changes
	C2	I3	over 90 %	over 90 %	Good
	C10	I12	YES	YES	Good
	C3	I4	0	20	Low
III	C12	I14	-5 %	25000	Check after implementing changes
	C2	I3	over 90 %	less than 80 %	Low
	C10	I12	YES	NO	Low
	C3	I4	0	0	Good
IV	C12	I14	-5 %	26141	Check after implementing changes
	C2	I3	over 90 %	between 80-90 %	Medium
	C10	I12	YES	YES	Good
	C3	I4	0	0	Good
V	C12	I14	-5 %	41344	Check after implementing changes
	C2	I3	over 90 %	less than 80 %	Low
	C10	I12	YES	YES	Good
	C3	I4	0	16	Low

Thanks to the implementation of our model in the analysed company, it is possible to define the key SD objectives:

- C12: non-renewable energy consumption
- C2: cost of training for maintenance, preventive maintenance time causing downtime
- C10: number of innovations carried out related to sustainable maintenance.

Moreover, based on Table 18, it is possible to define the needed corrective actions that the company must take to increase its SD level. In the considered case:

- reduction of non-renewable energy consumption: e.g., control energy consumption, systematic maintenance and service of machines, use of renewable energy,
- staff education: conservation according to the schedule, regular training of maintenance staff,
- innovation: intelligent solutions, modern warning systems, automated lubrication, operational diagnostics.

The universality of the proposed approach and its adaptability to the specificity of a given company allows it to be employed in different types of enterprises.

5. Conclusion

Industry 4.0 technologies and sustainability are popular organizational trends that are vital to increasing sustainable production [36]. However, despite numerous considerations regarding the positive aspects of the implementation of Industry 4.0 technology in the SD concept, further negative effects on the environment are also indicated by throwing outdated equipment [37], and therefore increased greenhouse gas emissions or the production of a large amount of waste [38].

As with all studies, this study owns up to certain limitations that further research should be able to overcome. Firstly, the use of normalized Euclidean distance, which does not take into account the correlation between attributes, and the lack of correlation between criteria and sub-criteria are considered limitations of the proposed approach. Secondly, the verification of a model was shown in the example of the Polish companies investigated and all the indicators were measured at the same moment in time; it would, therefore, be useful to provide such research over a longer time period. These conclusions and limitations suggest proposals for the direction of future research.

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