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An assessed framework for manufacturing sustainability based on Industry 4.0 under uncertainty

Khalid A. Eldrandaly [1], Mona Mohamed*[2], Nissreen El-Saber[1], and Mohamed Abdel-Basset[1]

[1]Faculty of Computers and Informatics, Zagazig University, Zagazig, 44519, Egypt

Emails: Khalideldrandaly@zu.edu.eg; naelsaber@fci.zu.edu.eg; mohamedbasset@ieee.org

[2]Higher Technological Institute,10th of Ramadan City, Egypt

*Corresponding Author: Mona Mohamed (Email: mona.fouad@hti.edu.eg)

Abstract: Globalization and the rapid growth of technologies are the main challenges facing the manufacturer and its sustainability and survival. Sustainability for any manufacturing plays an important role in competitive advantage which make the manufacturing firm a sustainable competitor. Sustainability in manufacturing is integrated with Industry 4.0 (I4.0) to achieve benefits of economic, environmental, and social. But it has many criteria and factors and contains incomplete and uncertain information. So, we used the neutrosophic sets to overcome this incomplete information and treat with uncertainty environment. The Single-Valued Neutrosophic Set (SVNS) is used to evaluate these criteria, which include three values (Truth, indeterminacy, and falsity). The SVNS is integrated with Multi-Criteria Decision Making (MCDM) methods. The MCDM concept is used in this paper to deal with many conflicting criteria. A Decision-making trial and evaluation laboratory (DEMATEL) is utilized for determining the relation between five main criteria and fourteen sub-criteria in this study. Analytic Hierarchy Process (AHP) is used to compute the weights of the main and sub-criteria. Our framework is applied to a real case study in Egypt to show the validity of our framework.

Keywords: Sustainability; Industry 4.0; AHP; Single-Valued Neutrosophic Sets; SVNSs; Multi-Criteria Decision Making; MCDM; DEMATEL.

1. Introduction

In the previous centuries, the industrial revolutions continued until advent of the fourth industrial revolution, known as I 4.0. This revolution includes the use of many technologies that help automate and digitalize operations. The manufacturing industry has undergone many radical changes [1].

This new digital industrial transformation has had a positive impact on manufacturing organizations. This made manufacturing more intelligent which led to businesses changing their way of working. I4.0 is an umbrella for various technologies such as big data analytics (BDA), Internet of Things (IoT) and cloud computing, Cyber-Physical systems (CPS), information and communications technology (ICT), Enterprise Architecture (EA), Enterprise Integration (EI) and Blockchain (BC) [2].

The benefits of utilization of I4.0 technologies in manufacturing are (i) it helped in the emergence of so-called smart manufacturing. Smart manufacturing is expressed in [3] as "manufacturing machines are characterized with interconnection through wireless networks according to modern manufacturing paradigm, monitored by sensors, and controlled by advanced computational intelligence to enhance the quality of product, increase productivity, and sustainability with reducing costs." (ii) manufacturing system becomes an integrated and cooperative production system that responds to any changing requirements and conditions in real-time [4]. (iii) high level of digitization through exchanging data, communication among parts, products, machines, and human-machine interaction (HMI). (iv) Optimization through energy and resource consumption. (v) Global competitiveness through productivity and operational efficiency. (vi) Beneficial decisions through tracking products effectively and analyzing the market on an ongoing basis. (vii) The cost is reduced, and profits are increasing by processing effective information are improving the production planning decisions [5, 6, 7]. (viii) Improvement of product development by transforming the traditional production and operations management techniques [6].

Consequently, manufacturing firms are becoming sustainable by applying I4.0 technologies. Despite it being a complicated process, not simple. From the TBL perspective [8] one of the sustainability requirements for the firm is achieving a balance between the economic, environmental, and social pillars. Sustainability of manufacturing according to TBL represents: Environmentally, products are environment-friendly through using resources efficiently. Socially, the production process is based on ethics and sustainability. Economically, manufacturing processes are highly efficient in saving energy, natural resources utilization and achieving a better global market reputation [9].

The sustainability of manufacturing based on I4.0 has many various conflict criteria, so the Multi-Criteria Decision Making (MCDM) is used to overcome this problem. Numerous MCDM techniques offer a huge variety of approaches for solving complex decision-making problems such as TOPSIS, DEMATEL, Analytic Hierarchy Process (AHP)…etc. MCDM is used in assessments containing numerous criteria to support decision-makers (DMs) and experts to make decisions based on their preferences by breaking the problems into smaller portions [13]. These techniques have been increasingly used in manufacturing practices [14]. According to [15] MCDM deal with many types of problems that contain huge and conflict criteria.

Researchers in [16] have introduced techniques to strengthen MCDM through utilizing Fuzzy Set (FS) where its function is to assign a degree of membership ranging between [0-1] for each element. In [17] an improvement of FS, called Intuitionistic Fuzzy Sets (IFS) is introduced. It considers the membership degree, non-membership degree, and hesitation degree. But the FS can't deal efficiently with the incomplete data due to lack of the indeterminacy value concept.

Neutrosophic theory embraces the idea of FS and IFS more comprehensively. It assigns a degree of membership, indeterminacy, and non-membership function for each element [18]. Furthermore, [19,20] proposed many benefits of neutrosophic theory such as: (i) Neutrosophy helps experts to present their opinions about uncertain preferences by using the degree of indeterminacy to present obscure information. (ii) It deals with different conditions of decision-making through applying truthiness, indeterminacy, and falsity. (iii) It expresses odds between DMs and experts. (iv) It can handle uncertainty and various environments.

All of these are strong motivations for consolidating neutrosophic theory with MCDM techniques to rank and select the best solution (alternative) among possible solutions (alternatives) based on calculation weights of criteria through an expert panel [15]. For the maximum benefit, the criteria with the maximum weight is selected.

The focus of modern organizations is not limited to profitability, but it spans to eco-friendly items production, time utilization of challenging tasks, and increased productivity. In short, modern organizations seek sustainability [21].

The research on sustainability of manufacturing based I4.0 is in its early stages of growth [22]. In Section 2 of this work, more details are given via the Web of Science (WoS) database.

In this study, we will adopt the idea of the influence of I4.0 on manufacturing firms to be environmentally, socially, and economically sustainable. This study aims to fulfill the following objectives:

1. Attempting to answer the question (using literature analysis): Can the adoption of I4.0 technologies have a positive impact on promoting sustainability in manufacturing?

2. Identifying I4.0 enablers or criteria and sub-criteria that affect the achievement of manufacturing sustainability using literature.
3. Assessing the impact of determined I4.0 main and sub-criteria on each other to achieve sustainable manufacturing through a questionnaire offered to a committee of decision makers (DM) and experts.
4. Determine degree of influence among main and sub-criteria using the hybrid framework of MCDM with neutrosophic theory (N-DEMATEL).
5. Applying AHP-based neutrosophic for recommending the most positive influential criteria on three pillars of Triple Bottom Line (TBL).
6. Applying the proposed framework on a case study of real manufacturing firms.

This paper is organized as follows: section 2 presents systematic analysis of related articles and the research methodology used in this study, section 3 presents the literature review of I4.0 and sustainability of manufacturing related I4.0 illustrating basic concepts and technologies. Section 4 clarifies the proposed developed framework for criteria interrelations. In section 5, the hybrid framework validation is assessed through real case study. Finally, conclusions are highlighted in section 6.

2. Systematic Analysis and Research Methodology

In this section, systematic analysis is performed on the available published documents on the study topic. The analysis process facilitates knowing current trends of research in the literature related to a specific field [23,24]. Therefore, research papers and articles on "sustainable manufacturing" and "sustainable manufacturing based I4.0" are analyzed. The source of articles is Web of Science (WoS) database from 2015 until 2020. WoS database contains numerous famous publications and articles in different domains. Figure 1 illustrates the steps to be followed in the methodology.

The proposed research methodology consists of four steps as shown in Figure 1 and summarized below:

Step1: Search WoS database: The database is searched using two key concepts; "sustainable manufacturing" and "sustainable manufacturing based I4.0".

Step2: Trend Analysis: Based on the research results, the study focuses on number of publications in the field per year, type of the publication and area of research. These data are summarized and interpreted allowing for further insights. Table 1 shows the summarized search results.

Step3: Trend Analysis Results (potentials): the trend results are categorized into two parts. First part is for extracting the gaps and limitations in the research area. This is followed by highlighting the potential motivations for contributions in the manufacturing sustainability using I4.0 as part two.

Step4: Influence Evaluation Model: a model is developed for assessing the influence of criteria from I4.0 on the manufacturing sustainability.

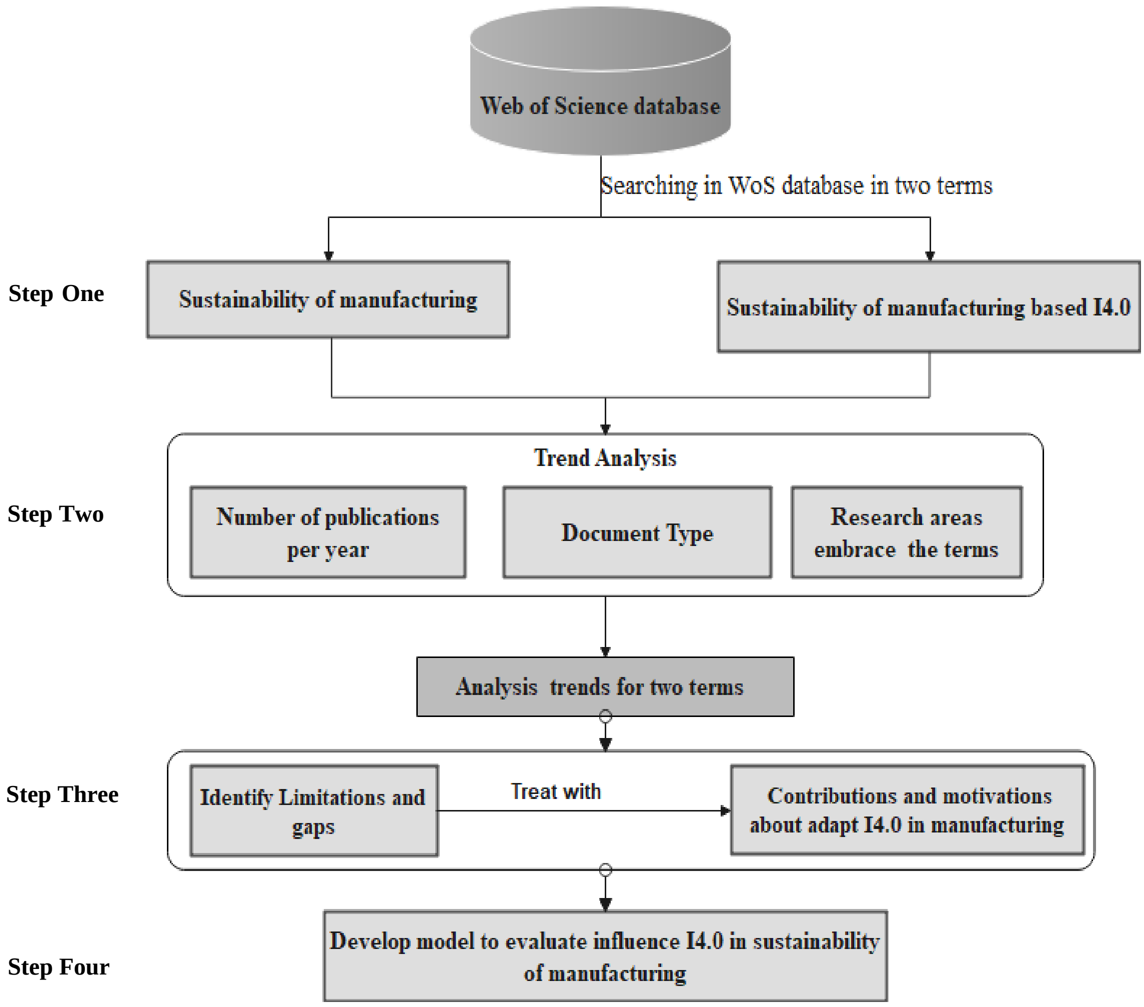

Fig 1. Steps of research methodology.

Table 1. Summary of previous work in sustainability manufacturing and I4.0.

	Sustainability of manufacturing		**Sustainability of manufacturing based I4.0**
No. of Publications		5446	231
Category of publications	Article:	3746	120
	Proceeding papers:	1260	71
	Review:	453	37
	Early Access:	149	11
	Book chapter:	135	0
	Editorial chapter:	35	4
	Books	2	0
Areas and fields	ENGINEERING:	2741	124
	Business Economics:	1562	58
	Computer Science:	301	25
	Telecommunications:	53	5
	Chemistry:	229	4

3. Literature Concepts

3.1 Industry 4.0

In 2011, I4.0 was presented at the Hannover Fair [24]. Later, in 2013, the German government introduced I4.0 [25]. The term "I4.0" is associated with other terms such as smart manufacturing, smart production, or smart factories, due to the use of numerous technologies [26]. For [27], I4.0 includes the connection between physical and digital technologies such as CPS, cloud computing, big data…etc to share information and make intelligent decisions to gain the organization a competitive advantage in the market through fulfilling the needs of clients.

Technologies of I4.0 in [28] are classified into two categories front-end technologies and base technologies as shown in Fig. 2. Other researchers support a different view of base technologies as [29] supposes CPS, IoT, cloud, fog computing, and BDA are yield to base technologies. Reseach in [30] assumes CPS, IoT, ICT, EA, and enterprise integration are base technologies. Moreover, technologies of I4.0 as IoT, CPS, and artificial intelligence (AI) in [33] is a futuristic construct that boosts the development of production systems. That is due, as mentioned in [34] to the capacity of its technologies to enhance the energy, equipment, and use of the human resource. Thus, Organizations are becoming more sustainable and competitive globally.

The goal of I4.0 is to connect intelligent products, manufacturing processes, and machines by developing a network between them [31]. Conforming to that, [32] proposes that organizations are improving their capabilities for data processing through I4.0 which permits each part to interact with each other. Achieving organizational sustainability requires a balance between three pillars of Trible Bottom Line (TBL) economic, environmental, and social perspectives as [35] reported sustainability for industries in Brazil-based three pillars.

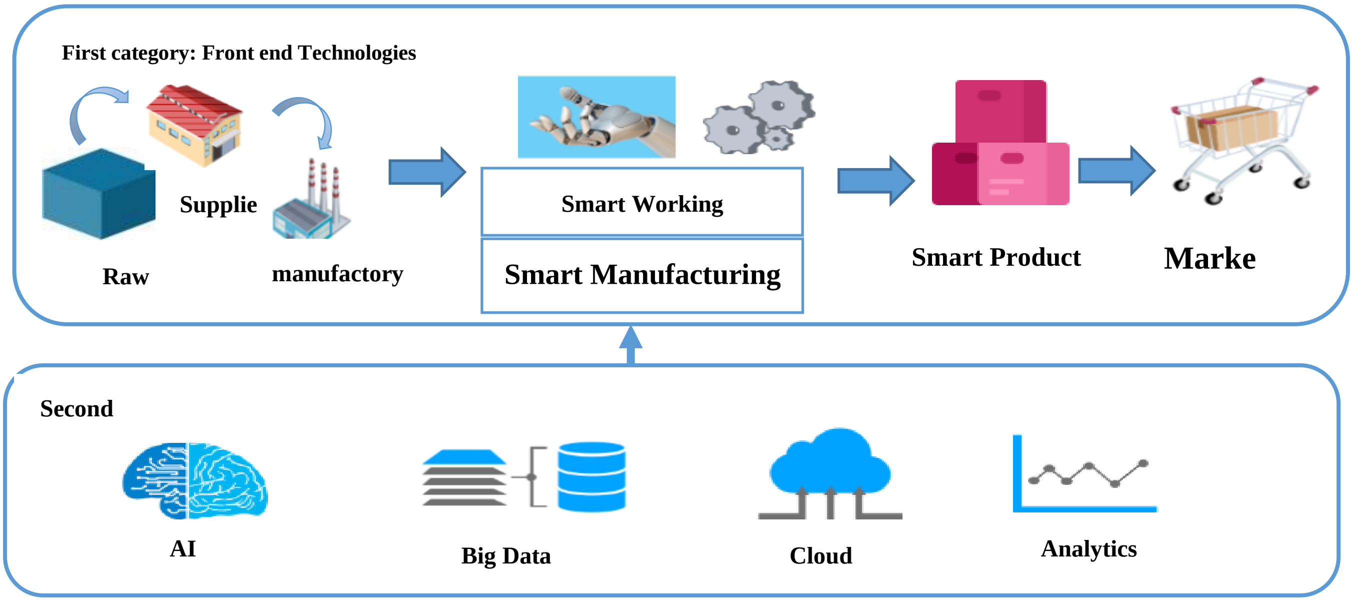

Fig. 2. Classification of I4.0 Technologies adapted from [28]

3.2 Sustainability of Manufacturing Based Industry 4.0

Sustainable Manufacturing is defined in [36] as processes and systems that are merged to use resources such as energy and raw materials wisely for producing a product of high quality, customer satisfaction, and regulatory compliance. Although manufacturing organizations strive to balance three pillars to achieve sustainability, there may be challenges that are threatening their sustainability. The plastics industry in [5] suffers from challenges of three pillars. Addressing such industrial challenges through [37,38] by adopting I4.0 technologies that utilize energy efficiently and effectively and tracking the life cycle of the product from design to delivery. In [39] there are many countries are adopting I4.0 technologies in their manufacturing sector like Australia, China, and Thailand for instance . General Electric Company (GE) is adapted the Predix platform which helps in connectivity, analytics, and machine learning, processing, and analysis big data for adding multiple benefits to its users[40].

CPS [41] is used in many sectors such as automotive, medical, and manufacturing aerospace with a special focus in the United States and the European Research Council. This is due to its ability to acquire and collect data through the sensor and to deal with a large volume of data. This technology is named 5C as for its five levels: Smart Connection, Data-to-Information Conversion, Cyber, Cognition, and Configuration. It consolidates information and machines to enhance the performance of the industry and the decision becomes decentralized [42]. Optimization of production through dynamic models is used in CPS to manage and organize the activities through manufacturing procedures [43]. Its ability to collect and analyze data according to [44] makes it able to increase productivity with higher quality and low cost, promote growth, and increase the efficiency of workers.

IoT supports the manufacturing process and offers advanced methods such as monitoring, managing, and optimizing the operation of manufacturing. International Telecommunication Union (ITU) defined IoT as the ability to connect anytime, anyplace to anyone [45,46]. Also, plays an important role in the observation of energy consumption to save energy thus the energy crisis is reduced [47].

Big Data Analytics are used to obtain information and make an accurate decisions based on analyzing the collected data obtained via IoT technology [9]. The utilization of big data Positively affected the quality of production and monitoring of the damage and work of each machine to facilitate the maintenance of machines and equipment [48].

The manufacturing process can be environmentally friendly by integrating Additive manufacturing to reduce scrap production and facilitates complex designs so, the product becomes flexible and consistent [49]. Applying these new technologies aims to increase efficiency and improve the performance of the entire industrial chain. I4.0technologies have a socially robust impact from the perspective of [44] in transforming operating patterns, design, product services, and production systems to smarter patterns and dispensing with human beings. [50] believes that technologies have a positive impact on the environment through energy consumption is more efficient and safer. Based on [51] I4.0 technologies are adapting to achieve circular economies. The conclusion from the foregoing is that the I4.0 technologies are promoting sustainable development by positively affecting

TBL. Many quantitative and qualitative studies are aimed to analyze and evaluate the impact of the I4.0 on the sustainability of each pillar of TBL's pillars. Robust Best Worst Method (RBWM) is one of the MCDM techniques used to assess the degree of influence of enablers in [10] for I4.0 technologies on the sustainability of manufacturing. Developed frameworks are used Fuzzy Evaluation Method (FEM) for identifying the importance of enablers of I 4.0 as in [52].

Factors affecting sustainability are classified and categorized in [53] into cause and effect. It used DEMATEL as requirements of government (F1), Social responsibility (F2), Green image (F3), and other factors. Grey-based DEMATEL is used in [54] to evaluate the influential strength of drivers for I4.0 to achieve sustainability in Supply Chains (SC). AHP is the most famous technique of MCDM which is used to analyze the drivers in [55] for advanced sustainable manufacturing. A hybrid MCDM techniques-based fuzzy decision-making trial and evaluation laboratory and analytic network process (FDANP with PROMETHEE) in [56] to analyze sustainable risks in the manufacturing of surgical cotton for helping manufacturing organizations avoid unwanted accidents, as well as through early knowledge for sustainable risks.

In this section, the following lierature concepts are introduced; Industry 4.0, sustainability of manufatcuring based I4.0, and related technologies. The proposed framwork is introduced in the following section.

4. Mathematical Model

As mentioned in introduction section, we are identifying I4.0 criteria and suncriteria that achieve sustainability of manufacturing. Assessment process for I4.0's criteria/subcriteria is vital process.

4.1 DMs prespectives based MCDM with neutrosophoic uncertainity method

In this section, we integrated the SVNSs with the MCDM methods to evaluate the criteria I4.0 with sustainability manufacturing. Firstly, the DEMATEL method is applied to show the interrelationships among criteria. The SVNSs are used to scale as [57]. Secondly, the SVNSs AHP is used to compute the weights of the criteria. Fig 3 shows the proposed framework of this paper.

4.2 Determine influencing main/sub criteria Based on N-DEMATEL

Step 1: Select decision-makers and experts who have expertise in this field. The main and sub-criteria of sustainability manufacture based on I4,0 technologies are collected. Then decision-makers offered to evaluate the criteria based on the Single-Valued Neutrosophic Numbers (SVNNs) as in [57].

Step 2: Constructed Pairwise comparison matrices based on relation between criteria by DMs panel.

Step 3: Transformation of pairwise comparison matrices for criteria to deneutrosophic form via Eq. (1).

$$\boldsymbol{s(a_{ij}) = \frac{(2+T-I-F)}{3}} \tag{1}$$

Where $\boldsymbol{T, I, F}$ represent truth, indeterminacy, and falsity, $\mathbf{a_i}$ refers to the value in the comparison matrix and i refers to the number of criteria.

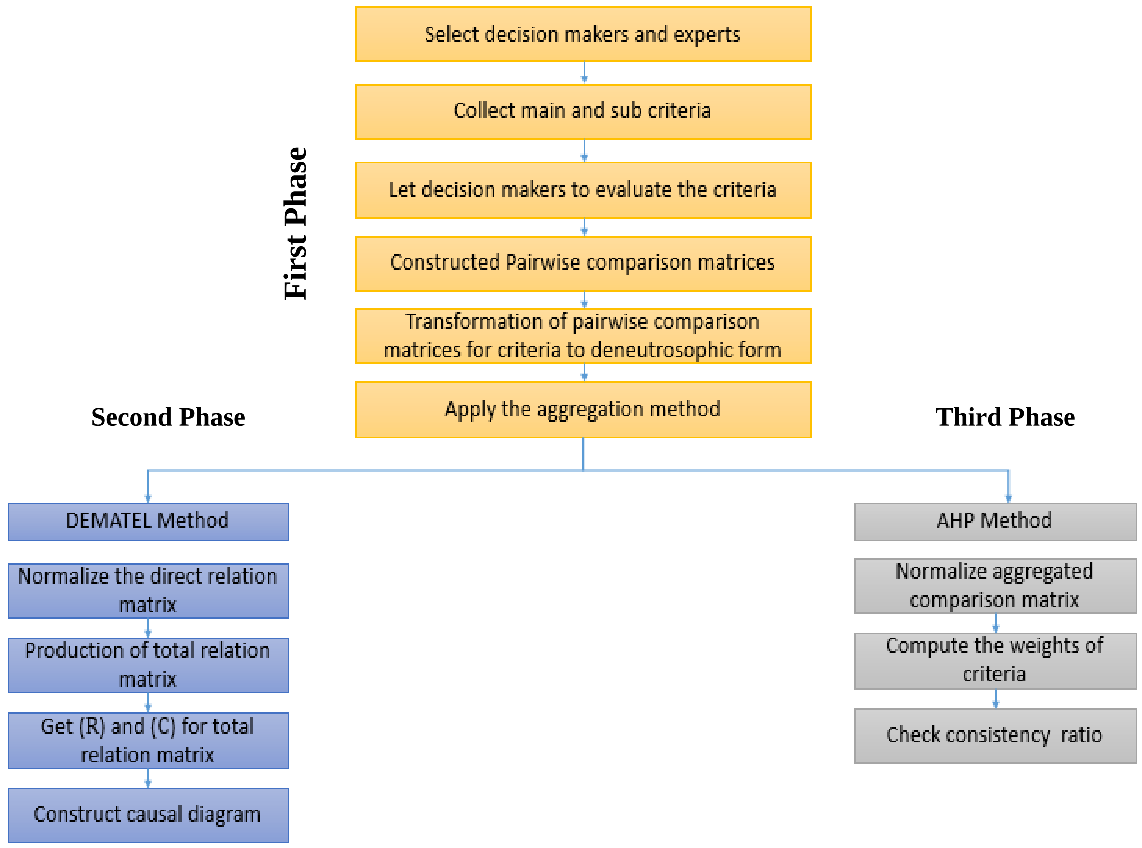

Fig. 3. The proposed Framework

Step 4: Apply the aggregation method to aggregate the opinions of experts into one matrix to obtain the direct relation matrix.

Step 5: Normalize the direct relation matrix as Eqs. (2, 3)

$$S = K * Y \tag{2}$$

where $\boldsymbol{Y}$ refers to the direct relation matrix as in the previous step.

$$K = \frac{1}{max_{1\leq i\leq n}(\sum_{j=1}^{n} a_{ij})} \quad (i, j = 1,2, \dots, n) \tag{3}$$

Where a_{ij} represent the sum of each raw (i) in matrix Y, $\max_{1\leq i\leq n}(\sum_{j=1}^{n} x_{ij})$ represent the maximum value of a_{ij} and n refers to the number of criteria. a_{ij} refers to the value in the direct relation matrix.

Step 6: Production of total relation matrix

We use the MATLAB software to obtain the total relation matrix as Eq. (4)

$$T = S(I - S)^{-1} \tag{4}$$

Where I refers to the identity matrix.

Step 7: Get (R) and (C) for total relation matrix T.

The Sum of rows (R) and columns (C) are obtained as in Eqs. (5,6).

$$T = [a_{ij}]_{n\times n}, i, j = 1,2,3, \dots n$$

$$R = \left[\sum_{i=1}^{n} a_{ij}\right]_{1\times n} = [a_j]_{n\times 1} \quad (5)$$

$$C = \left[\sum_{=1}^{n} a_{ij}\right]_{1\times n} = [a_j]_{n\times 1} \quad (6)$$

Step 8: Construct a causal and effect diagram by the horizontal axis R+C and vertical axis R-C.the values of R-C determine cause and effect criteria/subcriteria. criteria/sub criteria are cause when its values of R-C are positive.

4.3 Neutrosophic AHP Method

Step 1: Repeat steps from 1 to 4 mentioned in section 4.1 to obtain the aggregated pairwise comparison matrix.

Step 2: Normalize aggregated/Average comparison matrix as Eq. (7).

$$Norm_{ij} = \frac{a_j}{\sum_{j=1}^{n}(a_j)}, j = 1,2, \dots \dots . n \quad (7)$$

Where $\sum_{j=1}^{n}(a_j)$ the sum of criteria per column in the aggregate matrix, a_j point to the preference of criterion in aggregated comparison matrix.

Step 3: Compute the weights of criteria by the row average of the previous step.

Step4: Check the consistency ratio (CR) as [58].

$$CR = \frac{CI}{RI} \quad (8)$$

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

Where n point to number of criteria/sub criteria in this study, RI is consistency ratio where its value determines based on number of criteria/sub criteria are used in the model.

5. **Case Study and Results**

We apply our methodology in a manufacturing enterprise in Egypt. This enterprise is responsible for producing household electrical appliances such as irons, food blenders, ceiling fans, vacuum cleaners, etc. The criteria of sustainable manufacutring based on I4.0 are introduced to the enterprise to increase the performance and achieve sustainability..

5.1 Results of Neutrosophic DEMATEL

Step 1: Table 2. represents demographic information about the experts who evaluated the criteria in this study. We collected five main criteria and fourteen sub-criteria as in Table 3.
Step 2: Four comparison matrices are obtained.
Step 3: Transform these matrices into crisp values-based Eq. (1).
Step 4: Obtain the direct relation matrix by the aggregation method.
Step 5: Obtain the normalized relation matrix based on Eq. (2,3) as Table 4.

Step 6: Obtain the total relation matrix as in Table 5.
Step 7: Obtain the values of R-C and R+C
Step 8: Obtain the causal diagram for the main and sub-criteria. Fig 4. shows the causal diagram. From Fig 4. C_5 is the best criteria and C_1 is the worst criteria.

Table 2. Demographic information about the expert panel

Demographic Information	Gender	Age	Qualifications	Job Title
First member	Male	40	Ph.D.	Executive Manager
Second member	female	35	Bachelor	Financial Consultant
Third member	Male	45	Master	Maintenance Engineer
Fourth member	Male	40	Bachelor	Quality and Safety Manager

Table 3. The main and sub-criteria

Main Criteria	Sub-Criteria
DBA(C1)	Exploration of new customers and opportunities (C_{1-1}). Technologies Upgradation for analyzing(C_{1-2})
Additive Manufacturing(C2)	Green design and environmentally friendly process (C_{2-1}). Ease testing and prototyping (C_{2-2}) Health and safety (C_{2-3}) Reduction cost of operations (C_{2-4})
IoT(C3)	Real time control (C_{3-1}) Efficiency monitoring and traceability(C_{3-2})
Flexible Manufacturing (C4)	Reduction lead time (C_{4-1}) Increase productivity and quality(C_{4-2}) Energy efficient consumption (C_{4-3}) Enhance ethical and sustainable process (C_{4-4})
CPS(C5)	Interactions between human and machine are friendly (C_{5-1}) Automation DM instead human (C_{5-2})

Table 4. Normalized relation matrix

Criteria	C_1	C_2	C_3	C_4	C_5
C_1	0.051368	0.067292	0.067806	0.073456	0.067806
C_2	0.238221	0.051368	0.076538	0.049313	0.0488
C_3	0.170256	0.225449	0.051368	0.084244	0.043663
C_4	0.147062	0.462174	0.125288	0.051368	0.078593
C_5	0.190045	0.305762	0.31727	0.135555	0.051368

Table 5. Total relation matrix

Criteria	C_1	C_2	C_3	C_4	C_5
C_1	0.18232	0.223463	0.15843	0.13358	0.114364
C_2	0.378852	0.218592	0.177966	0.123952	0.108227
C_3	0.368491	0.427165	0.176694	0.171914	0.116716
C_4	0.461954	0.741624	0.310335	0.182239	0.183401
C_5	0.548225	0.686383	0.526992	0.293146	0.177187

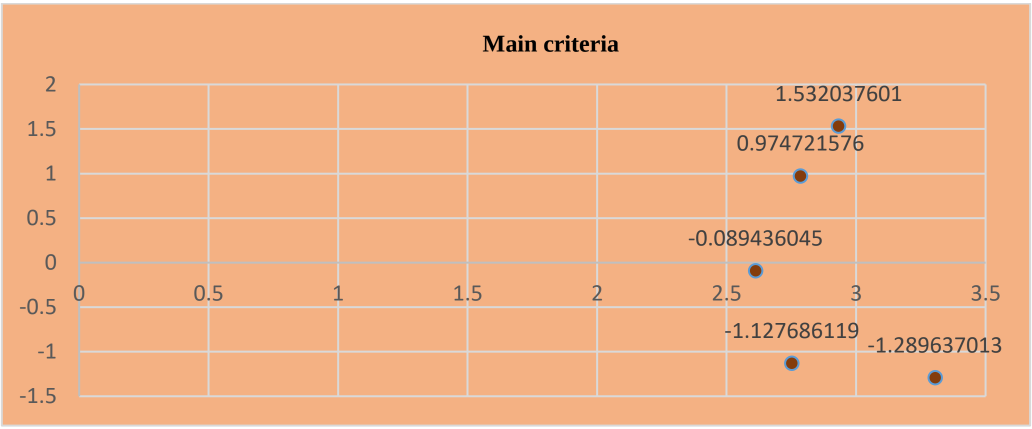

Fig. 4. Causal and effect for main criteria

For sub-criteria, we applied the Neutrosophic DEMATEL method in five sub-criteria. From Fig 5,6,7,8 and 9, we found that C_{1-1} has the highest impact and C_{1-2} has the lowest impact. C_{2-4} has the highest impact and C_{2-1} has the lowest impact. C_{3-2} has the highest impact and C_{3-1} has the lowest impact. C_{4-4} has the highest impact and C_{4-1} has the lowest impact. C_{52} has the highest impact and C_{5-1} has the lowest impact.

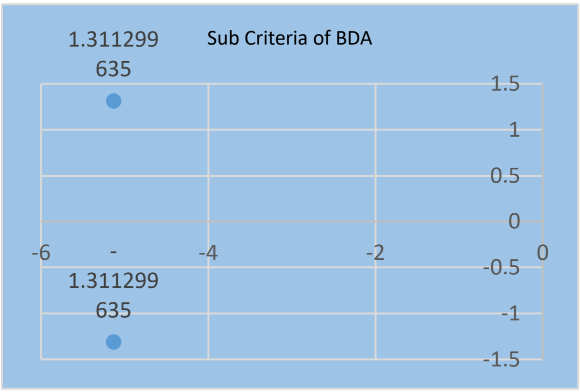

Fig. 5. Causal and effect for BDA sub- criteria

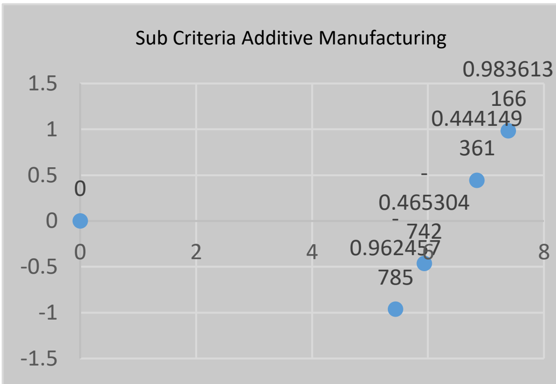

Fig. 6. Causal and effect for Additive Manufacturing sub- criteria

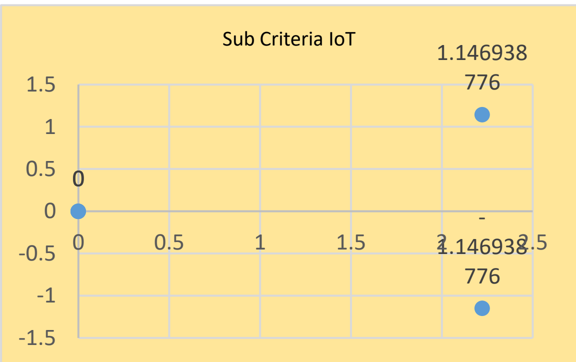

Fig. 7. Causal and effect for IoT sub- criteria

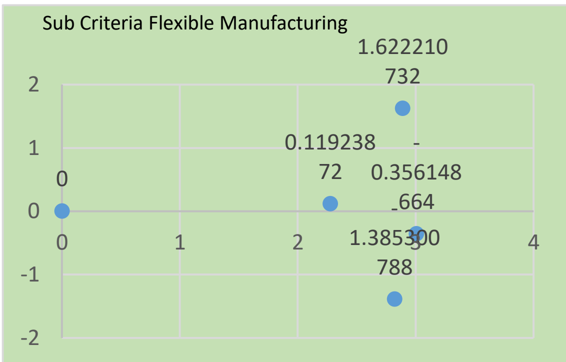

Fig. 8. Causal and effect for Flexible Manufacturing sub- criteria

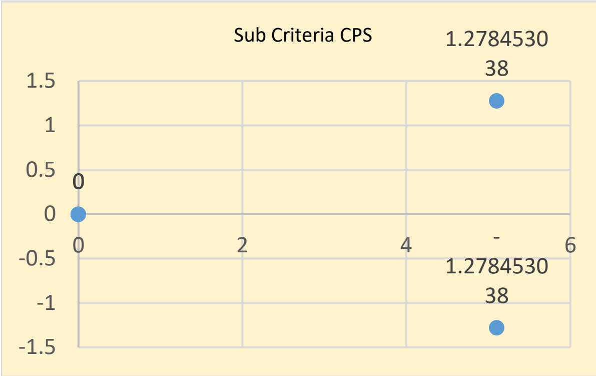

Fig. 9. Causal and effect for CPS sub- criteria

5.2 Results of Neutrosophic AHP Method

Start with the aggregated comparison matrix, then normalized it using Eq. (7) in Table 6. After that, from Table 6. we compute the weights of criteria by the row average in the normalized comparison matrix. The weights of the main criteria are obtained as $W_1 = 0.13026, W_2 = 0.151669, W_3 = 0.172228, W_4 = 0.239525, W_5 = 0.306318$. This means that C_5 has the highest weight and C_2 has the lowest weight. Then we compute the weights of sub-criteria and compute the global weights by multiplying the weights of main criteria by the weights of local criteria. Fig 10. shows the weights of global criteria. From Fig. 10. we deduce that $C_{5\text{-}2}$ has the highest weight and $C_{2\text{-}1}$ has the lowest weight.

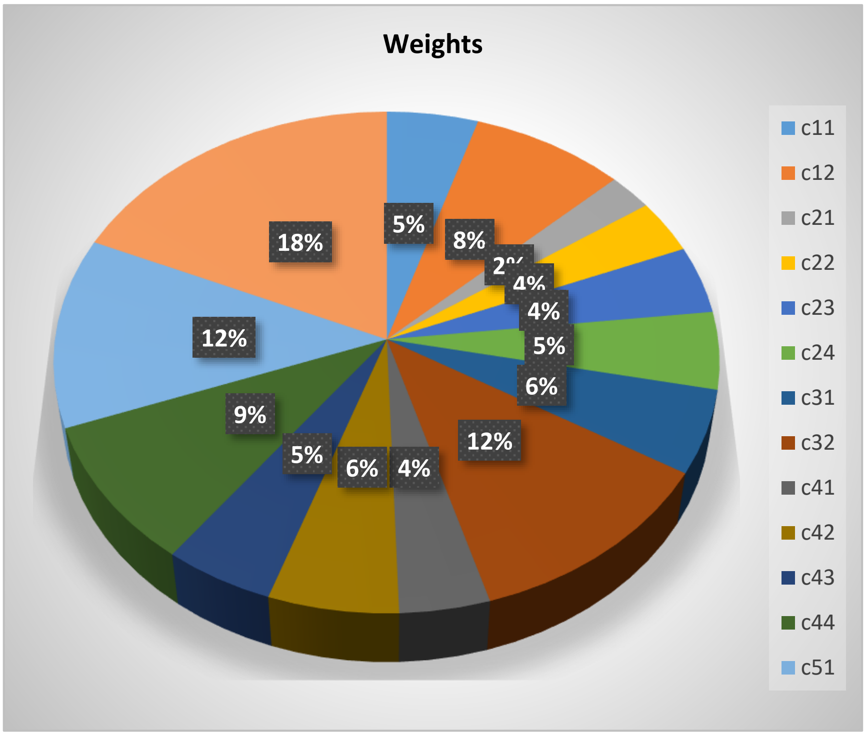

Fig 10. The global weights

Table 6. Normalized aggregated comparison matrix by the AHP method

Criteria	C_1	C_2	C_3	C_4	C_5
C_1	0.064456	0.060512	0.106234	0.186468	0.233628
C_2	0.298915	0.046192	0.119915	0.125181	0.168142
C_3	0.213634	0.202734	0.08048	0.213851	0.150442
C_4	0.18453	0.415607	0.196293	0.130397	0.270796
C_5	0.238465	0.274955	0.497077	0.344103	0.176991

6. Conclusions

Merging I4.0 in the industrial sector contributes to making flexible and efficient processes to produce better quality products with low cost to achieve competitive advantage. I4.0 has a significant impact on digitalizing manufacturing-based technologies as seen earlier.

This study contributes to the understanding of how manufacturing achieves sustainability according to TBL through I4.0 technologies. So, manufacturing firms are encouraged to fully integrate new technologies which have a positive impact on TBL pillars into their practices.

Wherefore, we developed a hybrid framework based on MCDM techniques to analyze and evaluate the factors and criteria based on sustainability manufacture related to I4.0. Four decision-makers and experts are selected to evaluate these criteria. Five main and fourteen sub-criteria are collected. The framework has been applied to a real case study in a manufacturing firm in the electrical industry. SVNSs are integrated with the DEMATEL and AHP methods in this work. The DEMATEL method is used to show the relation between the main and sub-criteria while the AHP method is used to compute the weights of the criteria.

Many methods like TOPSIS, VIKOR, and Entropy, can be applied to this problem in future directions. Moreover, the proposed framework can eventually be applied to many MCDM problems with more criteria.

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