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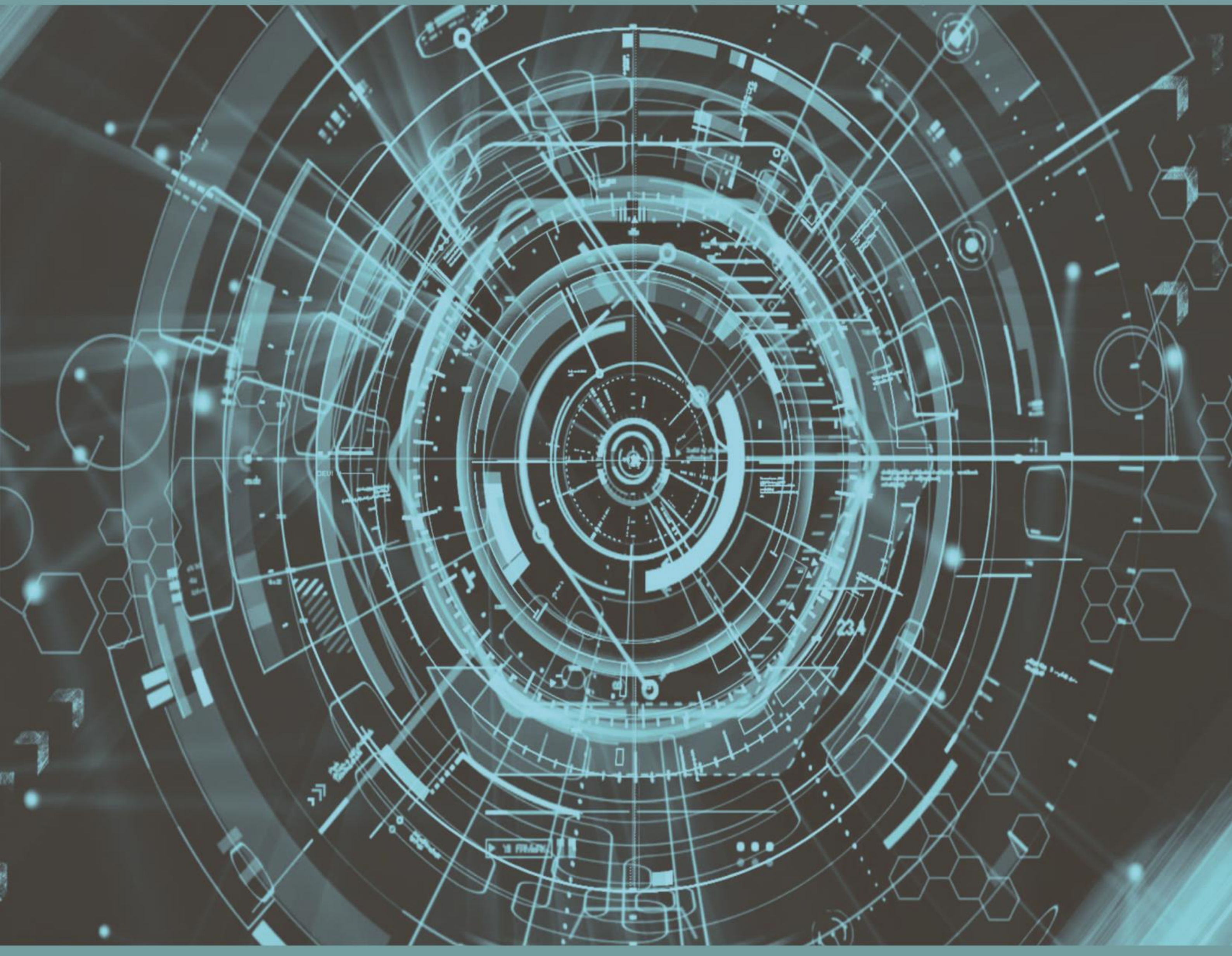

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Paper Type: Research Paper

Performance Prediction of Green Supply Chain Using Bayesian Belief Network: Case Study of a Textile Industry

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Abstract

In managing a supply chain, the green approach has become pivotal for the sake of environmental, economic, and social sustainability. In this paper, we consider the environmental performance prediction in managing sourcing of a textile industry supply chain. Specifically, this research focuses on the dying sector of an emerging economy. We identify eleven green supply chain performance indicators and four performance measures and perform both qualitative and quantitative analyses. The performance is predicted using a probabilistic model based on a Bayesian Belief Network (BBN). The robustness of the findings is validated through a sensitivity analysis. The outcomes suggest that 'Total Suspended Solids' (TSS) and 'Volatile Organic Compounds' (VOC) are the most important indicators for the case company in this study with the highest entropy reduction. Also, 'air emission' was found to be the most impactful performance measure for entropy reduction. This research work will help improve the decision-making capability of the managers and practitioners considering the total environmental performance of the green supply chain. The improved decision-making will also improve overall organizational performance of a green supply chain.

Keywords: Green supply chain, Sustainability, Bayesian, Performance prediction, Textile industry.

1 | Introduction

Bangladesh is one of the largest export trading countries for Readymade Garments (RMG) and apparel in the world. For many years, textile industry has long been the lifeblood of the Bangladesh's economy [15]. Bangladesh's RMG export has significantly over the last few years (*Fig. 1*) and contributed heavily on the nation's GDP. However, textile manufacturing processes have long been chastised for contributing to detrimental environmental activities such as excessive non-renewable resource waste and global warming and other severe poisonous chemicals, as well as global warming materials. These procedures and the usage of numerous chemicals not only generate environmental concerns, but they also cause greenhouse gas emissions, water and resource depletion, acidification, and a variety of health issues.

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The UN's 12th sustainable development goal strives for "responsible consumption and production" with objectives including effective use of natural resources, ecologically sound chemical and waste management, improved technological integration, and knowledge distribution about these practices. The manufacture of textiles, which is resource-intensive owing to the procedures of washing, dyeing, and finishing, is the largest problem for the RMG industry [20].

The Green Supply Chain Management Process (GSCMP), which addresses environmental safety at every stage of the process, is seen to be an effective way to reduce the negative environmental consequences of textile manufacturing [2]. Furthermore, implementing GSCMP can assist textile firms in saving a significant amount of operating energy, lowering costs, increasing efficiency, and reducing the quantity of hazardous waste generated [19], [25]. Again, adopting GSCMP is a requirement for asserting greater commercial prospects and gaining a strong market position by generating a sense of excellent brand image among customers [31]. Because of growing competitive, regulatory, and societal demands, companies are now attempting to include environmental performance into the evaluation of total supply chain performance [12], [33].

Companies must create and implement plans to reduce the environmental effects of their products and services in a supply chain [36], [41]. The fundamental ideas on which a company's business is founded can be examined and revised for the firm to present a green image. Furthermore, addressing environmental concerns is critical for a firm to establish a distinctive competitive advantage and increase the value of its main business activities [28], [30], [32]. According to Alzubi and Akkerman [7], poor environmental awareness reduces stakeholders' concerns to improve their sustainable SCM. Market expectations, risk management, regulatory compliance, and company efficiency are some of the components that establish a competitive advantage via environmental performance, according to the Confederation of British Industries in 1994. Researchers and practitioners utilize Green Supply Chain Management (GSCM) as an effective method to handle all these components correctly [21]. As a result, GSCM allows a firm to grow profit and market share while simultaneously increasing its ecological efficiency [27]. GSCM aims at achieving three sustainability pillars – economic, environmental, and social [4], [22].

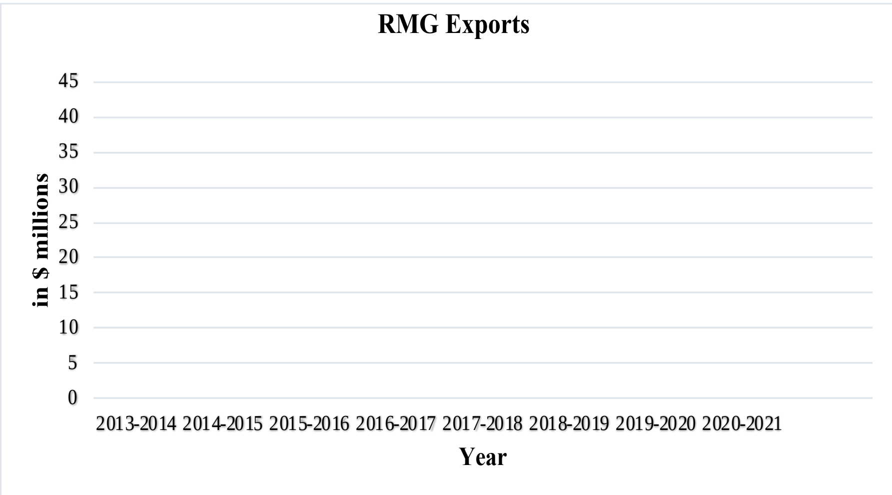

Fig. 1. Bangladesh's RMG exports (2013-2021) [9].

Bangladesh's typical textile factory utilizes 300 liters of water per day, putting substantial strain on the country's freshwater supplies considering the scale of the industry (DATABD.CO). *Fig. 2* depicts how environmental effects are divided across the various phases of the manufacturing process on average, with the raw material extraction and input production processes being the most concentrated. Because of growing public awareness and government restrictions, the textile sector is under pressure to develop environmentally friendly supply chain procedures. Manufacturers usually incorporate those components in such environmentally friendly procedures that have the least detrimental influence on human health and the environment throughout the manufacturing, use, conservation, and disposal of textile goods.

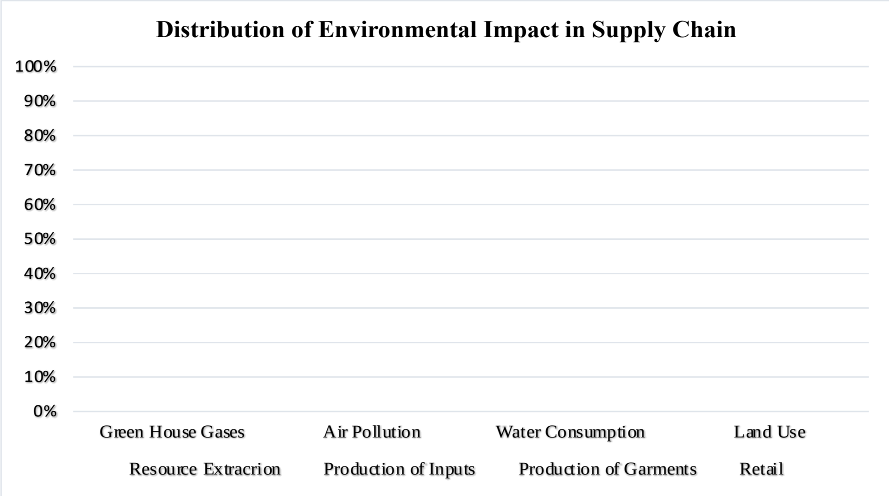

Fig. 2. Distribution of environmental impact in RMG supply chain [34].

As some of the cases raw materials are affected on the environment so it is important that to identify which raw materials affect rapidly our environment and which are also green raw materials for textile industry [3], [16]. GSCMP is critical for recognizing certain types of raw materials. Because of recent advancements in the field of GSCM, its performance prediction is gaining attraction [6], [11]. Although various metrics for measuring supply chain performance have been proposed, they do not cover all components of the green supply chain. As a result, more comprehensive environmental performance indicators are required. The goal of this research is to discover these performance indicators and utilize them to forecast the success of green supply chains in various circumstances. There have been several studies on traditional supply chain performance assessment, but only a handful have focused on the supply chain's environmental performance. As a result, none of the available research focuses on creating and applying probabilistic and quantitative approaches to forecast the performance of green supply chains.

This research aims to answer the aforementioned research issues by establishing GSCM performance metrics through a review of the current literature and expert opinion, as well as constructing a quantitative and probabilistic model utilizing a Bayesian Belief Network (BBN). A real-world case study of a textile industry is used to show the model's efficacy, as well as sensitivity and diagnostic studies to assess the influence of various indicators on overall performance. By BBN model identifying the indicators were identified which materials are green and non-green. Those raw materials which are non-green but is needed for textile industry we suggested to use alternative raw material/ by recycling those raw materials.

2 | Literature Review

GSCM is defined as "the process of transforming environmentally friendly inputs into outputs that can be reclaimed and re-used at the end". Consumers will ask more questions about the products they buy as they become more aware of environmental issues and global warming. Companies must prepare to answer questions about how environmentally friendly their manufacturing processes are [14]. GSCM integrates environmental thinking into supply-chain management which includes product design, material sourcing and selection, manufacturing, processes, final product delivery to consumers, and product end-of-life management after its useful life [40].

Sustainable development has made significant progress toward establishing environmental and social sustainability. Sustainability is comprised of three components: economic, environmental, and social. GSCM is concerned with making the entire supply chain more efficient and environmentally friendly. GSCM can be used for a variety of purposes, such as being required by law and regulations, differentiating oneself in a competitive industry by being environmentally friendly, and finally, implementing GSCM to remain competitive if your competitors have already adopted GSCM. Organizations with greener supply chain management practices will have a competitive advantage over companies that are hesitant to embrace

GSCM as customer awareness and regulatory norms rise [39]. As a result, there is a shift in the industry's focus on GSCM creating value for customers and shareholders [14], [38].

Most respondents proved that their textile organizations had embraced a redesigned supply chain system to decrease carbon footprint, streamline transportation operations to decrease carbon footprint, eliminate, reduce, and alternately repurpose manufacturing waste, and increase utilization of renewable vitality sources as well as eliminate/lessen hazardous/toxic materials. Employee's values were the highest influencing element influencing company choice for usage for GSCM taken after promises by the top administration [2]. It is important for RMG sector to apply green activities in their supply chain system to effectively use resource and save the nature from uncertain pollution which leads to sustainable business and eco-friendly world. Factors in material, manufacturing, recovery procedure [18].

In these papers listed in *Table 1*, authors depict the supply chain management in textile industry, gave recommendation showing the ways to reduce the waste, importance of implementing GSCM, performance measures if this was implemented in various industries. In our paper, we adopt the research framework developed by Rabbi et al. [35] who performed GSCM performance prediction analysis for a manufacturing industry. We conduct this study for a textile industry.

Table 1. Summary of the literatures studied.

Source	Approacg Used	Reaserch Contribution
Rabbi et al. [35]	BBN	Analyzed various green supply chain performance measures and indicators.
Ahmed et al. [2]	Information was sourced from 200 respondents.	The majority of respondents proved that their textile organizations had embraced a redesigned supply chain system.
Gomes and Daud [18]	Information and data has collected through several interview.	Proper use of the raw materials in their roductionprocess to minimize the waste of resources due to limited of natural resource.
Ali and Habib [5]	The analisis of this research is based on secondary data.	Developed a customized supply chain model for the textile sector in Bangladesh.
Farhan Shahriar et al. [15]	Secondary data were collected from various publications.	Bangladesh garment industry improvement is desired in reducing the supply time required to produce and fulfill the orders placed by foreign companies.
Akter and Uddin [3]	Primary and secondary data	Different areasof apparel industry and provided recommendation for these areas.
Dey and Islam [13]	A standard method for sampling	The samples were analyzed for various physicochemical parameters. They have given a solution to use ETP.
Mia et al. [29]	Based on secondary data	Showed ways of preventing pollution in different factories of Bangladesh.
Hossain and Roy [23]	The study is mainly based on secondary data and merely on primary data.	Importance of supply chain in the growth of MRG Industry, problems toward sustainable RMG growth and provide recommendation.

3 | Research Methodology

The goal of this research is to find out the performance measures and indicators that are harmful for our environment. This research is focused on Bangladesh textile industry's dyeing sector. The four-step research framework used in our paper is shown in *Fig. 3*.

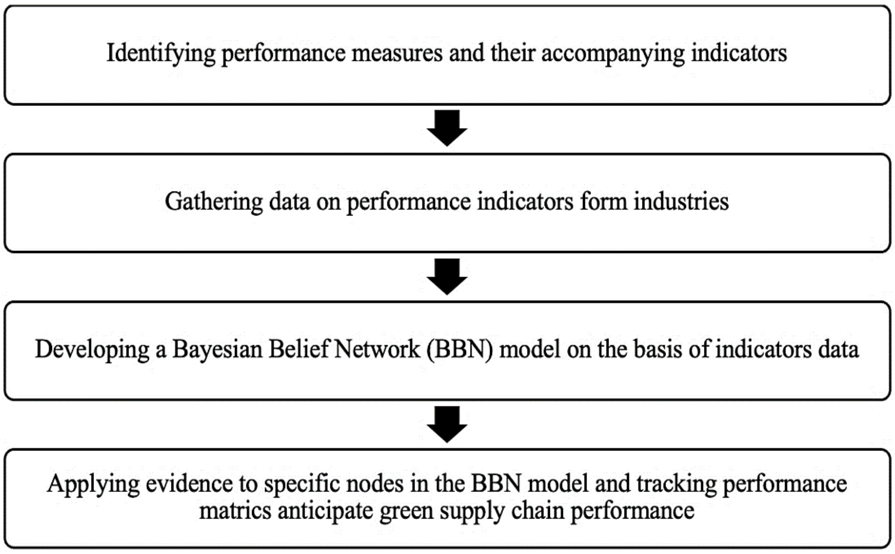

Fig. 3. Research framework of this study [35].

Step 1. Identifying performance measures and their accompanying indicators: in this step, we identified some indicators with their corresponding measures that were relatable with green supply chain performance. All the indicators were identified by reviewing some literature review and papers. For green performance indicators, researchers looked at papers on green purchasing, green consumption, green marketing, green manufacturing, green 3R (reduce, reuse, recycle), and supply chain performance evaluation.

Step 2. Gathering data on performance indicators form industries: in this step, we gathered data about selected indicators from industries. Among these data which were more acceptable we selected them for next step.

Step 3. Developing a BBN model based on indicators data: in this step, we developed a BBN model regarding the selected data. Here we used two hypothesis states (satisfactory state and unsatisfactory state) for calculating performance level.

Step 4. Applying evidence to specific nodes in the BBN model and tracking performance metrics anticipate green supply chain performance: in this step, we applied some analysis to validate the BBN model so that we could be sure that our outcome is right, and, in this way, we can find which performance measures (*Fig. 4*) and indicators affect mostly our environment.

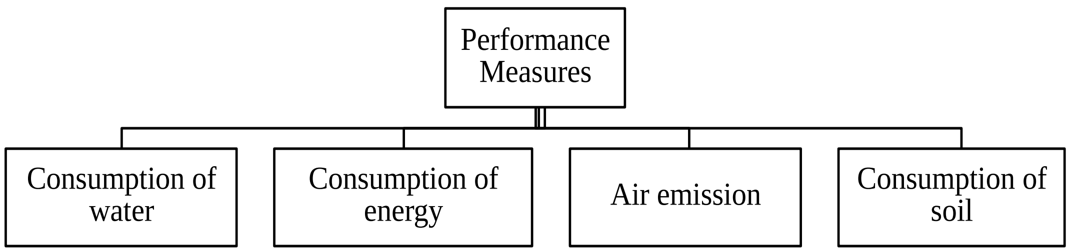

Fig. 4. Selected performance measures.

3.1 | Identifying Performance Measures and Their Corresponding Indicators

For identifying performance measures and their corresponding indicators we viewed some research papers in which the selected indicators used. Our environment is affected mostly by water pollution, air pollution, consumption of soil and energy. In our work, we took four types of performance measures as they affected our environment mostly. Under the four performance measures identified 11 indicators by reviewing papers. *Table 2* shows four performance measures with their corresponding indicators.

Table 2. Green supply chain performance measures and indicators.

Performance Indicators Measures	Indicators	References
Consumption of water	Biological Oxygen Demand (BOD)	[24], [29], [37]
	Chemical Oxygen Demand (COD)	[24], [29], [37]
	Total Suspended Solids (TSS)	[24], [37]
Consumption of energy	Total Dissolved Solids (TDS)	[24], [37]
	Potential of Hydrogen (PH)	[24], [37]
	Adsorbable Organic Halides (AOX)	[24], [37]
	Greenhouse gas emission	[24]
Air emission	Emission of CO_2	[24], [37]
	Smog	[24], [37]
	Volatile Organic Compounds (VOC)	[24], [37]
	Rate of toxic material	[24]
Consumption of soil		

3.1.1 | Consumption of water

For industrial operations, the dyeing and printing industries consume a lot of water. In terms of both volume and effluent composition, wastewater from the dyeing and printing industries has been identified as the most polluted water. Because of the ease with which raw materials and completed products can be transported, these are generally located along riverbanks. As a result, industrial effluent flows directly into the river, with no filtering or treatment of polluted water [29]. That's why we selected consumption of water as performance measures. BOD, COD, TDS, TSS, PH, AOX all of these are indicators which indicate the quality of water.

Biological Oxygen Demand (BOD): the BOD is a measure of the amount of oxygen required to break down organic materials in water. A higher BOD means that more oxygen is required, implying that the water quality is poor. Low BOD indicates that less oxygen is taken from water, implying that the water is usually purer.

Chemical Oxygen Demand (COD): the amount of dissolved oxygen that must be present in water to oxidize chemical organic compounds is known as COD. The presence of decaying plant debris, human waste, or industrial effluent is common in water with a high COD.

Total Suspended Solids (TSS): TSS are a water quality metric defined as the number of particles suspended in a known volume of water that can be trapped in a filter.

Total Dissolved Solids (TDS): TDS stands for total dissolved solids, which refers to the inorganic salts and small amounts of organic matter that are present in solution in water.

Potential of Hydrogen (PH): the PH of water is a measurement of how acidic or basic it is. The range is 0 to 14, with 7 being the neutral value. Acidity is indicated by a PH less than 7, while a PH greater than 7 indicates a base. PH is a measurement of the proportion of free hydrogen and hydroxyl ions in water.

Adsorbable Organic Halides (AOX): the organic halogen load at a sampling site, such as soil from a landfill, water, or sewage waste, is measured using AOX. The technique detects comparable halogens such as chlorine, bromine, and iodine, but does not detect fluorine in the sample.

All these indicators are the measurement indicators of water that is why this research selected these types of indicators for water consumption.

3.1.2 | Consumption of energy

The textile sector is a big energy consumer with a low energy usage efficiency. Improved energy efficiency should be a top priority for textile plants, especially in times of high energy price volatility. Every textile plant has a variety of energy-efficiency opportunities, many of which are cost-effective but aren't implemented due to a lack of information or a high initial cost [37].

Greenhouse Gas Emission: we selected greenhouse gas emission as an indicator of consumption of energy. Every year, the textile sector emits 1.22 to 2.93 billion metric tons of Carbon Dioxide (CO_2) into the atmosphere. As a result, the life cycle of textiles (including laundry) is estimated to account for 6.7 percent of all worldwide greenhouse gas emissions [10].

3.1.3 | Air emission

The textile industry's air pollution is also a key source of concern. Pollutants are emitted into the air by boilers, thermo packs, and diesel generators. Suspended Particulate Matter (SPM), sulphur dioxide gas, oxide of nitrogen gas, and other pollutants are produced. The emission of hazardous gas into the atmosphere has a negative impact on the human population in the surrounding areas. Reducing the toxins released by the textile sector has become vital.

Emission of CO_2: CO_2 emissions from burned fossil fuels are a major component to the greenhouse effect [37]. CO_2 is a colorless, non-poisonous gas that is produced by the burning of carbon and by the breathing of living beings. The release of greenhouse gases and/or their precursors into the atmosphere over a defined area and time is referred to as emissions.

Smog: Smog is a type of air pollution that was named from the combination of smoke and fog in the atmosphere. Smog is created by a mixture of smoke and sulfur dioxide and occurs when significant amounts of coal are burned in a certain area. Smog is a problem in many places and continues to be harmful to people's health. Seniors, children, and persons with heart and lung problems like emphysema, bronchitis, and asthma are especially vulnerable to ground-level ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide.

Volatile Organic Compounds (VOC): certain solids or liquids emit VOCs as gases. VOCs are a group of compounds that can have both short- and long-term health consequences. Many VOC concentrations are continuously greater (up to ten times higher) indoors than outdoors. Industrial solvents, such as trichloroethylene; fuel oxygenates, such as Methyl Tert-Butyl Ether (MTBE); or chlorination by-products, such as chloroform, are examples of VOCs. Petroleum fuels, hydraulic fluids, paint thinners, and dry-cleaning chemicals all contain VOCs. VOCs are typical pollutants found in groundwater. In textile industry there are used some materials which mainly polluted our air. By using these types of materials there are produced smog, CO_2. By this, our environment is polluted. By measuring smog quantity, CO_2 emission, VOC we can easily identify the air quality.

3.1.4 | Consumption of soil

There are many raw materials that cause soil pollution for textile industry.

Rate of Toxic Material: heavy metals are persistent by nature, and certain of them (such as cadmium, lead, and mercury) can bioaccumulate and/or be poisonous. Although they are found naturally in rocks, their usage by industry can release large amounts of them into the environment, causing ecosystem damage. Heavy metal complexes do not decompose into innocuous elements, although they can recombine to generate new ones [37]. Some types of material are involved in soil pollution. For this we consider the emission rate of toxic material which are mainly involved in this pollution.

3.2 | Data Collection

To develop a BBN model it is necessary to collect data from an industry. Based on the data, we can easily select that which indicator and performance measures mostly affect the environment. We collected six months data from the industry. We selected two states, one is satisfactory state and another one is unsatisfactory state for these data. All the indicators have standard value. When the data meet with the standard range then it will be satisfactory state. If not, then it will be in unsatisfactory state. Data table for the 11 indicators is given in *Table 3*.

Table 3. Data table for the 11 indicators.

Indicator (unit)	1st Month	2nd Month	3rd Month	4th Month	5th Month	6th Month	Recommended Limit
BOD (mg/L)	330	350	200	30	50	100	≤50
COD (mg/L)	100	150	200	700	750	800	≤200
TDS (mg/L)	1000	1500	3000	2700	2000	1300	≤2100
TSS	100	200	310	270	200	230	≤150
PH	7.5	9	10	11	8	9	6-9
AOX (mg/L)	0.87	1	7	5	9	6	≤5
Emission if CO_2 (tons)	512	100	200	2500	3000	2500	≤400
Smong (ppm)	1.9	2	7	5	9	6	≤2.5
VOC (kg)	0.5	400	310	450	500	320	≤0.750kg
GHG emission (tons)	0.87	1	7.5	5.7	9	6	≤4.6
Rate of toxic material (ppm)	200	60	70	200	250	180	≤100

Sample calculation for BOD: from the table data we can see that 4th and 5th month's data meet the satisfactory level. So, these two data will be in satisfactory state. The other data will be in unsatisfactory state:

I. Satisfactory state = 2/6*100% = 33.33%,
II. Unsatisfactory state = 4/6*100% = 66.67%,

We perform the same calculation for the other indicators and summarize the findings in *Table 4*.

Table 4. Anterior probabilities for green supply chain performance indicators.

Performance Indicators	State Probability (%)	
	Satisfactory (s)	Unsatisfactory (u)
BOD	33.33	66.67
COD	50	50
TDS	66.67	33.33
TSSs	16.67	83.33
PH	66.67	33.33
AOX	33.33	66.67
Emission of CO_2	33.33	66.67
Smong	33.33	66.67
VOCs	16.67	83.33
Greenhouse gas emission	33.33	66.67
Rate of toxic material	33.33	66.67

3.3 | Bayesian Belief Network

A Bayesian Belief Network (BBN), or essentially "Bayesian Network," gives a straightforward method of applying Bayes Hypothesis to complex issues. Bayesian probability is the investigation of abstract probabilities or faith in a result, contrasted with the frequentist approach where probabilities depend simply on the previous event of the occasion.

A Bayesian Network is made of hubs and circular segments. Every hub addresses the arbitrary factors, and a variable can be discrete or persistent. Coordinated bolts or curves compare to the causal

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connection between the factors. These coordinated connections associate the pair of hubs in the graphical model.

In these connections, one hub straightforwardly influences the other hub, and in case there is no immediate connection, the factors are free of one another. A Bayesian Network has two parts: B = (G, θ). G is a directed acyclic graph with nodes and arcs in the first portion. The nodes represent the data set's variables $X_1,\ldots, X_n$, whereas the arcs represent direct dependencies between the variables. The independence relationships in the domain under research are then encoded in the graph G [8]. The conditional dependency distribution of is the second component of BBN, where $\theta_{(x_i|x_i)} = P_B(x_i \parallel x_i)$ is the set of direct parent variables of x_i in G [1]. The network B can be represented by using the joint probability distribution:

$$P_B\ X_1, X_2, \ldots \ldots \ldots X_N) = \prod_{i-1}^{n} P_B\ X_i|\pi X_i) = \prod_{i=1}^{n} X_i|\pi X_i).$$

Random variables are represented by nodes in a BBN, and probabilistic interdependence between the corresponding random variables are represented by edges connecting the nodes. Given the observation of complementary subset variables, a BBN is a probabilistic model that can compute the posterior probability distribution of any unobserved stochastic variable [17]. "Backward" probability propagation is also possible in a BBN, which is useful for determining the most likely scenario based on the evidence set.

4 | Results

4.1 | BBN Model Development

Netica software was used to create the BBN model. *Fig. 5* displays the prior probabilities of the states.

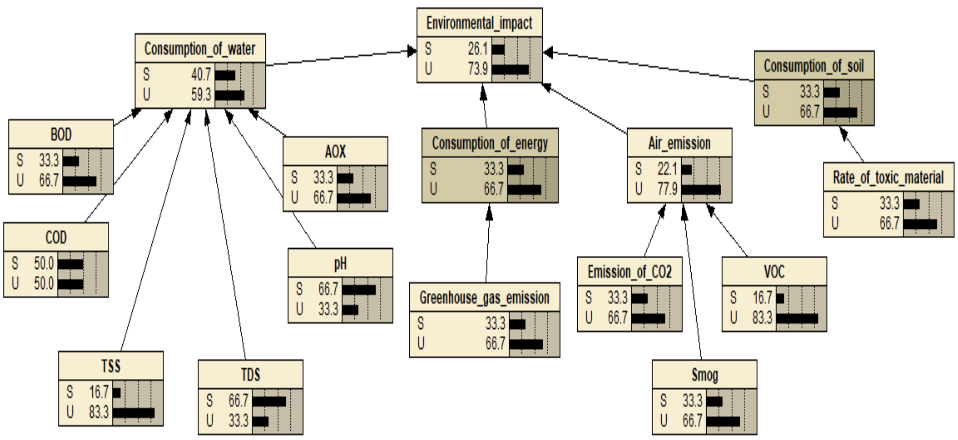

Fig. 5. BBN model for predicting green supply chain performance indicators.

From *Fig. 5* it can be found that the satisfactory state of "consumption of water" is 40.7% and unsatisfactory state is 59.3%, satisfactory state of "consumption of energy" is 33.3% and unsatisfactory state is 66.7%, satisfactory state of "air emission" is 22.1% and unsatisfactory state is 77.9% and satisfactory state of "consumption of soil" is 33.3% and unsatisfactory state is 6.7%. The outcome of this figure is the satisfactory state of "environmental impact" is 26.1% and unsatisfactory state is 73.9%. This outcome is based on current anterior probabilities of performance indicators that were calculated from industrial data.

4.2 | Model Confirmation

The suggested model was validated using both qualitative and quantitative confirmation methods [26]. For this, extreme-condition test and scenario analysis, and sensitivity analysis were performed, respectively.

4.2.1 | Qualitative analysis

Qualitative analytics is used by businesses to examine circumstances where hard metrics are unavailable. In appraising a situation, quantitative analytics is objective and deductive, but qualitative analytics is subjective and inductive. Qualitative research is more abstract. This analysis was done with extreme – condition test and scenario analysis.

This research considers two extreme conditions to justify the model. In extreme – condition test we considered two cases. Case 1 is that when all the performance indicators are in good condition and case 2 is that when all the performance metrics are in a poor state of repair. *Fig. 6* and *Fig. 7* demonstrate the outcomes for extreme versions 1 and 2, respectively.

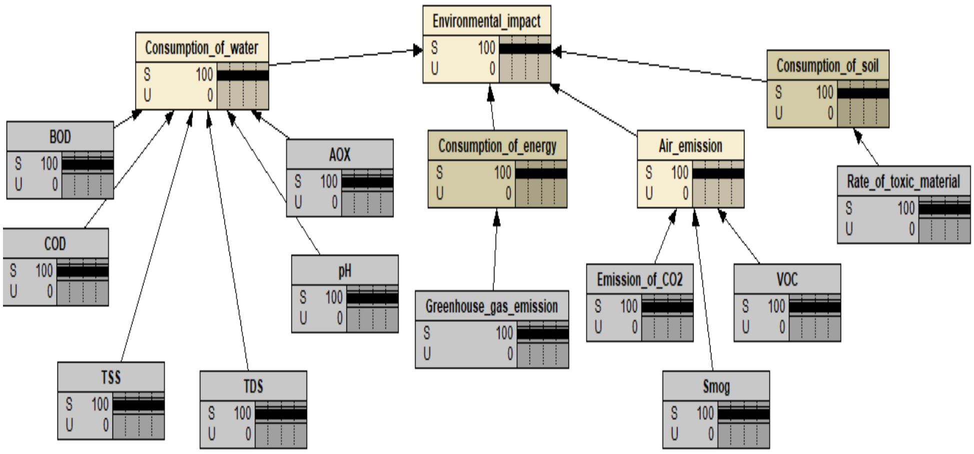

Fig. 6. Extreme case 1 when all performance indicators are in good condition.

Outcome: from extreme case 1, when all the performance indicators are satisfied, the environmental impact has a 100 % chance of being satisfactory. Again, from extreme case 2, when all the performance indicators have a 100% chance of being in an unsatisfactory state, the environmental impact has 0 percent chance of being satisfactory. As a result, the extreme – condition tests reveal that the suggested environmental performance model behaves as predicted.

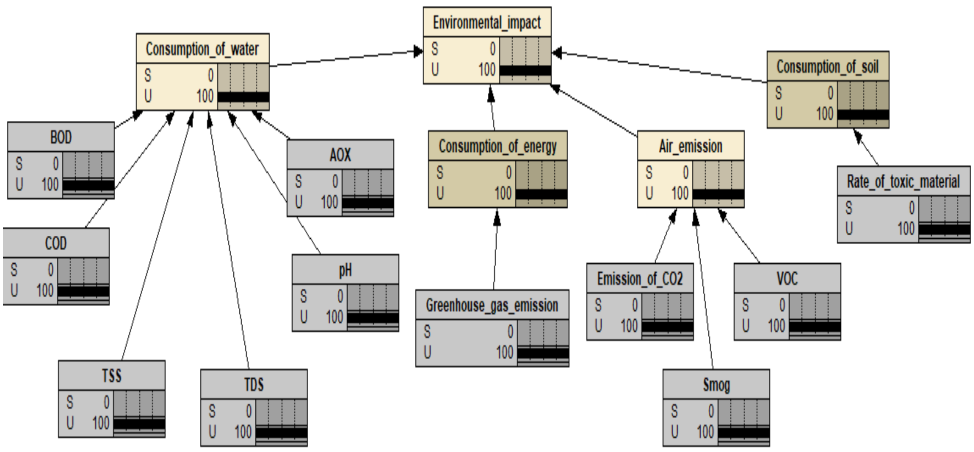

Fig. 7. Extreme case 2 when all the performance metrics are in a poor state of repair.

In this assessment, considered those indicators which have maximum level of unsatisfactory state that could be found from *Fig. 5*. Four performance indicators namely BOD, TSS, AOX, and VOC were considered for this assessment. Also, two performance measures namely "consumption of water" and "air emission" were considered for this analysis. Ten scenarios were considered for this assessment. In this analysis, all the satisfactory state were increased, and unsatisfactory state were decreased from the current values. The analysis' findings are depicted in *Fig. 8* to *Fig. 17* and displayed in *Table 5*.

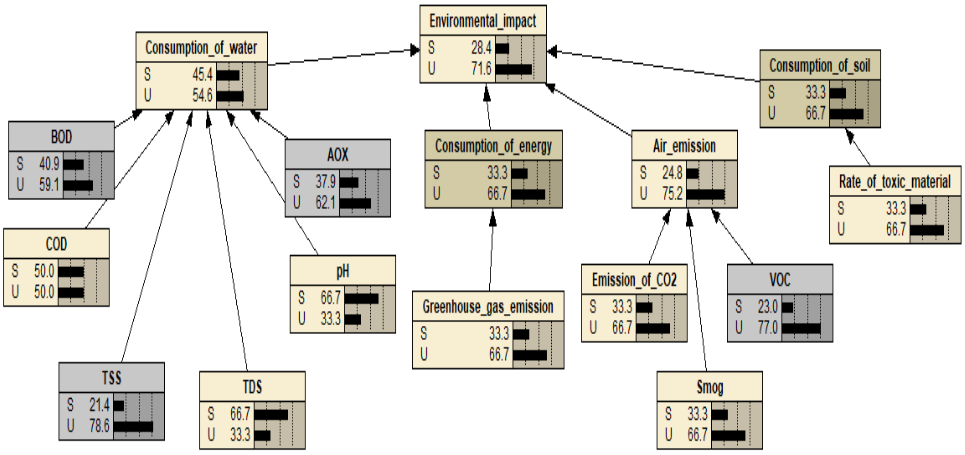

Fig. 8. Scenario analysis 1 of simultaneous change of BOD, TSS, AOX and VOC.

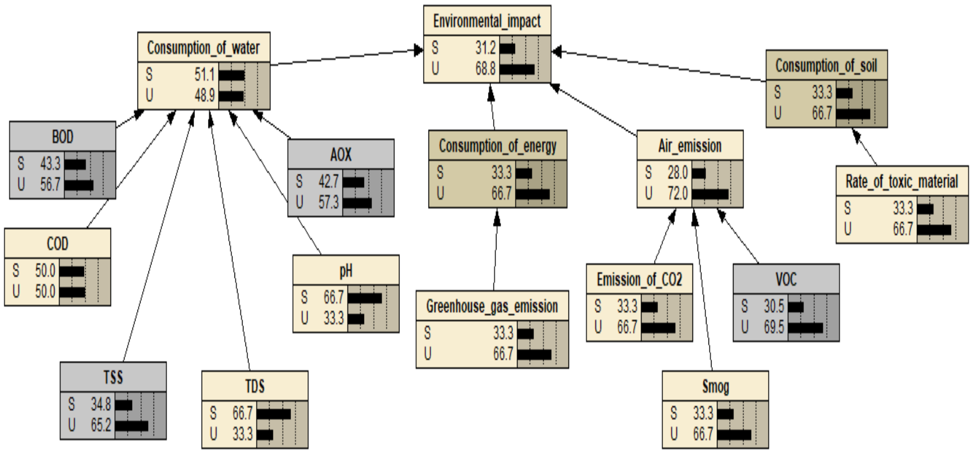

Fig. 9. Scenario analysis 2 of simultaneous change of BOD, TSS, AOX and VOC.

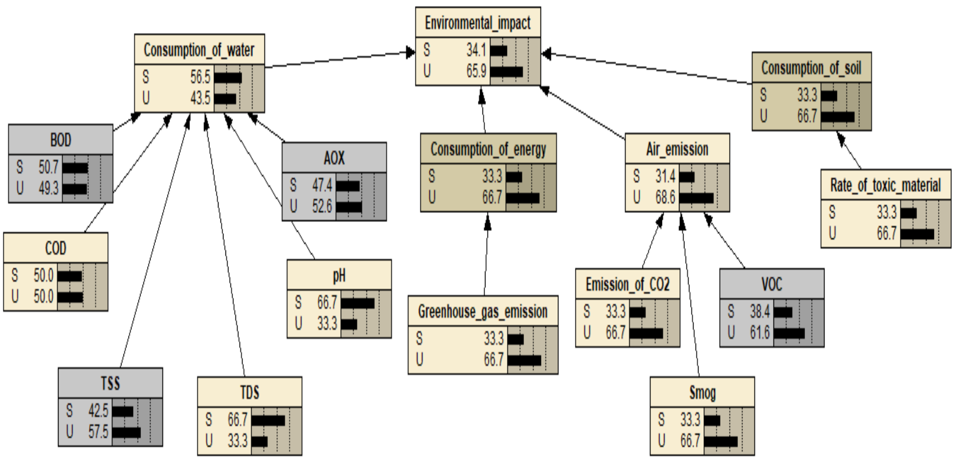

Fig. 10. Scenario analysis 3 of simultaneous change of BOD, TSS, AOX and VOC.

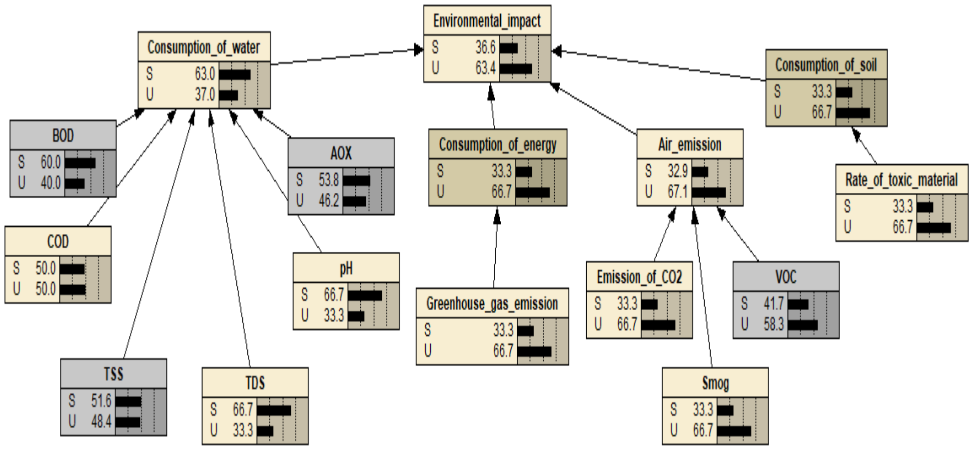

Fig. 11. Scenario analysis 4 of simultaneous change of BOD, TSS, AOX and VOC.

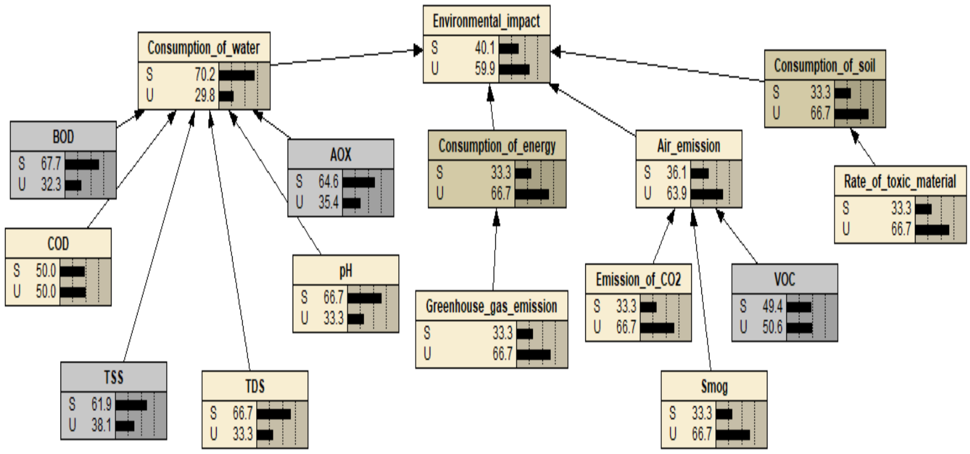

Fig. 12. Scenario analysis 5 of simultaneous change of BOD, TSS, AOX and VOC.

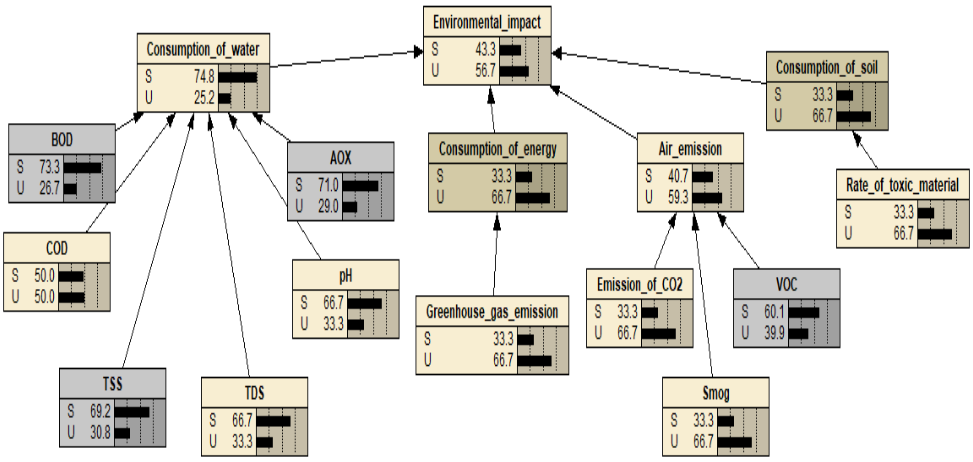

Fig. 13. Scenario analysis 6 of simultaneous change of BOD, TSS, AOX and VOC.

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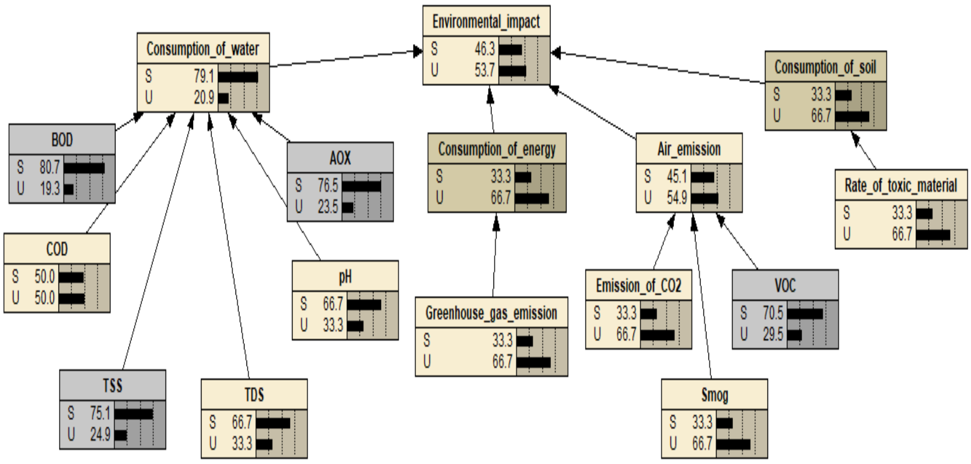

Fig. 14. Scenario analysis 7 of simultaneous change of BOD, TSS, AOX and VOC.

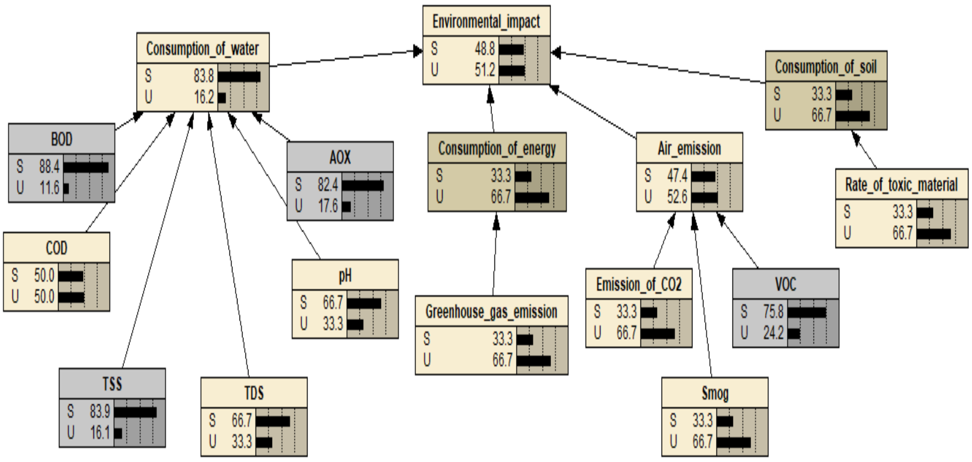

Fig. 15. Scenario analysis 8 of simultaneous change of BOD, TSS, AOX and VOC.

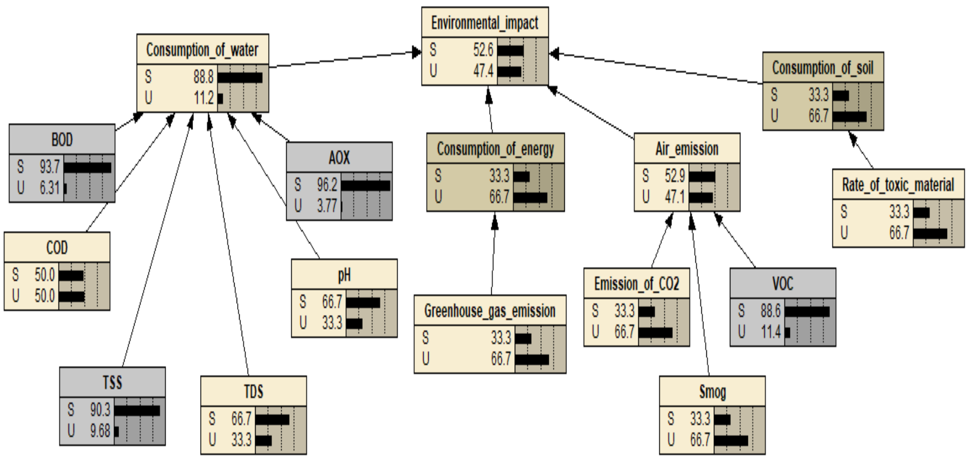

Fig. 16. Scenario analysis 9 of simultaneous change of BOD, TSS, AOX and VOC.

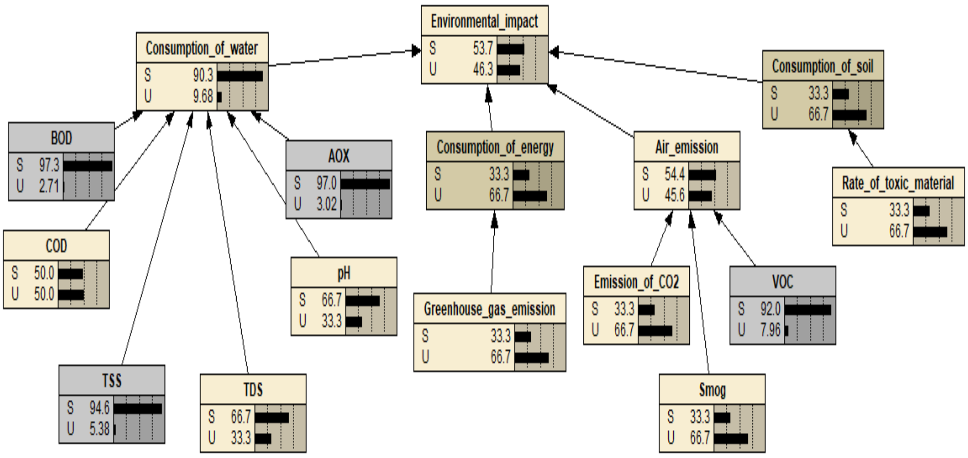

Fig. 17. Scenario analysis 10 of simultaneous change of BOD, TSS, AOX and VOC.

Outcome: these ten possibilities all represent the model's expected behavior. When the selected indicators were improved then environmental impact was also improved simultaneously that are illustrated in table. Similarly, different combinations of performance indicators are explored to construct alternative scenarios, and the probability distribution of their environmental impact is assessed to provide model verification. In *Table 5* satisfactory is indicated as S, unsatisfactory is indicated as U, and results using Netica software is given below:

Table 5. The presented BBN-based model's scenario analysis findings.

Nodes	States	Conditional Probabilities of Different Scenarios (%)									
		Sc1	Sc2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10
BOD	S	40.9	43.3	50.7	60.0	67.7	73.3	80.7	88.4	93.7	97.3
	U	59.1	56.7	49.3	40.0	32.3	26.7	19.3	11.6	6.31	2.71
TSS	S	21.4	34.8	42.5	51.6	61.9	69.2	75.1	83.9	90.3	94.6
	U	78.6	65.2	57.5	48.4	38.1	30.8	24.9	16.1	9.68	5.38
AOX	S	37.9	42.7	47.4	53.8	64.8	71.0	76.5	82.4	96.2	97.0
	U	62.1	57.3	52.6	46.2	35.4	29.0	23.5	17.6	3.77	3.02
VOC	S	23.0	30.5	38.4	41.7	49.4	60.1	70.5	75.8	88.6	92.0
	U	77.0	69.5	61.6	58.3	50.6	39.9	29.5	24.2	11.4	7.96
Consumption of water	S	45.4	51.1	56.5	63.0	70.2	74.8	79.1	83.8	88.8	90.3
	U	54.6	48.9	43.5	37.0	29.8	25.2	20.9	16.2	11.2	9.68
Air emission	S	24.8	28.0	34.1	32.9	36.1	40.7	45.1	47.4	52.9	54.4
	U	75.2	72.0	68.6	67.1	63.9	59.3	54.9	52.6	47.1	45.6
Environmental impact	S	28.4	31.2	34.1	36.6	40.1	43.3	46.3	48.8	52.6	53.7
	U	71.6	68.8	65.9	63.4	59.9	56.7	53.7	51.2	47.4	46.3

4.2.2 | Quantitative analysis

Quantitative analytics in business employs such characteristics to produce information that managers can use to make effective decisions. Looking at real facts, or numbers, is a part of quantitative analysis. This analysis was done by sensitivity analysis.

A sensitivity analysis was used to determine the influence of each unique element in the model output. This analysis shows how small changes in input factors such as emission of CO_2 and TSS can alter the prediction model, which in this case is environmental impact. Entropy measures the impurity of collection of datasets. Information gain is a measure of the decrease in disorder achieved by partitioning the original data set. The reduction in entropy or surprise achieved by changing a dataset is known as information gain, and it is frequently utilized in the training of decision trees. The entropy of a database

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during a modification is used to calculate information gain. The steps for sensitivity analysis are shown in *Fig. 18*.

Fig. 18. Framework for sensitivity analysis.

The formulae for this analysis are given below:

Entropy, E(d):

$$E\ d) = -\sum_{i-1}^{n} p_i \log_2 p_i).$$

Where,

pi = probability of state,

K = no of state for every indicators / measures.

d = the indicator / measure.

Entropy for a partition, E(d,a):

$$E\ d, a) = \sum \frac{n_j}{n} * E(d_j).$$

Where,

n_j/n = probability of the selected state of environmental impact.

E(d_j) = Entropy of the selected state of indicators / measures.

Information gain, I(d,a):

Where,

E(d) = Entropy of environmental impact.

E(d,a) = Entropy for an indicator / a measure.

$$I\ d, a) = E\ d) - E\ d, a).$$

Calculation of information gain for indicators: entropy calculation for BOD is done as follows:

From the previous table we get data for BOD:

I. Satisfactory state of BOD = 33.3%,
II. Unsatisfactory state of BOD = 66.7%,
III. So, probability of satisfactory state = 0.333,
IV. Probability of unsatisfactory state = 0.667,
V. Entropy for satisfactory state = - (0.333*log2 (0.333)) = 0.528273,
VI. Entropy for unsatisfactory state = - (0.667*log2 (0.667)) = 0.389689,
VII. Total entropy for BOD = 0.917962.

Similarly, we calculated all other indicators and performance measures of entropy by MS Excel and the results are summarized in *Table 6* and *7*.

Table 6. Entropy for indicators.

Name of Indicators	Entropy of Satisfactory State	Entropy of Unsatisfactory State
BOD	0.528273	0.389689
COD	0.5	0.5
TSS	0.389689	0.528273
TDS	0.389689	0.528273
PH	0.389689	0.528273
AOX	0.528273	0.389689
Greenhouse gas emission	0.528273	0.389689
Emission of Co_2	0.528273	0.389689
Smong	0.528273	0.389689
Voc	0.431207	0.219588
Rate of toxic material	0.528273	0.389689

Table 7. Entropy for performance measures.

Performance Measures	Entropy of Satisfactory State	Entropy of Unsatisfactory State	Total Entropy
Consumption of water	0.527938	0.44706	0.974898
Consumption of energy	0.528273	0.389689	0.917962
Air emission	0.481312	0.280677	0.761989
Consumption of soil	0.528273	0.389689	0.197962
Environmental impact	0.505786	0.322465	0.828252

Calculation of combined entropy and information gain for indicators and performance measures: from figure, it can be seen that, the satisfactory state of environmental impact is 26.1% and unsatisfactory state is 73.9%. So, their probability (n_j/n) will be respectively 0.261 and 0.739.

Partition for BOD, E(d,a)= (0.528273*0.261) + (0.389689*0.739) = 0.425859446.

Similarly, we calculated combined entropy for other indicators and measures by MS Excel using formula and summarized the findings in *Table 8*. Then for next step calculated information gain/entropy reduction for all indicators and measures. The calculation for BOD is shown below:

Information gain for BOD, I(d,a)=E(d)-E(d,a)= 0.828252 – 0.425859446 = 0.402392194.

For other indicators and measures information gain were calculated by MS Excel that are given below in *Table 8* and *Table 9*.

Table 8. Combined entropy and information gain of indicators.

Name of Indicators	Combined Entropy, E(d, a)	Information Gain, I(d, a)= E(d)-E(d, a)
BOD	0.425859446	0.402392194
COD	0.5	0.32825164
TSS	0.274820994	0.553430646
TDS	0.492102694	0.336148946
PH	0.492102694	0.336148946
AOX	0.425859446	0.402392194
Greenhouse Gas Emission	0.425859446	0.402392194
Emission of Co_2	0.425859446	0.402392194
Smong	0.425859446	0.402392194
VOC	0.274820994	0.553430646
Rate of toxic material	0.425859446	0.402392194

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Table 9. Combined entropy and information gain of performance measures.

Name of Performance Measures	Combined Entropy, E(d, a)	Information Gain, I(d, a)= E(d)-E(d, a)
Consumption of water	0.4681433	0.3610834
Consumption of energy	0.425859446	0.402392194
Air emission	0.333043004	0.495208636
Consumption of soil	0.425859446	0.402392194

The outcome of sensitivity analysis of indictors and performance measures represent in *Fig. 18* and *Fig. 19*.

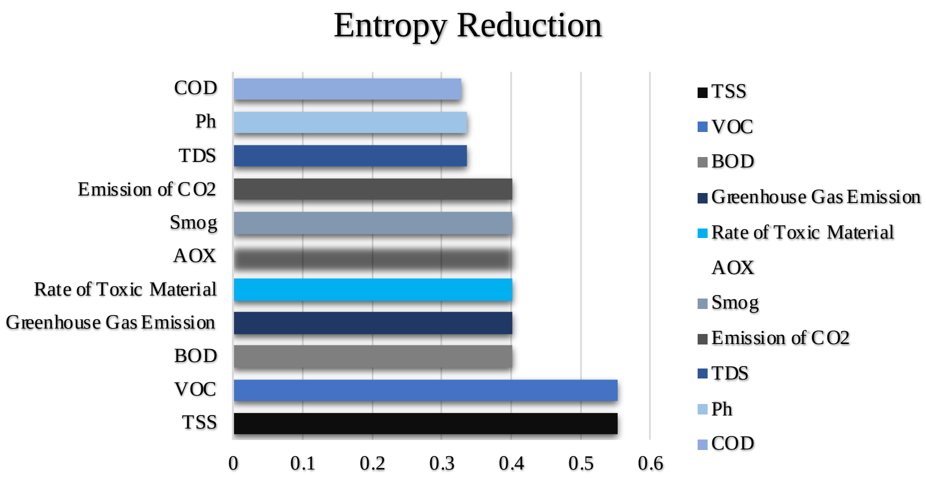

Fig. 18. Sensitivity analysis of environmental impact for indicators.

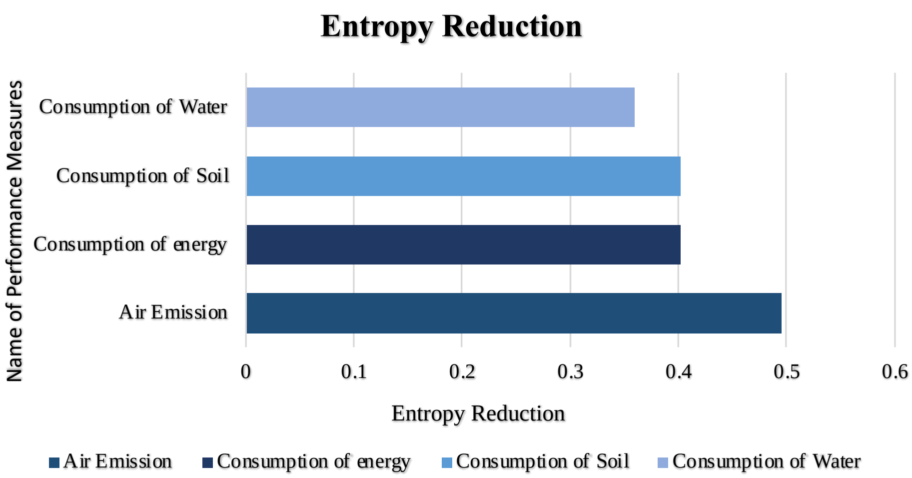

Fig. 19. Sensitivity analysis of environmental impact for performance measures.

Outcome: sensitivity analysis enables the decision-maker to find the input parameters that have the greatest impact on the output and emphasize them in the choice process. From *Fig. 18* and *Fig. 20*, managers should decide what he/she should focus for lowering environmental impact. If the manager chooses indicators, then he/she should prioritize to decrease TSS and VOC and if the manager choose performance measures then he/she should focus to decrease air emission.

Diagnostic analysis takes the insights gained from descriptive analytics and delves down to find the reasons of those outcomes. Organizations make advantage of this type of analytics as it generates more linkages between data and finds patterns of activity. A diagnostic analysis can be used to calculate the marginal probability of base or parent nodes. This methodology can be used to find the prior probability dependent on the pooled risk. *Table 10* and *Fig. 20* and *21* show the confidence level of the current node conditioned on aggregated risk.

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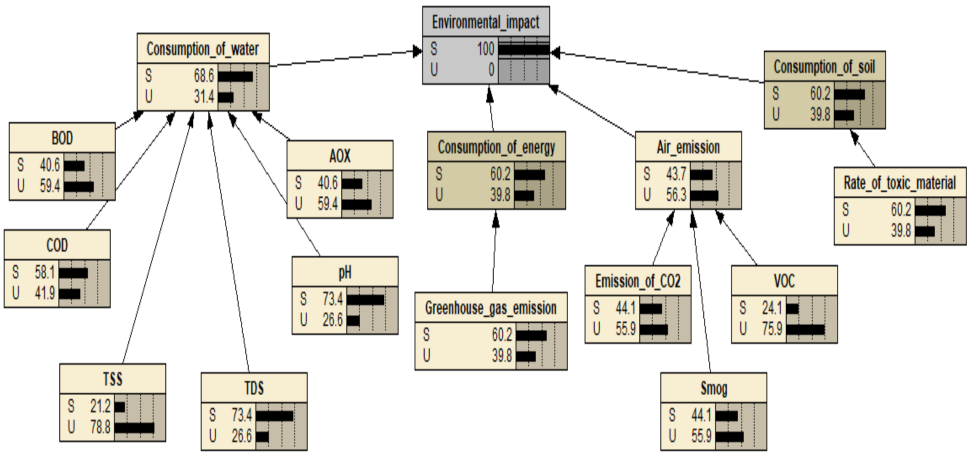

Fig. 20. Parent node posterior probabilities based on environmental impact satisfactory state.

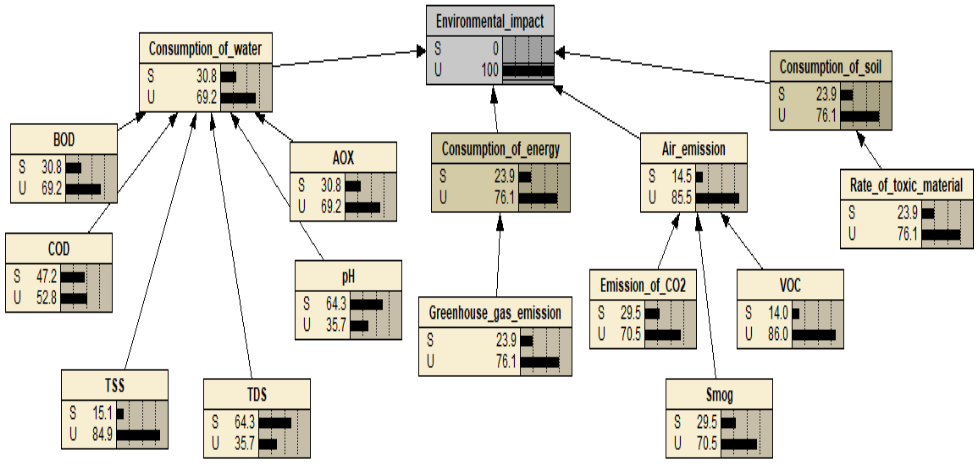

Fig. 21. Parent node posterior probabilities based on environmental impact unsatisfactory state.

Table 10. Parent node posterior probabilities based on environmental performance.

Parent Nodes	Posterior Probabilities of States	Environmental Impact	
		Satisfactory	Unsatisfactory
BOD	Satisfactory	0.406	0.308
	Unsatisfactory	0.594	0.692
COD	Satisfactory	0.581	0.472
	Unsatisfactory	0.419	0.528
TSS	Satisfactory	0.212	0.151
	Unsatisfactory	0.788	0.849
TDS	Satisfactory	0.734	0.643
	Unsatisfactory	0.266	0.357
PH	Satisfactory	0.734	0.643
	Unsatisfactory	0.266	0.357
AOX	Satisfactory	0.406	0.308
	Unsatisfactory	0.594	0.692
Greenhouse gas emission	Satisfactory	0.602	0.239
	Unsatisfactory	0.398	0.761
Emission of Co2	Satisfactory	0.441	0.295
	Unsatisfactory	0.559	0.705
Smong	Satisfactory	0.411	0.295
	Unsatisfactory	0.559	0.705
VOC	Satisfactory	0.241	0.14
	Unsatisfactory	0.759	0.86
Rate of toxic material	Satisfactory	0.602	0.239
	Unsatisfactory	0.314	0.692

Outcome: in two extreme situations of environmental performance, *Table 10* demonstrates the change in the probability of performance indicators and measures. When environmental performance swings from an unsatisfactory to a satisfactory state, all the chances for an unsatisfactory state drop. On the other side, the chances of being in a satisfied state increase. This is consistent with the model's expected behavior.

5 | Discussions

Following a review of the available literature, eleven green supply chain performance indicators and four green supply chain performance measures were chosen, and BBN was used to develop the model that would predict total environmental performance. Collected data about the indicators from a renowned industry were used for analysis in Netica software. Here, we considered two states for BBN model; one was satisfactory state and another one was unsatisfactory state. This model will give the decision-makers an overview of the total environmental performance of the green supply chain. For evaluating the model, qualitative and quantitative analysis were done. In qualitative analysis, extreme condition test and scenario analysis were done. This will enable the management to see how the performance metrics affect the overall performance of the green supply chain. Again, in quantitative analysis, sensitivity analysis was done. A sensitivity analysis identifies the most critical performance indicators and offers a ranking of the metrics in order of priority to decision-makers. The outcome TSS and VOC were found to be the most important indicators for the case company in this study, with the highest entropy reduction. And 'air emission' was the most impactful performance measures among the four. By this, manager could give focus on reducing high TSS, high VOC and air emission. This methodology can also assist a manager in meeting the predetermined GSCM performance goals.

6 | Conclusions

This research used BBN model for anticipating performance indicators and measures for environmental impact. For validation of the BBN model some analyses were done. These all analysis provided a message that if indicators satisfactory state is increased then the overall environmental impact will be good but if not, then then overall environmental impact will be bad. Among them sensitivity analysis proved that for reducing environmental impact a decision maker should focus either on indicator 'TSS' and 'VOC' or performance measure of 'air emission'. In this way, unsatisfactory state of environmental impact would be reduced. For reducing TSS, VOC, and air emission a manager needs to choose a proper green raw material so that environment will not be hampered as well as it will be effective to earn more profit, and this is the focus of GSCM.

SC managers will be able to identify the significant performance indicators that most affect GSCM performance of their company using this model. They will also be able to prioritize and allocate resources for the performance indicators for highest environmental performance. Moreover, the managers will be able to monitor current environmental performance and set the target performance indicator level target accordingly.

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Conflicts of Interest

All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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A Fuzzy BWM Approach to Prioritize Distribution Network Enablers

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Abstract

In any country's economy, the distribution is one of the most important industries and infrastructure. The industry's 8% portion of national income, explains the wide range of this industry and consequently the key role of this industry in the supply chain of many industries in the country. Not using all the capabilities of the distribution network and ignorance about distribution enablers will lead to chain costs failure and increase supply. In today's condition, maintenance and continuity of activities in the distribution network are considered as important subjects in a supply chain, and the reliability of the distribution network in a supply chain is grounded in recognition of the enablers. Identifying and prioritizing the distribution network enablers precede the development and proper implementation of the strategies and plans of a distribution network. The fuzzy logic has become a convenient tool for prioritizing due to the necessity of the comprehensive view to the supply chain, the uncertain space of it, and inconsistency in the views of decision-makers. This research tries to identify and prioritize the empowerment in order to direct and supply resources and thus to increase the productivity and effectiveness of the country's industrial distribution network. The theoretical framework of the study is based on the extracted enablers from the literature and selecting a final set of them by using the Lawshe method. The group of experts is comprised of 11 experts in the welding and cutting industry. The enablers are prioritized using the fuzzy BWM method and Lingo software. The results indicate that the most influencing factor on the distribution network is "on-time delivery" and the "logistic infrastructures" factor is the least important among the factors. The resulted prioritization could be used as a guideline for a better perception of the activities related to the distribution network. By analyzing the studies in this topic, a research gap can be identified in the field of not recognizing the distribution network enablers. Another study gap is not paying attention to the prioritization of enablers. However, in the real world, it is not possible to consider and apply all enablers owing to limits, and each enabler has a distinct preference, demonstrating the importance of prioritizing enablers and employing multi-criteria decision-making techniques.

Keywords: Distribution network, Distribution enabler, Fuzzy best-worst.

1 | Introduction

Nowadays, most organizations accept the concept of Supply Chain Management (SCM) and use it as a tool for gaining competitive advantages. SCM could be considered as integration and coordination of materials, information, and financial flows for using supply chain resources in the whole logic of the value chain. In practice, SCM includes processes such as inventory control, production planning, and optimizing distribution network or tendering logistic services [1]. Distributing strategy has an important role in the sale system of a supply chain. The distribution network empowers the chain market by collaborating in the growth of product delivery to different sectors. Furthermore, it collaborates to make the needed products get in reach [2]. In SCM, distribution is a set of actions for delivering the consumer the final products. Customer satisfaction is due to the ability of delivery

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network to transfer the products as quickly and economically as possible. Organization's success in a competitive global market is by maintaining inventory at distribution network [3].

The distribution network is very complex and has an important role in the economy of a country. Developing the distribution network theories could be considerably collaborative to decision-making in this industry. Thus, it is vital to develop a comprehensive view of enablers in sharing theories and proper recognition of facilitators as a predecessor to achieve the goals of the distribution network. Many enablers are influential on the success of a supply chain. Identifying the most important enablers is important in the management of these processes. By introducing the enablers, managers would be able to improve them and use their resources for the enablers with higher priority [1]. Hence, what are the distributors in the supply chain? In this research, we are trying to answer this question. What is the order and importance of each empowerment? Answering these questions is essential for managers in order to achieve the ability to obtain the needed information for making decisions in today's competitive environment and its advantageous aspects.

Different studies have been done to identify and prioritize supply chain enablers but without focusing on the distribution network. Due to this important issue, the present study has taken steps to provide a comprehensive distribution network enablers and complete this research gap. This descriptive-practical case study develops a framework to demonstrate the distribution network enablers by using a test group and deploying a quantitative method. Identifying the distribution network enablers could collaborate in developing proper strategies in order to achieve the goals as much as possible and help managers in this industry with a better vision. Introducing effective enablers needs an applicable and comprehensive method to achieve a comprehensive and clear prioritizing considering the importance of the enablers.

Decision-making techniques are the main tools for prioritizing different problems [4]. BWM is one of the most efficient techniques in multi-criteria decision-making that aim to minimize the absolute difference of weights, the number of pairwise comparisons, and achieve more compatible pairwise comparison matrix by recognition of the dynamic processes prioritization by using classical methods does not achieve highly reliable results. Many decision areas have highly ambiguous.these ambiguities lead to the presentation information that is not suitable for decision making [5]. Integrated fuzzy-MCDM model is used to find out the most suitable option [6]. Therefore, this study aims to minimize the limitations of classical methods, by using fuzzy approach and multi-criteria decision-making prioritization of distribution network enablers. The remainder of this paper is as follows:

In Section 2, the literature review is presented. In Section 3, the theoretical basics are described and the study approach is presented in Section 4. Section 5 presents, analyze and discuss the distribution network enablers and finally, the results and their implications are presented in the last section of this paper.

2 | Literature Review (Survey on Related Work)

Distribution network management is so important along with the other parameters of the supply chain and the marketing mix; because of the fact that logistic costs are among the most significant costs of a distribution network. So that succeeding in the distribution network is one of the most important supply chain problems. Many studies have been done to prioritize the supply chain enablers but studies that aim to identify the distribution network enablers are scarce.

Andalib Ardakani and Shams [7] identified and modeled the enablers of green SCM in Small and Medium-sized Enterprises (SMEs). They used structural equation modeling in order to analyze data and prioritize criteria. The results of their study indicate that influencing factors on the SCM enablers could be classified into five criteria: "Electronic Commerce", "Internal Operations", "Logistic Success", "Total Quality Management", and "Innovation ". The results of prioritizing show that "Internal Operations" has the most effect on green SCM and "Innovation", "Logistic Success", “Electronic Commerce", and "Total Quality Management" are in next priorities.

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Ostadi et al. [8] identified and prioritized the enablers of Supply Chain Quality Management (SCQM) based on weighting criteria using the Analytic Hierarchy Process (AHP) method. They identified the enablers through literature review then prioritized criteria based on pairwise comparison logic and AHP. The supply chain of a product should be focused on seven fields to implement SCQM and these fields should be developed and improved, simultaneously and in collaboration with each other, considering the correlation between them.

Abedini et al. [9] prioritize the enablers of the medicine supply and distribution chain using the DEMATEL approach. Their study consists of two library searching and surveying phases. In the first phase, the enablers were identified in 25 aspects by searching in scholarly resources. In the second phase, nine aspects were selected, based on the Pareto principle, as the basis for pairwise comparisons of the factors in the DEMATEL approach. The results indicated that "support from senior management", "using information technology", and "government interfering" are the first three factors among influencing factors; moreover, "processes", "quality of services", and "trust" are the first three factors among influenced factors. Furthermore, "support from senior management" and "government interfering" have been known as the most and the least interactive factors, respectively.

Salehi Sadaghiani and Ghasem Zadeh [10] identified the enablers in the agile supply chain in dairy industries. The results indicate that the eleven main factors for succeeding in a supply chain could be classified into six levels. The first level implies the "customer satisfaction" factor, which increases the market share and profits of the organization. At the last level, there are three factors including "process aggregation", "suitable planning", and "employees' skills development".

Kumar et al. [11] studied the enablers in the Circular Supply Chain (CSC) Industry 4.0. They identified the enablers through literature review, then in the final step, the influencing and influenced factors were determined using the Fuzzy DEMATEL method. The results showed that to adopt Industry 4.0, "knowledge of supply chain and Industry 4.0" is the most important factor followed by "top management commitment".

Gokarn and Choudhary [12] identified the main influencing factors on wastages of the food supply chain. This empirical study identified eight influencing factors. They used interpretive structural modelling technique and Micmac analysis to study the enablers. "Supervising institutions", "policies and market infrastructures" are the most important factors.

Prasad et al. [13] studied the key factors for success in a sustainable supply chain. This research has been conducted based on scholarly documentaries and 145 experts' ideas. Structural modelling technique indicated that the "internal space of the organizations" is an important factor in Indian steel industry SCM approaches.

Meyer and Torres [1] studied the enablers in supply chain projects. In their study, ten enablers for supply chain projects were evaluated through semi-structural interviews with supply chain experts. The results indicated that "communications and stakeholder management", "project clear goals", " supporting from senior management project", and "internal organization of project team" have been identified as the most important factors.

Behl et al. [14] identified and prioritized the enablers in Humanitarian Supply Chain Management (HSCM) by using gray-based Fuzzy DEMATEL. They considered flood in India as the case study and investigate the important factors for a successful implementation of humanitarian SCM. Furthermore, they modeled the enablers and classified them using a gray-based decision-making approach.

Adabavazaeh and Nikbakht [15] have identified the enablers in the reverse supply chain. They identified 159 factors through literature review and reached 73 factors after a preliminary reduction. Finally, 24 main success factors were identified using the Lawshe technique and were classified using interpretive structural modelling technique and experts' views. The results showed that the most influencing factor related to "inventory management" and “logistic" are among the connector factors which any minor change in them would fundamentally change the whole system.

Aschemann-Witzel et al. [16] conducted research on supply chain enablers to deal with food wastages. The multi-case study was presented by analyzing success factors in 26 current programs for reducing food wastages. Their findings indicated that "cooperation between stakeholders", "innovations sequence and time", "innovation abilities" are key success factors. There are three main innovations that are different in goals and specifications: "information and opportunity making", "redistribution" and "supply chain".

Raut et al. [17] identified the enablers of Indian oil and gas sustainable supply chain. 32 enablers were identified through literature review and ideas of experts and academics. Interpretive structural modelling and Micmac analysis indicated that "global climate pressure", "ecologic lack of resources" are the most important factors which might make industries implement sustainable approaches. Coo [18] investigated the enablers to improve distributing in exports of SMEs. They aimed to find out the enablers for small and medium-sized exporting enterprises and create the factors which have positive impact on their export. 15 success factors were identified based on 258 questionaries.

Kumar et al. [19] studied the enablers in the supply chain of Indian SMEs. 13 enablers were identified in SMEs. The results indicated that “top management commitment", "long-term strategy", "focusing on strengths", "dedicated resources to supply chain" and "strategy development" are among the influencing factors in a supply chain. To measure the performance improvement by the factors "different actions related to services", "customer satisfaction", "innovation and growth", "financial performance", and "internal jobs" were taken into account.

Major purpose of [20] research is identification and evaluating of effective factors on implementation of Green Supply Chain Management (GSCM) at Fanavaran Petrochemical Company by using statistical methods of Kolmogorov-Smirnov, mean and decision making method by topic Stepwise Weight Assessment Ratio Analysis (SWARA). Research methodology of present research base on purpose is practical and based on data gathering method is descriptive-measurement. In order to extracting the effective factors on GSCM at the company, in first, by literature review, 22 factors were identified. Then data’s were gathered by using of opinions of population members containing 55 persons of experts and senior managers in the first class of company. Finally after analyzing the questionnaires and statistical tests above, 11 factors were confirmed and selected. In continues, in order to evaluating the final factors and ranking them base on importance in success implementation of GSCM system, the SWARA technique is used. The aim of [21] study is to identify and prioritize a list of key digitization enablers that can improve SCM. This study seems to be the first of its kind in which 25 digitization enablers categorized in four main categories are ranked using a Multi Criteria Decision Making (MCDM) tool. This study is also first of its kind in ranking the organizations in their SC performance based on weights/ranks of digitization enablers. The BWM has been applied to evaluate, rank and prioritize the key digitization and IT enablers beneficial for the improvement of SC performance.

Della Valle and Oliver [22] study provided solid contributions to understanding blockchain innovation and presents some main features and guidelines for how to boost blockchain implementation in industry. As explorative research, this paper presents a grounded theory analysis based on 18 expert interviews. Renowned worldwide experts provided us with powerful input to run this analysis and with a general overview of the current situation.

Bamel and Bamel [23] paper aimed to identify the Big Data Analytics (BDA) based enablers of Supply Chain Capabilities (SCC) and competitiveness of firms. This paper also models the interaction among identified enablers and thus projects the relationship strength of these enablers with SCC and a firm's competitiveness. In order to achieve the research objectives of this paper, we employed fuzzy Total

Interpretive Structural Modeling (TISM), an integrated approach of an interpretive structural model and TISM. In a brief view, the supply chain/distribution network enablers from experts' perspective could be concluded in the following table.

Aazami and Saidi-Mehrabad [24] investigated the generation and distribution planning of perishable products with fixed lifetime in seller and buyer systems. This research studied three solutions, and because the problem is NP-hard, a novel hierarchical approach based on Genetic Algorithm (GA) is provided. Hendalianpour et al. [25] presented a hybrid optimization approach for a multi-channel, multi-product, multi-level distribution system. The goal of this article is to improve the flow of product transportation inside a multi-channel, multi-product, multi-level distribution network under uncertain conditions. A hybrid approach based on Benders Decomposition (BD) and Lagrangian Relaxation (LR) is designed to solve the given model. Five distinct scenarios with varying degrees of service are studied, and numerical results are reviewed in relation to earlier findings.

Identifying the distribution network enablers would improve the balanced capacity of all the memberships of a supply chain. The distribution network needs stakeholders' support, developing related regulations and policies, accurate planning, needs assessment, and providing resources and facilities. In a distribution network, sufficient human resources, facilities, and requirements, a product tracking information system, sufficient financial resources, and a proper management and leadership system are needed to provide on-time and high-quality services. The performance of a distribution network could be improved by using the suggested enablers.

The literature review indicates that many studies have briefly investigated the supply chain enablers, but a few of them considered the distribution network enablers. The fuzzy logic has become a convenient tool for prioritizing due to the necessity of the comprehensive view to the supply chain, the uncertain space of it, and inconsistency in the views of decision-makers. By analyzing the studies in this topic, a research gap can be identified in the field of not recognizing the distribution network enablers. Another study gap is not paying attention to the prioritization of enablers. However, in the real world, it is not possible to consider and apply all enablers owing to limits, and each enabler has a distinct preference, demonstrating the importance of prioritizing enablers and employing multi-criteria decision-making techniques.

Table 1. The research gap of the supply chain/distribution network enablers.

Researcher/ Researchers (Year)	Research Tools	Study Approach		Research Results		Studied Industry
		Fuzzy	Classic	Introducing Enablers	Presenting Model/Pattern	
Andalib Ardakani and Shams [7]	PLS	-	✓	✓	✓	GSM
Abedini et al. [9]	DEMATEL	-	✓	✓	-	Medicine
Ostadi et al. [8]	AHP	-	✓	✓	-	SCQM
Salehi Sedighiani et al. [10]	ISM	-	✓	✓	✓	Diary
Kumar et al. [11]	Fuzzy DEMATEL	✓	-	✓	-	CSC Industry 4.0
Gokarn and Choudhary [12]	ISM	-	✓	✓	✓	Food
Prasad et al. [13]	SEM	-	✓	✓	✓	Steel
Meyer and Torres [1]	Semi Structured Interviews	-	✓	✓	-	SCM
Behl et al. [14]	Grey DEMATEL	-	✓	✓	-	HSCM

Table 1. Continued.

Researcher/ Researchers (Year)	Research Tools	Study Approach Fuzzy	Study Approach Classic	Research Results Introducing Enablers	Research Results Presenting Model/Pattern	Studied Industry
Adabavazaeh and Nikbakht [15]	ISM	-	✓	✓	✓	Aerial
Aschemann-Witzel et al. [16]	Multiple Case Study	-	✓	✓	-	Food
Raut et al. [17]	ISM	-	✓	✓	✓	Oil and Gas
Coo [18]	PPML, Regression Analysis	-	✓	✓	-	SMEs
Kumar et al. [19]	Statistical Tools	-	✓	✓	-	SMEs
Nasiri el al. [20]	SWARA	-	✓	✓	-	Petrochemical
Gupta et al. [21]	BWM	-	✓	✓	-	
Della Valle and Oliver [22]		-	✓	✓	-	blockchain technology
Bamel and Bamel [23]	TISM	✓	-	✓	-	
Aazami and Saidi-Mehrabad [24]	BDA & GA	-	✓	-	✓	perishable products
Hendalianpour et al. [25]	BD-LR	-	✓	-	✓	supply chain distribution
This Study	Fuzzy BWM	✓		✓	✓	supply chain distribution

3 | Theoretical Basics

3.1 | Fuzzy Set

Assume $A_1 = \; l_1, m_1, u_1)$, $A_2 = \; l_2, m_2, u_2)$ are two triangular fuzzy numbers and $k > 0$ is a constant number. In this case, calculations on fuzzy numbers are as *Eqs. (1)-(5)* [26]:

$$\widetilde{A}_1 + \widetilde{A}_2 = \; l_1 + l_2, m_1 + m_2, u_1 + u_2). \tag{1}$$

$$\widetilde{A}_1 - \widetilde{A}_2 = \; l_1 - u_2, m_1 - m_2, u_1 - l_2). \tag{2}$$

$$\widetilde{A}_1 \times \widetilde{A}_2 = \; l_1 \times l_2, m_1 \times m_2, u_1 \times u_2). \tag{3}$$

$$kx\widetilde{A}_1 = \; kxl_1, kxm_1, kxu_1), \quad k > 0). \tag{4}$$

$$\frac{\widetilde{A}_1}{k} = \left(\frac{l_1}{k}, \frac{m_1}{k}, \frac{u_1}{k}\right), \quad k > 0. \tag{5}$$

In order to compare triangular fuzzy numbers, the Graded Mean Integration Representation (GMIR) is defined as follows.

$$R\left(\widetilde{A}_1\right) = \frac{l_i + 4m_i + u_i}{6}. \tag{6}$$

3.2 | Fuzzy Best-Worst Method

The fuzzy BWM was developed by Guo and Zhao [27] for the first time. This method includes five main steps.

Step 1. In this step the decision-making criteria set, which is used to reach the goal decision, should be determined.

Step 2. In this step the decision-makers determine the best and worst criteria by considering the problem and the related views. The best criterion indicates the most suitable or important influencing criterion on the decision and the worst criterion has the minimum utility and importance for decision-making.

Step 3. In this step, pairwise comparisons are made between the best criterion and other criteria. The preference of the best criterion than other criteria is determined using 5-degrees triangular fuzzy numbers and the Best to Others (BO) matrix should be created according to the *Table 2*. This step aims to determine the preference and importance of the best criterion in comparison to other criteria.

Step 4. The pairwise comparison between the worst criterion and other criteria should be made. In this step the preference of other criteria than the worst criterion is determined using 5 degrees triangular fuzzy numbers and the Others to Worst (OW) matrix would be created according to the *Table 2*.

Table 2. Pairwise comparisons for triangular fuzzy numbers.

Spoken Variables	Membership Function
Equal Importance (EI)	(1,1,1)
Weak Importance (WI)	(2/3,1,1.5)
Fairly Important (FI)	(1.5,2,2.5)
Very Important (VI)	(2.5,3,3.5)
Absolutely Important (AI)	(3.5,4,4.5)

The BO and OW fuzzy vectors are defined according to *Eq. (7)*:

$$a_{Bj} = \left(l_{Bj}, m_{Bj}, u_{Bj}\right), a_{jW} = \left(l_{jW}, m_{jW}, u_{jW}\right),\ \widetilde{\omega}_B = \ l_B^{\omega}, m_B^{\omega}, u_B^{\omega}),\ \widetilde{\omega}_W = \ l_W^{\omega}, m_W^{\omega}, u_W^{\omega}). \quad (7)$$

Step 5. In this step, the optimal weight vector $w_1^*, \dots, w_n^*)$ would be determined. The optimal weight of the criteria is a weight that for each pair the statement comes true, all parameters of the model are defined as triangular fuzzy numbers:

$$\begin{aligned}
&\text{Min}\xi^* \\
&\text{s.t.} \quad \left|\frac{(l_B^w,\ m_B^w,\ u_B^w)}{(l_j^w,\ m_j^w,\ u_j^w)} - (l_{Bj},\ m_{Bj},\ u_{Bj})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_j^w,\ m_j^w,\ u_j^w)}{(l_W^w,\ m_W^w,\ u_W^w)} - (l_{jw},\ m_{jw},\ u_{jw})\right| \le \ k^*,\ k^*,\ k^*), \\
&\textstyle\sum_j R(\widetilde{\omega}_j) = 1, \\
&l_j^w \le m_j^w \le u_j^w, \\
&l_j^w \ge 0, \qquad j = 1, \dots, n.
\end{aligned} \quad (8)$$

Using $\xi^* = \ k^*,\ k^*,\ k^*)$ as the compatibility ratio, the compatibility would increase by higher amount of ξ^* and comparisons would be more reliable.

4 | Methodology

This study is practical and descriptive-surveying research from goal and research methodology perspectives. The experts' group includes 11 experts in the welding and cutting industry. The enablers have been adopted and identified through an extensive study on "supply chain" and "distribution network" literature. The fuzzy BWM is used to prioritize the distribution network enablers. The fuzzy BWM is a modern method in multi-criteria decision-making that is a suitable alternative for pairwise comparison-based methods.

This method has specifications such as the reduced number of pairwise comparisons and higher reliability in the results [28].

The current study is divided into two parts. The appropriate enablers were retrieved in the first half through an in-depth review of the subject literature. The expertise of specialists was employed to screen and rank the enablers. The Lawshe questionnaire was used as a research tool in this step, and expert members were asked to rate the components' necessity and relevance. The Lawshe technique was used to confirm the questionnaire's content validity and reliability. The best-worst method was employed as one of the novel multi-indicator decision-making techniques in the final part of the research to weight the components. To create the questionnaire, the best and worst fuzzy criteria were selected first, followed by the most important and least important criteria. Experts then made pairwise comparisons of criteria. Lingo software was used to analyze the data of this part and solve the model.

5 | Results

Defining the evaluation criteria of distribution network enablers

The most important step is identifying the influencing criteria for selecting and prioritizing. The influencing criteria on a distribution network have been identified and extracted by reviewing similar studies and available data. In this step, the content validity analysis questionnaire has been given to experts to reduce the number of criteria. To reduce the uncertainty, the quantitative Lawshe method is used. The results of the data analysis are presented in *Table 3*.

Table 3. The distribution network enablers.

Features	Reference	CVR	Features	Reference	CVR
Trust	[29]-[31]	0.52	Speed and agility	[31], [50]-[55]	0.55
EN_1 responsibility	[32]	0.78	Planning	[30], [56]	0.58
Performance	[32]	0.48	Stakeholders' role	[57]-[59]	0.51
EN_2 flexibility	[32]-[37]	0.82	Employees' ability	[44]	0.55
EN_3 coordination	[32]	0.91	Fund	[34], [58]	0.55
EN_4 information flow	[32]	0.91	Innovation	[39], [43], [46], [60]-[62]	0.55
Motivation	[32]	0.55	Employees' sufficiency	[44]	0.52
Customers' services	[33]-[34], [38]-[43]	0.58	EN_7 logistic infrastructures	[45]	0.67
EN_5 inventory management	[44]	0.91	EN_8 on-time delivery	[45]	0.97
Customer satisfaction	[32], [46]-[47]	0.58	Commercial infrastructure quality	[45]	0.45
EN_6 transportation	[37], [48]-[49]	0.91	EN_9 product tracking	[45]	0.72
Quality management	[35], [44]	0.50	Coordinating with the policy of the organization	[44]	0.48

Considering 11 number of members in experts' group, the minimum acceptable Content Validity Ratio (CVR) is 0.59. According to the results, " responsibility", "supply chain flexibility", "supply chain coordination", "information flow", "inventory management", "transportation", "logistic infrastructures", "on-time delivery", and "product tracking" are the final criteria.

Determining the best and worst criteria for evaluating the distribution network enablers

The experts have identified "on-time delivery" as the best and "logistic infrastructures" as the worst criteria, regarding the vast specification of a distribution network.

Determining the preference of the best criterion in comparison to other criteria

In this step, the experts have evaluated the preference of the best criterion in comparison to other criteria using a 5-degree fuzzy spectrum. *Table 4* shows the resulting BO matrix based on experts' ideas. To create the matrix, it is needed to calculate the mean of preference number of the best criterion in comparison to other criteria. Vector a_B indicates the preference of the best criterion B than the criterion j.

Table 4. Pairwise comparisons between the best criterion and other criteria.

EN_1	EN_2	EN_3	EN_4	EN_5	EN_6	EN_7	EN_8	EN_9	$\tilde{a}_B$	EN9
(2/3,1,1.5)	(2/3,1,1.5)	(2/3,1,1.5)	(2/3,1,1.5)	(1.5,2,2.5)	(2/3,1,1.5)	(3.5,4,4.5)	(2/3,1,1.5)	(2/3,1,1.5)		

Determining the preference of the other criteria in comparison to the worst criterion

The experts determine the preference of the other criteria in comparison to the worst criterion. The OW matrix is presented in *Table 5* based on experts' ideas. To create the OW matrix, it is needed to calculate the mean of preference number of the other criteria in comparison to the worst criterion. Vector a_W indicates the preference of the criteria than the worst criterion$W$.

Table 5. Pairwise comparisons between other criteria and the worst criterion.

	EN7
EN_1	(3.5,4,4.5)
EN_2	(3.5,4,4.5)
EN_3	(3.5,4,4.5)
EN_4	(3.5,4,4.5)
EN_5	(3.5,4,4.5)
EN_6	(3.5,4,4.5)
EN_7	(1,1,1)
EN_8	(3.5,4,4.5)
EN_9	(2.5,3,3.5)

Calculating the optimal criteria weight

A linear programming *Model (8)* is presented based on BO and OW vectors:

$$
\begin{aligned}
&\text{Min } \xi \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_1^w,\ m_1^w,\ u_1^w)} - (l_{81},\ m_{81},\ u_{81})\right| \le\ k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_2^w,\ m_2^w,\ u_2^w)} - (l_{82},\ m_{82},\ u_{82})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_3^w,\ m_3^w,\ u_3^w)} - (l_{83},\ m_{83},\ u_{83})\right| \le\ k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_4^w,\ m_4^w,\ u_4^w)} - (l_{84},\ m_{84},\ u_{84})\right| \le\ k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_5^w,\ m_5^w,\ u_5^w)} - (l_{85},\ m_{85},\ u_{85})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_6^w,\ m_6^w,\ u_6^w)} - (l_{86},\ m_{86},\ u_{86})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{87},\ m_{87},\ u_{87})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_8^w,\ m_8^w,\ u_8^w)} - (l_{88},\ m_{88},\ u_{88})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_9^w,\ m_9^w,\ u_9^w)} - (l_{89},\ m_{89},\ u_{89})\right| \le (k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_{f1}^w,\ m_1^w,\ u_1^w)}{(l_7^w,\ m_7^w,\ u_{f7}^w)} - (l_{17},\ m_{17},\ u_{17})\right| \le\ k^*,\ k^*,\ k^*), \\
&\left|\frac{l_2^w,\ m_2^w,\ u_2^w)}{(l_7^w,\ m_7^w,\ u_7^w)} -\ l_{27},\ m_{27},\ u_{27}\right| \le\ k^*,\ k^*,\ k^*), \\
&\left|\frac{(l_4^w,\ m_4^w,\ u_4^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{47},\ m_{47},\ u_{47})\right| \le\ k^*,\ k^*,\ k^*),
\end{aligned}
\tag{9}
$$

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$$
\begin{aligned}
&\left|\frac{l_5^w,\ m_5^w,\ u_5^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - l_{57},\ m_{57},\ u_{57})\right| \leq\ k^*,\ k^*,\ k^*),\\
&\left|\frac{(l_6^w,\ m_6^w,\ u_6^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{67},\ m_{67},\ u_{67})\right| \leq\ k^*,\ k^*,\ k^*),\\
&\left|\frac{(l_7^w,\ m_7^w,\ u_7^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{77},\ m_{77},\ u_{77})\right| \leq\ k^*,\ k^*,\ k^*),\\
&\left|\frac{(l_8^w,\ m_8^w,\ u_8^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{87},\ m_{87},\ u_{87})\right| \leq\ k^*,\ k^*,\ k^*),\\
&\left|\frac{(l_9^w,\ m_9^w,\ u_9^w)}{(l_7^w,\ m_7^w,\ u_7^w)} - (l_{97},\ m_{97},\ u_{97})\right| \leq\ k^*,\ k^*,\ k^*),\\
&\textstyle\sum_{j=1}^{9} R(\widetilde{\omega}_j) = 1,\\
&l_{fj}^w \leq m_{fj}^w \leq u_{fj}^w, \qquad l_{fj}^w \geq 0,\ \ j = 1, \dots, 9.
\end{aligned}
$$

$\xi^* = (l^{\xi}, m^{\xi}, u^{\xi})$ and $R(\omega_j^{\sim})$ indicate the defuzzied of $\omega_j^{\sim}$ which could be determined according to *Eq. (6)*. The optimal fuzzy weight could be calculated by using the presented mathematical model by Guo and Zhao [27]. By applying fuzzy comparisons in mathematical *Model (8)*, the mathematical *Model (9)* would be developed:

$$
\begin{aligned}
&\text{Min } k^*\\
&l_8 - 2/3 \times u_1 - u_1 \times k \leq 0,\ l_8 - 2/3 \times u_1 + u_1 \times k \geq 0,\ m_8 - 1 \times m_1 - m_1 \times k \leq 0,\\
&m_8 - 1 \times m_1 + m_1 \times k \geq 0,\ u_8 - 1.5 \times l_1 - l_1 \times k \leq 0,\ u_8 - 1.5 \times l_1 + l_1 \times k \geq 0,\\
&l_8 - 2/3 \times u_2 - u_2 \times k \leq 0,\ l_8 - 2/3 \times u_2 + u_2 \times k \geq 0,\ m_8 - 1 \times m_2 - m_2 \times k \leq 0,\\
&m_8 - 1 \times m_2 + m_2 \times e \geq 0,\ u_8 - 1.5 \times l_2 - l_2 \times k \leq 0,\ u_8 - 1.5 \times l_2 + l_2 \times k \geq 0,\\
&l_8 - 2/3 \times u_3 - u_3 \times e \leq 0,\ l_8 - 2/3 \times u_3 + u_3 \times k \geq 0,\ m_8 - 1 \times m_3 - m_3 \times k \leq 0,\\
&m_8 - 1 \times m_3 + m_3 \times k \geq 0,\ u_8 - 1.5 \times l_3 - l_3 \times k \leq 0,\ u_8 - 1.5 \times l_3 + l_3 \times k \geq 0,\\
&l_8 - 2/3 \times u_4 - u_4 \times k \leq 0,\ l_8 - 2/3 \times u_4 + u_4 \times k \geq 0,\ m_8 - 1 \times m_4 - m_4 \times k \leq 0,\\
&m_8 - 1 \times m_4 + m_4 \times k \geq 0,\ u_8 - 1.5 \times l_4 - l_4 \times k \leq 0,\ u_8 - 1.5 \times l_4 + l_4 \times k \geq 0,\\
&l_8 - 1.5 \times u_5 - u_5 \times k \leq 0,\ l_8 - 1.5 \times u_5 + u_5 \times k \geq 0,\ m_8 - 2 \times m_5 - m_5 \times k \leq 0,\\
&m_8 - 2 \times m_5 + m_5 \times k \geq 0,\ u_8 - 2.5 \times l_5 - l_5 \times k \leq 0,\ u_8 - 2.5 \times l_5 + l_5 \times k \geq 0,\\
&l_8 - 2/3 \times u_6 - u_6 \times k \leq 0,\ l_8 - 2/3 \times u_6 + u_6 \times k \geq 0,\ m_8 - 1 \times m_6 - m_6 \times k \leq 0,\\
&m_8 - 1 \times m_6 + m_6 \times k \geq 0,\ u_8 - 1.5 \times l_6 - l_6 \times k \leq 0,\ u_8 - 1.5 \times l_6 + l_6 \times k \geq 0,\\
&l_8 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_8 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_8 - 4 \times m_7 - m_7 \times k \leq 0,\\
&m_8 - 4 \times m_7 + m_7 \times k \geq 0,\ u_8 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_8 - 4.5 \times l_7 + l_7 \times k \geq 0,\\
&l_8 - 2/3 \times u_9 - u_9 \times k \leq 0,\ l_8 - 2/3 \times u_9 + u_9 \times k \geq 0,\ m_8 - 1 \times m_9 - m_9 \times k \leq 0,\\
&m_8 - 1 \times m_9 + m_9 \times k \geq 0,\ u_8 - 1.5 \times l_9 - l_9 \times k \leq 0,\ u_8 - 1.5 \times l_9 + l_9 \times k \geq 0,\\
&l_1 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_1 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_1 - 4 \times m_7 - m_7 \times k \leq 0,\\
&m_1 - 4 \times m_7 + m_7 \times k \geq 0,\ u_1 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_1 - 4.5 \times l_7 + l_7 \times k \geq 0,\\
&l_2 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_2 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_2 - 4 \times m_7 - m_7 \times k \leq 0,\\
&m_2 - 4 \times m_7 + m_7 \times k \geq 0,\ u_2 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_2 - 4.5 \times l_7 + l_7 \times k \geq 0,\\
&l_3 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_3 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_3 - 4 \times m_7 - m_7 \times k \leq 0,\\
&m_3 - 4 \times m_7 + m_7 \times k \geq 0,\ u_3 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_3 - 4.5 \times l_7 + l_7 \times k \geq 0,\\
&l_4 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_4 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_4 - 4 \times m_7 - m_7 \times k \leq 0,\\
&m_4 - 4 \times m_7 + m_7 \times k \geq 0,\ u_4 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_4 - 4.5 \times l_7 + l_7 \times k \geq 0,\\
&l_5 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_5 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_5 - 4 \times m_7 - m_7 \times k \leq 0,
\end{aligned}
\tag{9}
$$

$m_5 - 4 \times m_7 + m_7 \times k \geq 0,\ u_5 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_5 - 45 \times l_7 + l_7 \times k \geq 0,$
$l_6 - 3.5 \times u_7 - u_7 \times k \leq 0,\ l_6 - 3.5 \times u_7 + u_7 \times k \geq 0,\ m_6 - 4 \times m_7 - m_7 \times k \leq 0,$
$m_6 - 4 \times m_7 + m_7 \times k \geq 0,\ u_6 - 4.5 \times l_7 - l_7 \times k \leq 0,\ u_6 - 4.5 \times l_7 + l_7 \times k \geq 0,$
$l_9 - 2.5 \times u_7 - u_7 \times k \leq 0,\ l_9 - 2.5 \times u_7 + u_7 \times k \geq 0,\ m_9 - 3 \times m_7 - m_7 \times k \leq 0,$
$m_9 - 3 \times m_7 + m_7 \times k \geq 0,\ u_9 - 3.5 \times l_7 - l_7 \times k \leq 0,\ u_9 - 3.5 \times l_7 + l_7 \times k \geq 0,$
$l_1 \leq m_1 \leq u_1,$
$l_2 \leq m_2 \leq u_2,\ l_3 \leq m_3 \leq u_3,\ l_4 \leq m_4 \leq u_4,\ l_5 \leq m_5 \leq u_5,\ l_6 \leq m_6 \leq u_6, l_7 \leq m_7 \leq u_7,$
$l_8 \leq m_8 \leq u_8,\ l_9 \leq m_9 \leq u_9,$

$\frac{1}{6} \times (l_1 + 4 \times m_1 + u_1) + 1/6 \times (l_2 + 4 \times m_2 + u_2) + 1/6 \times (l_3 + 4 \times m_3 + u_3) +$

$\frac{1}{6} \times (l_{f4} + 4 \times m_{f4} + u_{f4}) + \frac{1}{6} \times\ l_{f5} + 4 \times m_{f5} + u_{f5}) + 1/6 \times (l_{f6} + 4 \times m_{f6} + u_{f6}) +$

$1/6 \times (l_{f7} + 4 \times m_{f7} + u_{f7}) + \frac{1}{6} \times\ l_{f8} + 4 \times m_{f8} + u_{f8}) + \frac{1}{6} \times\ l_{f9} + 4 \times m_{f9} + u_{f9}) = 1,$

$l_1 \geq 0, l_2 \geq 0,\ l_3 \geq 0, l_4 \geq 0l,\ l_5 \geq 0, l_6 \geq 0l, l_7 \geq 0, l_8 \geq 0l,\ l_9 \geq 0,\ k \geq 0.$

Table 6. The optimal weights of criteria for evaluating the distribution network enablers based on fuzzy BWM.

Enablers	Wj*
EN_1 responsibility	ω*1 =(0.09045471, 0.1064450, 0.1224353) = 0.106445003
EN_2 flexibility	ω*2 =(0.09045471, 0.1064450, 0.1224353) = 0.106445003
EN_3 coordination	ω*3 =(0.09045471. 0.1064450, 0.1224353)= 0.106445003
EN_4 information flow	ω*4 =(0.09045471, 0.1064450, 0.1224353) = 0.106445003
EN_5 inventory management	ω*5 =(0.09045471, 0.1064450, 0.1224353) = 0.1117751
EN_6 transportation	ω*6 =(0.09045471. 0.1064450, 0.1224353)= 0.106445003
EN_7 logistic infrastructures	ω*7 =(0.03198057, 0.03198057, 0.03198057) = 0.03198057
EN_8 on-time delivery	ω*8 =(0.1014287, 0.1414044, 0.1653898) = 0.1360743
EN_9 product tracking	ω*9 =(0.07616132, 0.08459363, 0.09045471) = 0.083736553
ξ*= (0.6715729, 0.6715729, 0.6715729), CI=8.0, CR= 0.6715729/8.04= 0.08352897	

Computing the compatibility ratio is an important criterion to check the compatibility of pairwise comparisons in fuzzy BWM. Regarding to the a_{BW} = (3.5,4,4.5) interval, the compatibility ratio has been calculated equal to 0.084 which indicate a high compatibility in comparisons. The results of prioritizing of criteria by experts is presented in *Table 6* and *Fig. 1*. The most important identified enablers in a distribution network are "on-time delivery", "inventory management", "transportation", "information flow", "coordination", "flexibility", "responsibility", product tracking", and "logistic infrastructure", respectively.

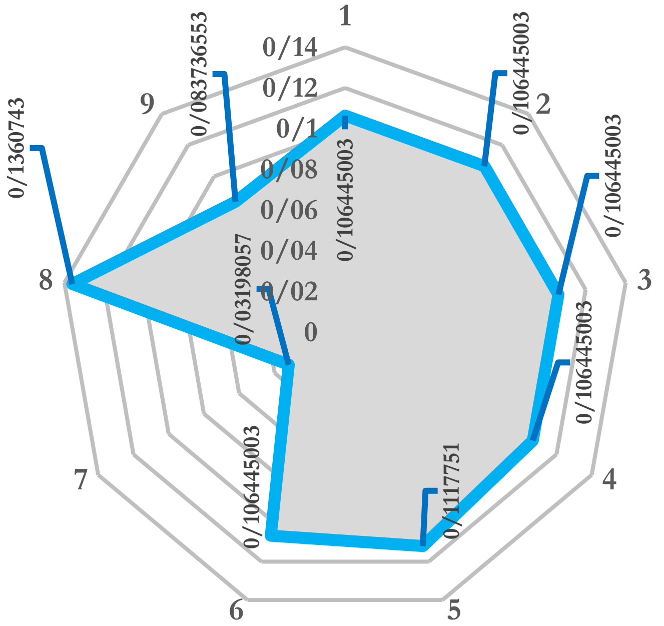

Fig. 1. The Radar (spider) chart of prioritizing of the distribution network enablers.

Fig. 1 shows how distribution network enablers are prioritized. Each axis in the diagram represents an enabler whose priority has been determined by experts. As can be observed, the highest priority is associated with the eighth enabler, while the lowest priority is associated with the seventh enabler. The total priority can be determined based on the area filled by each enabler.

6 | Discussion

The current study investigated the significance of effective distribution network enablers. A broad study of the research literature yielded nine enablers. The enablers were then weighted and prioritized using the fuzzy BWM approach. The BWM method's findings also show that "on-time delivery" is the most important factor in the distribution network. In Iran, the aspect of "transport infrastructure facilities" is less important.

According to the analysis, the optimum option in the distribution network is "on-time delivery," which weights 0.1360743. Compliance with customer-oriented needs is the primary condition of stability in today's non-monopoly and competitive market. Customers will be dissatisfied, and additional expenditures will be incurred if products are not delivered on time. As a result, project delays and proposing ways to resolve them are regarded as major issues in enterprises.

The second option is inventory management, which weights 0.1117751. Increasing attention to customer requests in the product manufacturing process and the characteristics and unavoidable expenses of manufacturing processes has driven researchers and artisans to manage orders and select the best inventory management policy. One of the most significant strategic decisions in the manufacturing process is the optimal inventory management policy.

The third solution, with a weight of 0.106445003, is the enablers of "responsiveness, flexibility, coordination, information flow, and transportation". SCM is one way to respond to long-term relationships. Because of the changing competitive environment, organizations are turning to lean and agile supply chain concepts to increase efficiency and responsiveness. The rapid changes and dynamics of the environment, changes in how companies interact with suppliers and customers, the complexity of markets, the shortening of product life cycles, and the importance of finding the time to respond to customers have doubled the importance of supply chain flexibility as a critical factor for an organization's competitiveness. As a result, flexibility has become one of the most useful and necessary tools in today's competitive and uncertain environments. Many studies in the last decade have focused on supply chain

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coordination to align the policies of chain members and use the maximum possible profit for the supply chain. Various mechanisms can be used to achieve coordination, with contracts being one of the most important. The information flow in the supply chain, along with the flow of goods and the flow of finance, are the main arteries of a supply chain, and the information flow is especially important in the meantime because it provides a suitable platform for creating a uniform flow of goods and financial exchanges. As a result, one of the most important aspects of efficient SCM is properly controlling information flow. The goal of the transportation network is to meet customer demands at the minimum cost, which necessitates an integrated approach in the fields of supply chain planning, distribution management, and product production planning based on capacity constraints considering various transportation parameters.

The fourth option is the "goods tracking" enabler, which weights 0.083736553. Today, blockchain technology is a new and growing technology that offers product transparency, traceability, and data security.

Finally, transportation infrastructure is known as a last-place option based on the country's situation. Building necessary facilities to support the national economy has received special attention. The availability of sufficient infrastructure, the establishment of limited and enclosed specialized functions, and the removal of the hurdles these regions are now encountering are prerequisites for the successful operation of these areas. The efficient utilization of transportation infrastructure facilities will surely expand the transportation industry and the country's economic development.

7 | Conclusions

The distribution network is influenced by many enablers, considering its importance and its activities at local, national, and international levels. Therefore, the distribution network should be properly planned and coordinated such that servicing to customers would not stop. The distribution network which is able to provide optimal services would gain a rapid growth in demand. Thus, the required facilities for providing services in a distribution network should be established. Managers and staff of a distribution network should be trained to provide services to final customers.

This research was carried out by using the fuzzy BWM to prioritize the distribution network enablers. The results indicate that the most important enablers in a distribution network are "on-time delivery", "inventory management", "transportation", "information flow", "coordination", "flexibility", "responsibility", product tracking", and "logistic infrastructure", respectively.

According to the results, the most important factor is "on-time delivery", so it is suggested that industry owners improve the process of "on-time delivery" as much as possible. The results of this study are correspondent to the results of the other studies in introducing the strategic requirement of organizations in "on-time delivery" as a competitive priority.

Determining optimal inventory policies has always been a challenge in inventory management. Nowadays, traditional inventory management has been replaced by "production management", "distribution" and "inventory" as the SCM system. Deploying mathematical tools in modeling and controlling the inventory management problem would be so useful.

The transportation section is one of the infrastructural sections of all countries, which its activities influence the economic development process of a country. As a result, the conditions of this factor and succeeding in that are important criteria of the development level and are determining factors in changing process of a distribution network.

Organizations should try to integrate their processes by adopting and implementing information systems technologies. The distribution network must manage the whole network from supplier to end customer to achieve the best output of the system. The goal is to communicate mutually between products and information of different memberships of the supply chain by doing managerial and operational activities.

Cooperation between the flexibility processes in a supply chain has an impact on agility and production flexibility is an important reference for chain agility. Flexibility does not directly guarantee cost productivity. But flexible production and agility through product variety management strategy influence significantly customers services.

Network responsibility influences the performance of a network. Responsibility and efficiency are the two main aspects of customers' expectations. Thus, determining the required responsibility level for the supply chain to design its suitable supply chain, is very useful. The results of this approach could be a reliable platform to develop the supply chain strategies in different fields such as inventory, transportation, locating, and information flow.

The supply chain can operate in an integrated way, if coordinated and accurate information of product status is in reach for all partners of the chain and every partner can receive this information and track their product whenever he needs.

The increase in transportation demand would bring difficulties in the transportation network. Focusing on the role of physical infrastructures in reducing transportation problems, supply chain security and proper responding are very important.

Also, the following suggestions are given for future studies:

I. The proposed enablers are theoretical. It is recommended to evaluate the distribution network through a case study and present appropriate approaches.
II. The mutual effects of the recognized enablers on each other have not been studied; therefore, it is recommended to study the mutual effect of the recognized enablers in future studies.
III. The development of distribution network enablers helps the efficiency and performance of the distribution network.
IV. For future studies, it is suggested to investigate other enablers in different industries by using different modern fuzzy methods and compare the results with this study.

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Design and Development of a Wind Turbine with Flanged Diffuser Operating in Low Wind Speed Regime

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Abstract

In this paper, the performance characteristics of a fabricated Horizontal Axis Wind Turbine (HAWT) with and without flanged diffusers were studied using wind tunnel experiment. Measurements of global parameters (power, torque, rotational speed efficiency, etc.) were carried out at wind speed regime between 3-7 m/s. Flanged diffusers of five different inlet-outlet diameter ratios were employed. The results showed minimum mean increments in Tip-Speed Ratios (TSRs) of about 45% with the smallest diffuser and a maximum of 80% with the largest diffuser. Increments in the torque even at modest wind speed of 4 m/s were as much as 65, 70 and 76% for the largest three diffusers and about 33% for the smaller diffuser. The power output (with and without diffuser) gradually increased from 3-7 m/s wind speed, while the power coefficient (Cp) increased from 3-5.5 m/s, and thereafter began to fluctuate as the wind speed approached 7 m/s. Comparatively, maximum C_p of the turbine without diffuser was 0.22 for $\lambda = 0.534$ at a wind speed of 7 m/s, while the maximum average value of C_p for turbine with flanged diffuser 3 was 0.34 for $\lambda = 0.706$ at the same wind speed. As a result of the flanged diffuser attachment, the maximum C_p increased by 36%. The results showed mean incremental values of 52 and 57% with the greater value obtained from the second largest diffuser (Di/Do = 0.70) and the least value from the largest diffuser (Di/Do = 0.80), while the first three diffusers achieved near identical increments of 55%. This consequently implies that increments in the extracted power (i.e., C_p) above 5 m/s wind speed declined with indications of separation and turbulence in the flows beyond the rotor.

Keywords: Model, Fabrication, Horizontal, Wind turbine, Flanged diffusers, Power output and power coefficient.

1 | Introduction

The improvement and availability of renewable, clean energy has become an area of great interest in recent time, due to the deleterious serious effects of global warming and rapid depletion of fossil fuels. In order to address the current energy crisis various means of alternative energy have been evaluated in a number of literature, hence, wind energy technologies are one of the most firmly promising energy sources in the world and it symbolizes a feasible alternative, as it is a virtually endless resource. However, in comparison with the overall demand for energy, the scale of wind power usage is still very meager [1], [2]. Wind energy is the World's fastest-growing energy source that can power homes, businesses and industry with clean, renewable electricity for future benefits.

Interestingly, people are also realizing that wind power is one of the most promising new energy sources that can serve as an alternative to fossil fuel-generated electricity.

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As population of Nigeria increases and people strive for a higher standard of living, the amount of energy required to sustain the society is on the increase. On the other hand, the availability of renewable energy sources, particularly liquid fuels, is rapidly depleting. Among the various means of renewable energy, wind energy technologies have developed rapidly, and has played a vital role in the field of renewable energy. However, in comparison with the overall demand for energy, the scale of wind power utilization is still very small; especially the level of development in Nigeria, as government and private organization pay little or no attention to wind power generation [3].

To this effect, various causes are conceived such as: limited local area suitable for wind power plants, low wind speed regimes, the complex terrain environment compared to those in European or North American Countries as well as turbulent nature of the local wind. Hence, the introduction of new wind power system that produces higher power output even in areas with lower wind speed regime, and complex wind patterns expected is strongly desired. Therefore, ways for a large increase in output should be employed, if possible, to create a slight increase in the velocity of the approaching wind to a wind turbine. Therefore, if the wind speed can be increase by utilizing the fluid dynamics concept around a structure or topography, or if the wind flow is concentrate within a particular axis, then the power output of a wind turbine can be increased substantially [4], [5]. Researches have shown that there are two parameters that affect the value of the power output in a wind turbine, which are: the swept area of the blades and the wind speed. Therefore, one of these parameters can be increased by incorporating a flange diffuser at the exit of the wind tunnel. Shahsavarifard et al. [6] understudied a work on Diffuser Augmented Wind Turbine (DAWT), which focuses on concentrating wind energy in a diffuser with a large open angle and boundary layer control with several flow slots to realize a flow that goes along the inside surface of the diffuser. Abe and Ohya [7] investigated the flow fields around flanged diffusers to develop small type wind turbines using Computational Fluid Dynamics (CFDs). Results showed that the performance of a flanged diffuser strongly depended on the loading coefficient as well as the opening angle because it greatly affected the nature of the separation appearing inside the diffuser. Researchers evaluating the effects of flange diffusers on wind turbines revealed that loading coefficient for the best performance of a flanged diffuser was considerably smaller than that for a wind turbine without flange diffuser. It also showed that the flanged diffuser significantly increased the power and torque outputs, and rotational speed of the turbine [7], [9]. Abe et al. [10] also carried out experimental and numerical investigation of flow fields behind a small wind turbine with a flanged diffuser. Results showed that the power coefficient of the shrouded wind turbine was about four times that of the wind turbine without flanged-diffuser. Ohya et al. [11] examined the optimum form of the flanged diffuser, and demonstrated that power augmentation by a factor of about four to five is possible, compared to wind turbine with no flanged diffuser. Although the majority of the diffuser developments were done for the Horizontal-Axis Wind Turbines (HAWT), there are few works that focused on diffuser design for Vertical-Axis Wind Turbine (VAWT) applications. Takahashi et al. [12] studied the behavior of rotor blade tip vortices of a wind turbine equipped with a brimmed-diffuser shroud. Ohya [13] proposed the use of control plates attached to the body of a diffuser to create a more structured vortex flow. Based on a study on rectangular bodies, it was observed that flow around the controlled plates created a stronger vortex shedding.

Matsushima et al. [14] studied the effect of diffusers' shape on wind speed. They observed that the wind speed in diffuser without a flange in comparison to that of Abe et al. [10] was greatly influenced by the length and expansion angle of the diffuser, while the maximum wind speed increased 1.7 times with appropriate diffuser shape.

For wind power generation, particularly in Nigeria, low wind speed prevalence in majority of locations in the country is a major limitation. While the average wind speed at a potential wind farm site is critical, wind energy is, in general, a very diffuse energy. This is due to the low density of air as compared to, for example, water, which is 800 times denser. Therefore, the development of a wind power system with moderately sufficient output in low wind speed regimes and even at low cost for effective harnessing of wind energy, through a flanged-diffuser becomes necessary.

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This works is aimed at designing a wind turbine with flange diffusers in order to study the performance characteristics (global parameters) of a wind turbine operating in low wind speed regime, with and without a mounted flanged-diffuser on its downstream side. In other words, a wind turbine designed with flanged diffuser operating in low wind speed regime is considered, for appraising the performance characteristics of global parameter of a wind turbine with and without a flanged diffuser. The objectives are to: measure the basic parameters of wind speed, torque and rotational speed of the wind turbines in controlled experiment with and/or without a flanged-diffuser; compute other parameters like power output, power coefficient and the Tip-Speed Ratio (TSR) from the basic data; measure wake velocities just behind the rotor and at the tip of the flange of the diffuser as a data base for future CFD studies; and to compare the obtained results for the wind turbine without the diffuser with those for the turbine with the diffuser. The principles behind incorporating a flanged-diffuser to a wind turbine is to act as an accelerator, i.e., increase the extracted power output by increasing the mass flow of the wind velocity that approaches the wind turbine. Therefore, the introduction of a novel wind power system that can produce higher power output even in areas where lower wind speed is expected was successfully achieved, vis-à-vis, enhanced the power and torque coefficients, thus, other parameters accordingly. Lastly, an understanding of the performance characteristics of the power output augmentation gives a more effective and efficient design of a wind turbine and flanged diffusers.

This work is restricted to uniform, steady and parallel flow conditions. Furthermore, emphasis is put on measurements in controlled conditions. Focus was to design and fabricate a model wind turbine, and use it to carry out an experiment in order to evaluate and compare the performance characteristic of global parameters of the wind turbine with diffusers of different dimensional configurations, tested at a small sub-sonic wind tunnel. The scope also includes measurement of electrical power output along the control axis of the hollow-structure and wake velocity at the flange of the diffuser for feature simulation analysis. Areas not covered in this work include wake analysis, vortex expansion, flow pattern, rotor-tower interaction.

2 | Materials and Methods

2.1 | Materials for the Flanged-Diffuser Development

These were designed and fabricated from metal sheet (1.0 mm gauge); Iron rods (10 mm)/ binding wires; M10 bolt and nut/washers; 4 sets of metal Iron rod of 1000 mm high with adjustable groove etc. For this work, the five flanged-diffuser inlet-to-outlet diameter ratios, Ai/Ao used were 0.50, 0.57, 0.66, 0.72, and 0.80. This is within the tolerance limit (0.50 to 0.80 specified by Lipian et al. [16]. The Airfoil NACA 4415 was used in this work. The airfoil model was made from a polyethylene material with a chord length of 165.0 mm and with a span of 10.0 mm.

2.2 | Methods for Developing the Wind Turbine with Flanged Diffuser

A comprehensive review of literature of past researchers work on wind turbine with diffuser was thoroughly examined. A small model wind turbine coupled with a dynamo and flanged diffusers was developed. The NACA 4415 airfoil cross-section was adopted for the blades which were made of high-density polyethylene materials which were machined to the blade geometry.

The experiments were conducted using analogue PLINT & Partners Subsonic wind tunnel machine (see, *Fig. 1*), carried out at the exit area of the wind tunnel, with a measurements section of 0.487 m by 0.487 m (width) × 0.95 m (height); center-line (reference point) from ground level, with a maximum wind velocity of 30 m/s. In this study, the wind turbine and the flanged diffuser is located 700 mm downstream of the wind tunnel exit. The wind tunnel exit diameter was taken as a reference point during the design stages, such that the diffuser inlet diameter was less than the tunnel exit geometry while the turbine rotor and swept area fed into the diffuser inlet area.

Fig. 1. Analogue PLINT & partners subsonic wind tunnel machine.

The wind turbine was three blade rotor with a diameter of 390.8 mm. The blade was designed with the aid of a design theory by Schubel and Crossley [15]. Other instruments/equipment include: a digital TSI AINOR Airflow hot wire anemometer which has a measuring range of 0 to 30 m/s, sensitivity of 0.01 m/s and accuracy of ±3%; a compact Digital Stroboscope with a range of 1 to 30,000 rpm and a sensitivity of 0.01 rpm; a length of thread, an assortment of masses in grams, mass hanger, a weighing balance, and stop watch (all for measuring torque); a 6-Watt, 4.6-V lamp; a voltmeter and connecting cables.

2.2.1 | Design of wind turbine and flanged diffuser

In order to optimize better output performance, several features including the geometry of the diffuser and flange was attached to it, the wind turbine (shaft bearing, rotor blades, etc) were designed and constructed.

2.2.2 | Design consideration

It has been confirmed that maximum performance can be achieved when the ratio of the diffuser length to inlet diameter L/D, and flange width to inlet diameter (H/D) is between (0.25-0.75 m); as in the case of this experiment [16]. The design constraints included: the use of Kano mean wind speed from 3.0 m/s to 5.0 m/s at 10-m height and extended to 7.0 m/s for extrapolated wind speeds of up to 60-m height for the same city [17], the use of flanged diffusers of inlet to outlet diameter ratios of 0.50, 0.57, 0.66, 0.72, and 0.80.

2.2.3 | Flange diffuser fabrication

The three main features such as: the diffuser inlet; the outlet portion of a diffuser; and the flange which is an extrusion of the diffuser located at the back outer edge of the diffuser were considered separately during design in order to direct sufficient amount of air velocity into the diffuser. Sketch of a typical diffuser with flange is shown in *Fig. 2*.

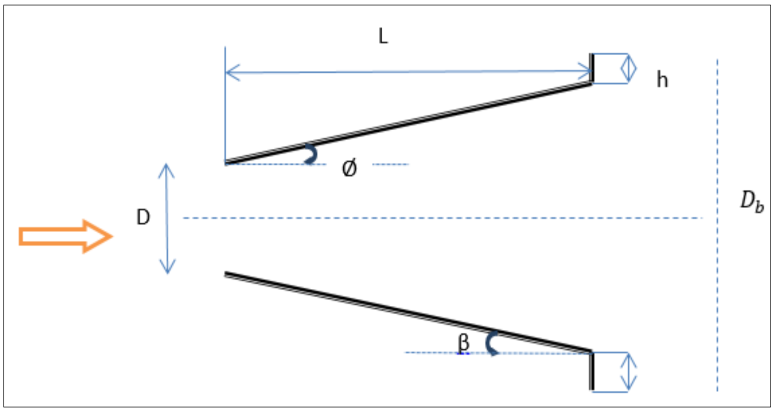

Fig. 2. A sketch of a diffuser with flange.

2.2.4 | Selection of shaft

The shaft was selected based on twisting moment or torque only. On the other hand, the torque transmitted by the shaft was calculated using *Eq. (1)* while the diameter was calculated using *Eq. (2)*.

$$T = WR. \tag{1}$$

$$T = \frac{\pi}{16} x \tau x d^3. \tag{2}$$

Considering a maximum permissible working torsional shear stress, (τ) = 42 MPa = 42 N/mm², Shaft + blade, W_R = 0.1219 kg; Mass of bearing = 0.10562 kg.

Total weight of bearing, W_T = m x g + FS = 0.10562 x 9.81+1.5 = 2.536 N.

Where, W is the actual weight exerted on the system, R is the radius about which the weight (needed to completely stop the shaft from turning) was suspended. The bearings were selected based on ability to withstand momentary shock loads, with accuracy of shaft alignment.

2.2.5 | Design of rotor blade

The three-bladed rotor model were made from High density thermoplastic (polyethylene) material of petroleum product for the purpose of high impact/good tensile strength; which can withstand temperatures up to (120℃/248°F for short periods, 110℃/230°F continuously); as well as reducing industrial noise. The blade tip clearance ratio was less than the inlet diameter of the diffuser. The Airfoil NACA 4415 was adopted because its profile was easily accessible, with a chord length of 165.0mm and spans 10.0mm, tapered at 66.0mm. The cross section was drawn to scale on a graph paper and then machined with the designed dimensions. The rotor assembly was mounted on a stand with respect to the required height. The stand was designed with a round heavy-hollow pipe cast steel in order to withstand axial load without buckling.

2.2.6 | Experimental procedures

The rotor, shaft, and the dynamo were supported by a single stand with a two-ball bearing system mounted on it, to allow for a low frictional rotation of the shaft. The arrangement was then placed at the exit of the wind tunnel to receive the incoming wind. The instruments were positioned at the right places for measurements, and the wind tunnel was powered and the air through it was varied by adjusting the screw to open the butterfly valve at the entrance. At each setting speed, the on-coming wind speed, the wind speed just behind the rotor, the wind speed around the flange of the diffuser, the rotor angular speed, the prevailing temperature, and the torque produced were measured and recorded. The experiment was conducted with and without flanged diffusers for nine different variations of wind speed. The results obtained were used to gather an array of output that determined the significance of each parameter on the output. Finally, the stoppage turning point of the rotor was determined through the suspension of masses via a thread tight process at the hub of the rotating shaft axle. This placement of the mass over the rotor was used to calculate the torque transmitted by the turbine system. The wind turbine rotor model assembly is as shown in *Fig. 3*.

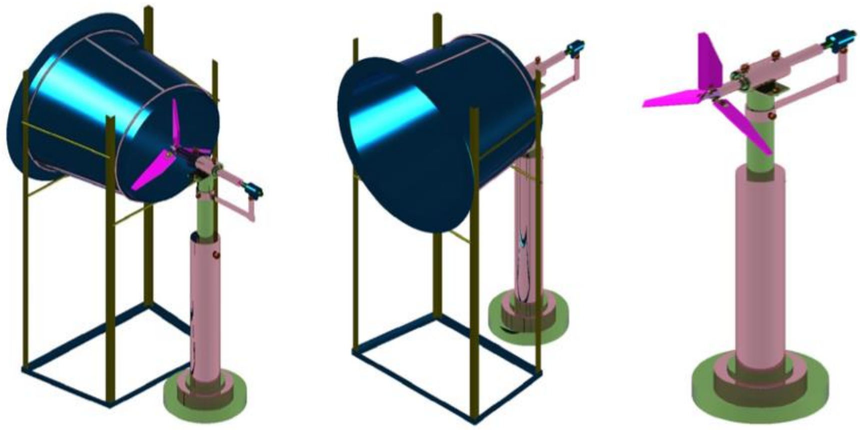

Fig. 3. Wind turbine rotor model assembly.

2.2.7 | Calculated performance parameters

The system mechanical shaft power becomes

$$P_s = \frac{2\pi NT}{60}. \quad (3)$$

From the moving fluid mass of *Eq. (3)*, the wind power is calculated using the expression in *Eq. (4)*:

$$P_w = \frac{1}{2}\rho AV^3. \quad (4)$$

The density of dry air at low pressure (1 atm) at the corresponding temperature in each wind velocities was derived from Steam Table for the computation of the extracted wind power by the rotor, using *Eq. (5)* below for the swept area, A:

$$A = \pi r^2. \quad (5)$$

The power coefficient was computed as thus [8],

$$C_P = \frac{\left(1 + \frac{V_w}{V}\right)\left(1 - \left(\frac{V_w}{V}\right)^2\right)}{2}. \quad (6)$$

Also, the turbine TSR, λ is calculated as

$$\lambda = \frac{r\omega}{U_o}. \quad (7)$$

But

$$\omega = \frac{2\pi n}{60}. \quad (8)$$

The power output extracted by the wind turbine without the flanged diffuser can be expressed as

$$P = \frac{1}{2}C_P\, \rho AU^3. \quad (9)$$

Eq. (1) to *(9)*, were then used to compute the parameters of the wind turbine with flanged diffuser.

3 | Results and Discussion

The results obtained from experimental and other calculations carried out in this study are presented and discussed in this section.

3.1 | Data Presentation

Generally, two methods are available to analyze the performance of wind turbines namely CFD, and Wind Tunnel Experiments (WTE). However, both methods are employed in some cases [8]. In this study, WTE was used. This section shows the results obtained with and without the flanged diffuser and the analysis of power output through measured and calculated values, using graphical plots. Performance of the wind turbine parameters without flanged diffuser are presented in *Table 1*.

Table 1. Measured data obtained without flanged diffuser (cut-in speed = 2.82m/s).

S/N	Wind Speed (m/s)	Electrical Power (W)	Rotational Speed (rpm)	V_w (m/s)	Mass (g)	Temperature (°C)
1	3.0	0.096	2	1.99	20	31.0
2	3.5	0.122	5	2.29	30	31.0
3	4.0	0.154	25	2.66	60	31.1
4	4.5	0.172	50	2.75	80	31.1
5	5.0	0.191	97	2.81	130	31.1
6	5.5	1.153	130	2.89	210	29.6
7	6.0	1.211	152	2.95	290	29.7
8	6.5	1.340	170	3.00	340	29.6
9	7.0	1.453	193	3.10	410	29.7

3.2 | Tip-Speed Ratio

This is the ratio of the angular speed of the rotor blades to the mean wind speed; the rotors of a wind turbine (especially used for electricity generation) need to spin fast in order to capture the wind for more energy conversion; for a three-bladed rotor, this ratio is usually greater than or equal to 1. *Fig. 4* shows the TSR of the wind turbine with and without the flanged diffuser.

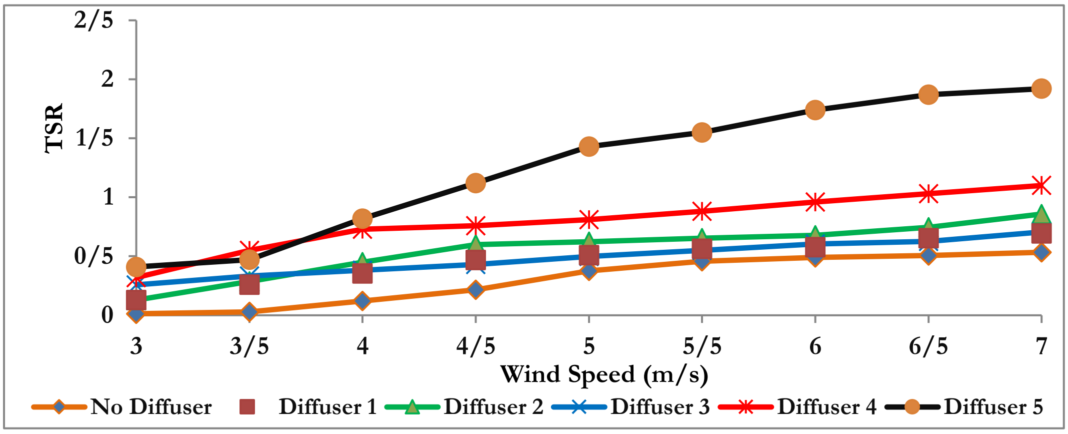

Fig. 4. TSR against wind speed for each diffuser.

This result shows improvements in the TSR with the use of the flanged diffusers; up to a wind speed of 6 m/s the TSR for the turbine without diffuser was less than 1, but with the diffusers this improved greatly, with the turbine with diffusers 4 and 5 (inlet-to outlet diameter ratios, Di/Do of 0.72 and 0.80, respectively) reaching a TSR greater than 1 even at cut-in speeds of about 3.5 m/s. The mean increments were a minimum of about 45% with the smallest diffuser (Di/Do = 0.5) and a maximum of about 80% with the largest diffuser. However, the later value is not necessarily an indicator of good performance as the rather high value may cause large amount of wind to pass through the rotors without commensurate yield in power. This is buttressed in the analysis for the power output and efficiencies shown later in this work.

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3.3 | Rotational Speed

Fig. 5 shows the results for the rotational speed obtained with and without the use of the flanged diffusers. Also, *Fig. 6* represent the results for the torque obtained with and without the use of the flanged diffusers at wind speeds ranging from 3-7 m/s.

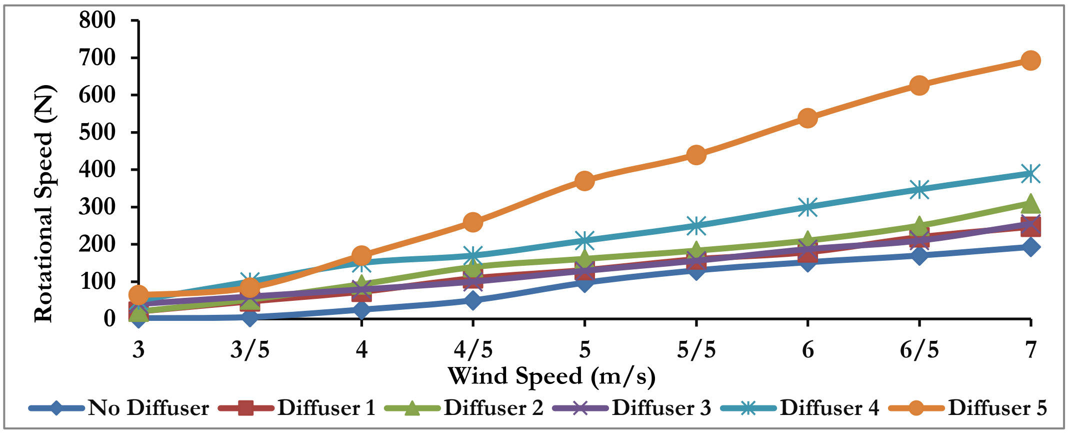

Fig. 5. Variation of rotational speed with wind speed across the diffusers.

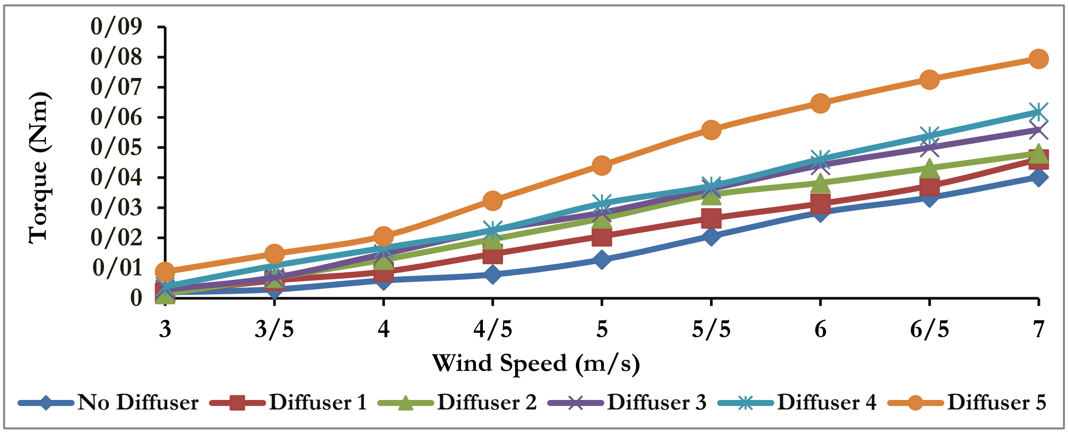

Fig. 6. Variation of torque with wind speed for each diffuser.

However, the more appreciable mean increments in torque were achieved with diffuser Di/Do ratios of and 0.60, 0.70 and 0.80 with mean increments of 46, 52 and 66%, respectively. Even at a modest wind speed of about 4.5 m/s the increments were as much as 65, 65 and 76% respectively for the later three diffusers. The results in *Fig. 6* shows that though the torque increased with increasing diffuser Di/Do ratio the lower ratios of 0.50, and 0.60, made only modest impacts on the realizable increments in torque with a mean maximum increment of about 24 and 33% respectively.

3.4 | Output Power

Results of output power obtained from the turbine with and without the flanged diffuser is shown in *Fig. 7*. The results of each model of the diffuser showed an increase in power output with wind speed which also indicated that, a wind turbine with flanged diffusers produced more power than the one without diffuser. The power increased from a wind speed of 3 m/s to a maximum wind speed of 5 m/s and declined to a minimum wind speed value of 7 m/s. The mean value of increment indicated that the increments are independent on the changing geometry (Di/Do ratio) of the diffusers, as mean increment across the speed range used for all five diffusers was between 52% and 57%. The variation was not in increasing order of the ratio, as the greater value was obtained with the second largest diffuser (Di/Do = 0.70) and the least value with the largest diffuser (Di/Do = 0.80). The first three diffusers achieved near identical mean increments of 55%. The results also showed that using flange diffuser improved the power output up to a moderate speed of 5 m/s; beyond this, the large increment in the TSR caused the wind turbine with diffuser to extract less power from the rapidly flowing wind speed. This is buttressed by the decline in the power output beyond 5 m/s wind speed.

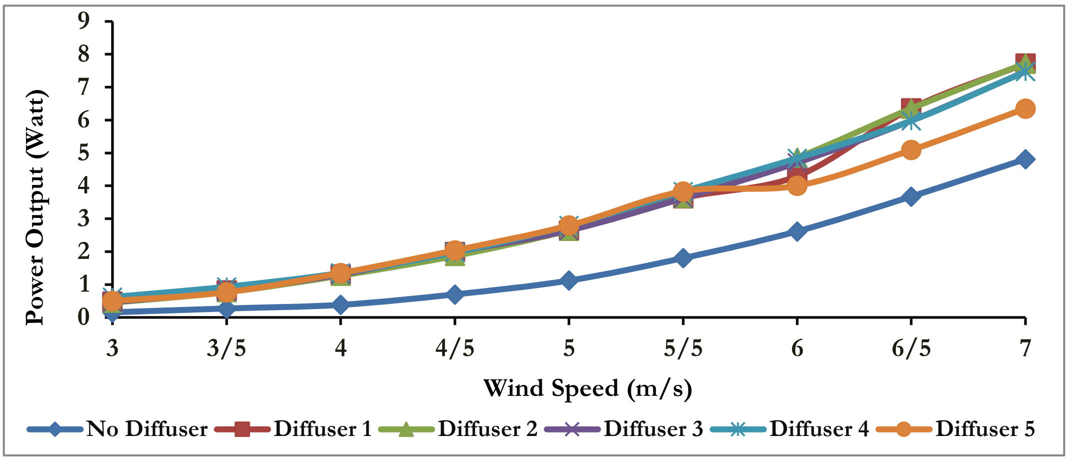

Fig. 7. Power output obtained for each diffuser.

3.5 | Power Coefficient (Cp)

The variation in power coefficient with changing wind velocity is shown in the performance curve of *Fig. 8*. The results indicated that wind turbine with flanged diffuser significantly enhanced the performance output compared to wind turbines operating without diffuser. The Figure shows that wind turbine with no diffuser had an efficiency of 0.09 within wind speed of 3.0 to 4.0 m/s, but increased to a maximum power coefficient of 0.22 at a wind speed of 7.0 m/s.

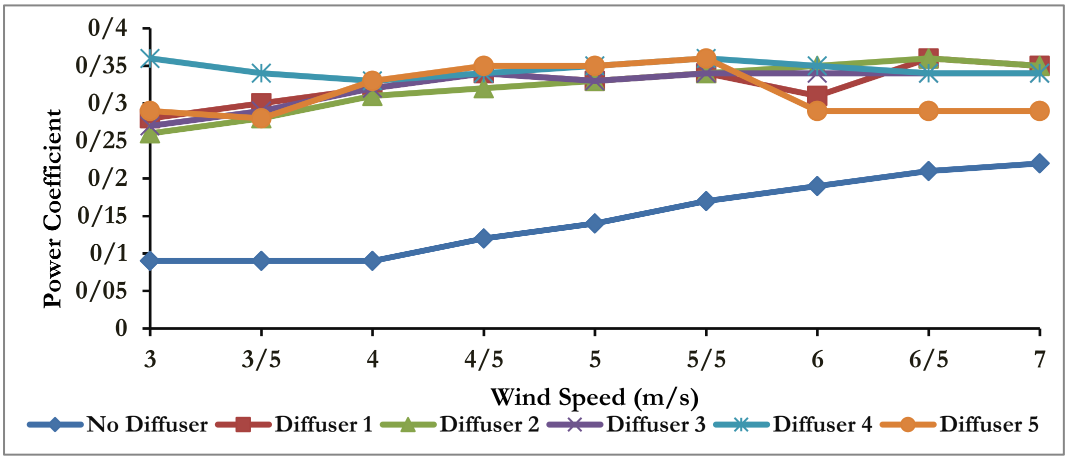

Fig. 8. Power coefficient (Cp) obtained for each diffuser.

However, there was an improvement in the efficiency of power extraction when the diffuser was introduced; the Cp increased from 0.28 to 0.35 across the speed range with the smallest diffuser; in the case of the largest diffuser this was from 0.29 to 0.36 at about 5.5 m/s wind speed and then remains constant up to the maximum wind speed of 7 m/s. This pattern is repeated for all the remaining diffusers, i.e., with the optimum efficiency occurring at about 5.5 m/s wind speed.

Comparatively, because the Cp is a function of the output power, the increments (from when the turbine is without the diffuser to when operating with the diffuser) are the same as described for the output power.

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3.6 | Velocities at the Wake and at the Periphery of the Flange of the Diffuser

In addition to using the velocities at the wake (just behind the rotor) for the computation of the Cp, together with the velocities at the periphery of the flange on the diffusers, provide basic inputs for use for future work on simulation with a CFD software for the purpose of comparison with the results of this experimental work as well as for prediction with different rotor and flanged diffuser sizes and for revealing weak areas in their wakes with a view to improving the diffuser designs. In this way too, practical real-life wind turbine (with and without flanged diffuser) performance can be predicted. The predicted results from this simulation will of course need validation by results of practical (field) measurements.

4 | Conclusion

The performance characteristics of a Horizontal Axis Wind Turbine (HAWT), with and without flanged diffusers, using WTE were studied. Measurements of the global parameters (power coefficient, power output, torque, rotational speed and TSR) with and without the flanged diffusers were made at different wind velocities. The results showed different effect each diffuser had on the power output based on the geometry of the diffuser. Though the wind speed simulated was for low (whose mean wind speed at 10.0m height is between 4.0 and 5.0 m/s), the speed range was extended up to 7.0 m/s, being about the extrapolated wind speed for the same low wind speed Region at a height of about 70 m.

The results show mean increments in the TSRs of minimum of about 45% with the smallest diffuser and a maximum of about 80% with the largest diffuser. Because the TSR is a function of the rotational speed, the results of the two are identical in the increments obtained with the use of the diffusers. As for the torque, only modest increments were obtained for the first two diffusers, with a maximum increment of about 33%. However, even at a modest wind speed of about 4.5 m/s the increments were as much as 65, 65 and 76% respectively for the later three diffusers. Lastly, both the power output and the power coefficient exhibited similar characteristics, as they both increased (with the diffuser on the turbine compared to without the diffuser) from as little a speed as 3 m/s to a maximum value of about 5m/s wind speed and thereafter declined to a minimum value of 7m/s wind speed. The mean values of increment revealed that the increments are independent on the changing geometry (Di/Do ratio) of the diffusers, as mean increment across the speed range used for all five diffusers was between 52 and 57%. The variation was not in increasing order of the ratio, as the greater value was obtained with the second largest diffuser (Di/Do = 0.70) and the least value with the largest diffuser (Di/Do = 0.80). The first three diffusers achieved near identical increments of 55%. The results also indicated that using flanged diffuser improved the power output and hence, the power coefficient up to only a moderate speed of 5 m/s. Beyond this, the large increment in the TSR caused the wind turbine with diffuser to extract less power from the rapidly flowing wind speed. This is buttressed by the decline in the power output beyond 5 m/s wind speed. Based on the analysis done so far in this investigation, the following are recommended for future studies:

I. Since improvement in power production at zones described by low wind speed can be achieved, the use of flanged diffusers may be implemented on stand-alone wind generators for small-scale businesses and rural communities in the area with low wind speed terrain, etc.
II. In this work, the lengths of the diffusers were kept constant; further studies may entail variation in both lengths and the inlet-to-outlet ratios.
III. The flanged diffuser optimization performance may be carried out with CFD in order to validate results with this experimental work, as well as reveal weak areas in the wake such as separation and turbulent flow, with a view to modifying the diffuser to mitigate these effects.
IV. A real life wind turbine may be built and tested with a flanged diffuser since the results from this work, though experimental, appears to be more ideal.

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Appendix

Table 1. Overall summary of both measured and calculated parameters without flanged diffuser.

	Measured Values				Calculated Values				
	Wind Speed (m/s)	Electrical Power (W)	Rotational Speed (rpm)	Temp. (°C)	Torque (Nm)	Mech. Power	TSR	Power Coefficient (C_P)	Power output(W)
1	3.0	0.096	2	31.0	0.00196	0.00041	0.013	0.09	0.1556
2	3.5	0.122	5	31.0	0.00294	0.0015	0.028	0.09	0.2716
3	4.0	0.154	25	31.1	0.0059	0.0154	0.121	0.09	0.3829
4	4.5	0.172	50	31.1	0.0079	0.0411	0.215	0.12	0.7006
5	5.0	0.191	97	31.1	0.0128	0.1296	0.376	0.14	1.1212
6	5.5	1.153	130	29.6	0.0206	0.2804	0.458	0.17	1.8037
7	6.0	1.211	152	29.7	0.0284	0.4529	0.491	0.19	2.6180
8	6.5	1.340	170	29.6	0.0334	0.5939	0.507	0.21	3.6778
9	7.0	1.453	193	29.7	0.0402	0.8130	0.534	0.22	4.8137

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Paper Type: Research Paper

Productivity Improvement through Ergonomics Sub-System Concern Using MCDM with Goal Programing: A Case Study

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Abstract

Productivity improvement is important for the sustainability of the business. However, before improvement it is important to measure the existing system Productivity Index (PI). In this sense, the PI of the case company has been measured by using the PO-P approach. Using this approach, the overall productivity of the case company has become 0.652 [14]. By having the performance objectives of the KPAs under ergonomics sub-system and strategic goals of the case company with the given target values, GP model has been formulated to show by how much percent does the ergonomics subsystem alone will improve the overall PI. For this, optimal (suggested) solution of PV of the performance objectives of the KPAs under the ergonomics sub-system have been obtained using excel solver. Having these values, the PI of the ergonomics sub-system became 1.492, in effect increased the overall PI from 0.652 to 0.776.

Keywords: Excel solver, Goal programming, MCDM, Sewing thread and yarn manufacturing, Suggested performance value.

1 | Introduction

Various models of Operations Research (OR)/Goal Programming (GP) have been developed to solve multi-criteria industrial problems [1]. Different methods have been developed to solve Multi Criteria Decision Making (MCDM) industrial problems [2], [3]. The study conducted by [4] have applied three MCDM methods, TOPSIS, VIKOR and COPRAS, selecting the optimal industrial investment and prioritizing industrial investment. Now a days GP, common and popular, is an important class of Multi-Criteria Decision (MCD) models widely used in engineering, management, and social sciences to analyze and solve applied problems involving decision making for conflicting objectives [5]. This decision making is influenced by objective and subjective aspects and usually for each specific situation there are various criteria which must be taken into consideration. The MCDM models are helpful to the managers to solve various problems, such as to minimize the cost of production, increase the productivity and use the available resources carefully and for healthy industrial growth [6]. There are many possible criteria arising from different fields of application but some of the most commonly arising relate at the highest level to cost, profit, time, distance,

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performance of a system, company or organizational strategy, personal preferences of the decision makers, safety consideration.

Management of companies must provide decision making processes to ensure smooth running of the company. Widely used approach for solving multi criteria decision problems is GP. In this sense the unique GP model have created by [7] for the implementation of strategic goals of the company into the business plan. As well as GP method in combination with analytical hierarchy process have applied in forest management to estimate the optimal stock level of different tree species considering environmental, economic, and social issues [8]. The study conducted by [9] have developed a new system evaluation model of MCDM with GP for Airport Ground Handling Service (AGHS) Equipment Vendor Selection (EVS) by considering both qualitative and quantitative methods which have tested the proposed approach on an AGHS company in Taiwan. On the other hand the new decision rule called target decision rule have developed by [10] as a new application area of GP which is helpful when solving uncertain problems since it is especially designed for neutral criteria, which are not taken into account in existing procedures developed for 1-DMU. The study conducted by [11] have applied three MCDM methods on a facility location selection problem and their relative ranking performances are compared. Because of disagreement in the ranks obtained by the three different MCDM methods, a final ranking method based on REGIME is also proposed to facilitate the decision-making process. Finally, the results of this study are compared by the results of the same study.

The goals in MCDM are usually conflicting so the right solution is a good compromise between all goals which are set in the company, hence compromising solution is the main idea of MCDM by using variety of methods. One of these methods is GP which is the most promising, powerful, and flexible technique that can be applied to a variety of decision problems involving multiple objectives [12]. GP over other techniques is dealing with real-world decision problems that allows decision maker to incorporate environmental, organizational, and managerial consideration into model through goal levels and priorities [13]. If the decision maker can provide an ordinal ranking of goals in terms of their importance to the organization and if all relationships of the model are linear, the problem can be solved by GP. GP is used to perform three types of analysis:

I. Determine the required resources to achieve a desired set of objectives.
II. Determine the degree of attainment of the goals with the available resources.
III. Providing the best satisfying solution under a varying number of resources and priorities of the goals.

In the literature review, most of the studies on MCDM with GP solution have given little consideration for the potential sub-systems within the system (case company). The studies conducted on this issue in developing countries' manufacturing sector are not enough like Ethiopia. Since Ethiopia is a developing country still the research in MCDM with GP solution is in the infant stage which is not enough to make management decision for the area which needs improvement.

In this research, the GP model has been applied in company management for calculation of target value of selected strategic goals in related with potential sub systems which have been identified during productivity assessment of the researcher's previous work: technology, marketing, production, and ergonomics [14]. The model has made especially for the implementation of calculated achievable value of strategic goals into the business plans through which company´s management can provide day to day activities of the company. There were set general strategic goals of the case company called Edget Yarn and Sewing thread S.C. entering the model: sales growth, profit maximization, and cost minimization.

The researcher has believed that the strategic goals of the case company are related with potential sub systems, defined as technology, marketing, production, and ergonomics. To maximize sales (marketing sub-system) requires increasing production volume (production sub-system). To maximize profit (marketing sub system) requires minimizing cost and volume of waste, machine, and labor cost, (technology and production sub-system), and maximizing sales (marketing sub-system). These all have been achieved if we are trying to provide a critical concern for ergonomic sub-system through workers health and safety issues. It requires maximizing the performance levels for each performance objectives under levels of personal fitness to the work, workplace environment and other issues key performance areas of the ergonomic sub system.

In general, by considering the system level overall productivity of the case company that have been measured, during the study of overall productivity assessment using PO-P approach in the researchers' priviuos study, mathematical GP model have been developed to improve the overall productivity. The model has been developed using the combinations of the strategic goals of the case company with their planned target values and the Performance Value (PV) of the KPAs under the ergonomics sub-system. This has finally depicted how much percent does the ergonomics sub-system alone will improve overall Productivity Index (PI) from 0.652 to crtain levels.

2 | Materials and Methods

2.1 | Linear Programming Versus GP Model

The formulation of GP problem is like that of Linear Programming (LP) problems. The major differences are an explicit consideration of goals and the various priorities associated with the different goals. In GP, instead of attempting to maximize or minimize the objective criterion directly, as in LP, the deviations between goals and what can be achieved within the given set of constraints are minimized.

The slack variables (deviations) in simplex algorithm of LP, take on a new significance in GP called deviational variable. This is represented in two dimensions, both positive and negative deviations from each sub goal or goal. Then the objective function becomes the minimization of these deviations based on the relative importance or priority assigned to them. The decision maker can determine the priority of the desired attainment of each goal or sub goal and rank the priorities in an ordinal sequence. Obviously, it is not possible to achieve every goal to the extent desired. The true value of GP, therefore, is its contribution to the solution of decision problems involving multiple and conflicting goals according to the decision maker's structure.

2.2 | General Goal Programming Model

2.2.1 | Objective function

Unlike in the basic model of LP, in GP approach are not used constraints, but system of goals which represents and behaves as constraints. If we want to define the basic theoretical framework of GP firstly, we must determine goals while each one has assigned the target value. Charnes and Cooper [17] presented the general GP model which can be expressed mathematically as

$$\text{Minimize } Z = \sum_{i=1}^{m} d_i^+ + d_i^-)n. \tag{1}$$

2.2.2 | General constraints

The objective function of the goal progrmaing model have been subjected to the following general constraints:

$$\text{Goal Constraints:} \quad \sum_{j=1}^{n} a_{ij}x_j - d_i^+ + d_i^- = b_i\,, \text{for } i = 1 \dots m, \tag{2}$$

$$\text{System Constraints:} \quad \sum_{j=1}^{n} a_{ij}x_j \begin{bmatrix} \leq \\ \geq \\ = \end{bmatrix} b_i\,, \text{for } i = m+1 \dots m+p, \tag{3}$$

with $d_i^+, d_i^-, x_j \geq 0$, for i=1…, m; for j=1…, n.

Where, there are m goals, p system constraints and n decision variables:

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Z = objective function = Summation of all deviations.

a_{ij} = the coefficient associated with variable j in the ith goal.

x_j = the jth decision variable.

b_i = the associated right hand side value.

d_i^- = negative deviational variable from the ith goal (underachievement).

d_i^+ = positive deviational variable from the ith goal (overachievement).

Both overachievement and underachievement of a goal cannot occur simultaneously. Hence, either one or both variables must have a zero value; that is, $d_i^+ * d_i^- = 0$.

2.3 | Identified Constriants

The case company has produced two prodcuts namely: yarn count 10 and count 21 and has strategic goals related with sales growth, profit maximization and cost minimizations. To be effective in attaining these goals they also planned the target value of profit, targe value of cost, target value of sales, target value of total hour of production, target value of total materials for production, target value of production capacity. By considering the starategic goal of the case company with its detail target values and the ergonomics sub-system, general constraint model has been developed in this study for the purpose of improving the productivity of the company. Under the ergonomics sub-system there are three KPAs (workplace environment, levels of personal fitness to the work, and other issues) with respective PI. Again, under each KPA there are different performance objectives having Objectivated Output (OO)/Objectivated Value (OV) with respective weights.

Let

g_1_target value of profit.

g_2_target value of costs.

g_3_target value of sales.

g_4_target value of total hour of production.

g_5_target value of total materials for production.

g_6_target value production capacity.

p_{1-n}_profit from one product.

c_{1-n}– cost of production of one product.

s_{1-n}– Sales price of one product.

x_{1-n}– Individual products of the company.

x_{3-I}- Performance objective I.

$pv(x_{3-I})$– PV for each performance objective I.

PIKPA$_i$ - PI of KPA i.

u-the component/subsystem.

v-the KPA.

y-the performance objectives.

W-the weightage factor.

Oyvu-the PV of POy in KPAv in component/subsystem u.

O'yvu-the OO of PO-y in KPAv in component/subsystem u.

Profit constraint: the profit from one product multiplied by production volume of that product. These results are summed, and then the sum is equal to or greater than the target value of the profit:

$$\sum_{i=1}^{n} p_i x_i \geq g_i. \tag{4}$$

Cost constraint: the cost for one product multiplied by production volume of that product. These results are summed, and then the sum is equal to or less than the target value of cost:

$$\sum_{i=1}^{n} c_i x_i \leq g_2. \tag{5}$$

Sales constraint: the sales revenue from one product multiplied by production volume of that product. These results are summed, and then the sum is equal to or greater than the target value

$$\sum_{i=1}^{n} s_i x_i \geq g_3. \tag{6}$$

Time capacity constraint: the time required to produce one product multiplied by the production volume of that product. These results are summed, and then the sum is equal to or less than the target value of total hours of production.

$$\sum_{i=1}^{n} t_i x_i \leq g_4 \tag{7}$$

Material capacity constraint: the material required to produce one product multiplied by the production volume of that product. These results are summed, and then the sum is equal to or less than the target value of total materials for production

$$\sum_{i=1}^{n} m_i x_i \leq g_5. \tag{8}$$

Production capacity constraint: the sum of the capacity to produce each product is specified to maximum value

$$\sum_{i=1}^{n} x_i \leq g_6. \tag{9}$$

Ergonomics constraint: because to satisfy product demand from the customers, sales revenue, and profit target of the company, the working environment should be safe and comfortable to every position worker.

$$x_{3...I} \geq pv(x_{3...I}) \tag{10}$$

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Hence the company must achieve not fewer than the OV/OO of each performance objective. Therefore, each performance objective is set to equal to or greater than the respective OV, where, I=11.

As well as, the PV of each performance objective is divided by the OO of that performance objective, then this value is multiplied by the respective weight. These results are summed, and then the sum is set to equal to or less than the calculated PV in *Table 1*

$$\sum_{I=11} w_{3-I}\left(\frac{X_{3-I}}{OV_{3-I}}\right) \leq PIKPA_{i}, \tag{11}$$

where I = 1, 2, 3.

Once, the optimal (suggested) PV of each performance objective has been obtained using the excel solver, the PI (the revised form) of each KPA has been calculated using *Eq. (12)*, the PI of the ergonomics sub-system has been calculated using *Eq. (13)* and finally the PI of the case company has been calculated using *Eq. (14)* to show the improvement in the overall system [14]:

$$(PI)_{vu} = \sum_{y=1} W_{yvu}\left(\frac{O_{yvu}}{O'_{yvu}}\right). \tag{12}$$

$$(PI)_{u} = \sum_{v=1} W_{vu}\,(PI)_{vu}. \tag{13}$$

$$PI = \sum_{u=1} W_{u}\,(PI)_{u}. \tag{14}$$

2.4 | GP Solution Methodology

There are GP computer software/computers required the availability of GP algorithms used to generate the primary GP problem solutions and to permit a post- solution analysis through supporting algorithms obtained in the primary solution. Collectively, these primary and secondary algorithms can be called GP solution methodologies. The primary GP algorithms and methodology are categorized and used to generate linear GP, integer GP and nonlinear GP solutions. Secondary GP methodologies: includes duality and sensitivity analysis used to obtain post-solution information. According to [15] there are seven types of changes that can be implemented as a part of sensitivity analysis in GP:

I. Changes in the right-hand-side values.
II. Changes in the weighting at a priority level.
III. Changes in the weighting of deviation variables within a priority level.
IV. Changes in technologies coefficients.
V. Changes in the number of goals.
VI. Changes in the number of decision variables.
VII. Reordering preemptive priorities.

2.5 | Computer Software Supporting GP Solution Analysis

For the calculation of defined GP model and obtaining solutions can be used various software programs. These include the most popular optimization software CPLEX Solver of GAMS software [16], Excel Solver, Multi Objective Programming (MOP) package. Excel solvers are most used in GP models and have been applied for this research. Solving a GP problem by using Excel is like solving a LP model, although not quite as straightforward. When using an excel spreadsheet to solve a GP problem, it must be solved sequentially. In this procedure, a new problem is formulated and solved for each priority goal in the objective function, beginning with the highest priority. In other words, the minimization of the deviational variable at the highest priority is the initial objective. Once a solution for this formulation is achieved, the value of the deviational variable that is the objective is added to the model as a constraint, and the second-priority deviational variable becomes the new objective. A new solution is achieved for each new objective sequentially until all the priorities are exhausted or a better solution cannot be reached. For our purposes, this means editing Excel's Solver for each new solution. The optimal solution from excel solver have been discussed by using answer report, sensitivity report. The results of data analysis have been discussed to draw vital conclusions and recommendations that are very useful for the success of the company.

3 | Result and Discussion

During productivity assessment one can understand that the PI of the other issues KPA with weight of 20% got better in productivity achievement among the three KPA under the ergonomic sub-system. Assume that by taking this value as reference, the maximum possible value of the productivity of the rest two KPAs is calculated proportionally and have been shown in *Table 1*.

Table 1. Calculated PI of the KPAs under ergonomics sub-system.

KPAs	Actual Prodcuctivity Index	Calculated/Expected Prodcuctivity Index
Workplace environment (50%)	0.7931	1.9
Levels of personal fitness to the work (30%)	0.5568	1.14
Other isuues (20%)	0.76	0.76

*Source: Own calculation of expected PI from actual PI.

Table 2. Performance objectives of the ergonomics sub system.

KPAs and Weight	Designation of Performance Objectives	Weight	OV	PV	PI
Levels of personal fitness to the work (30%)	X3: Does the mgt consider work-experience for the job?	40%	0.6	0.4	07931
	X4: Do the recruited staffs trained before using the available machines?	45%	0.82	0.53	
Workplace environment (50%)	X5: Do the supporting-facilities timely delivered to workers to aid the staffs in doing the job?	25%	0.7	0.56	0.556 8
	X6: Do working-tools advanced?	25%	0.8	0.65	
	X7: Doe the workplace- environment at satisfying level?	25%	0.6	0.4	
	X8: Doe work-load distribution is balanced throughout the workers?	25%	0.75	0.67	
Other issues (20%)	X9: Are there rules, regulations, and policies to shape the work culture?	75%	0.8	0.6	0.76
	X10: Is work-schedule & rotation fairly implemented?	15%	0.5	0.45	
	X11: Is there any staffs cased in unusual environmental stress?	10%	0.4	0.25	

* Source: [14].

To get the required results of GP in improving the productivity of the case company, necessary data have been obtained from the management staffs of the company. Data with target values of defined strategic goals have been gathered from production, technology, marketing department of the case company. The gathered data have been associated with the two main products of the case company namely count 10 and count 21, and each product is characterized by costs connected with its production, sales price and profit. The company also specified maximum and minimum possible amount for profit, cost, sales, production, material and production time. These input data have been shown in *Table 3*.

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Table 3. Input data from the companys' strategic goal to the GP model.

Products Variable	Count 10	Count 21
Unit cost (ETB)/kg	51.00	60.40
Unit price (ETB)/kg	57.83	66.96
Profit (ETB)/unit/kg	6.83	6.56
Production time(hour) for unit	2.01 sec=000558 hour	4.41 sec=001225 hour
Material(kg) for unit	1.25	1.25

*Source: the case company management staffs.

For each product group there is a maximum possible capacity or required minimum value

I. Target value of profit: 7, 680, 828 birr/year.
II. Target value of costs: 61, 548, 600 birr/year.
III. Sales (minimum): 69, 229, 428 birr/ year.
IV. Production amount (maximum): 1, 139, 100 kg (products)/year.
V. Total amount of material (cotton) for production (maximum): 1, 423, 875 kg/year.
VI. Total production time (maximum): 4500 hours/year.

By considering the strategic goal of the company; defined input data, target values, capacities, variables obtained from production, marketing, technology and ergonomics sub-systems, the following main priorities to goals and the objective function have been developed.

P1: achieving that capacity utilization will not violet the upper limit.

P2: maximization of sales price and profit. Product x_1 will satisfy the maximum demand.

P3: product x_2 will satisfy the maximum demand.

P4: to minimize cost the company would like to minimize time and material to produce unit product.

P5: because to satisfy product demand from the customers, sales revenue, and profit target of the company: the working environment should be safe and comfortable to every position worker and the productivity of each KPAs must be met. But this has been done on three stages which have been listed as: levels of personal fitness to the work (50%), workplace environment (30%), other issues (20%).

3.1 | The Goal Programing Model: Case Study

Minimize: $P_1d_6^+, P_2d_1^-, P_2d_3^-, P_2d_7^-, P_3d_8^-, P_4d_2^+, P_4d_4^+, P_4d_5^+, 0.4P_5d_7^+ + 0.45P_5d_8^+,\ 0.25P_6d_9^+ + 0.25P_5d_{10}^+ + 0.25P_6d_{11}^+ + 0.25P_6d_{12}^+, 0.75P_7d_{13}^+ + 0.15P_7d_{14}^+ + 0.1P_7d_{15}^+, 0.5P_8d_{16}^+ + 0.3P_8d_{17}^+ + 0.2P_8d_{18}^+.$

Subject to

$6.83 * x_1 + 6.56 * x_2 + d_1^- - d_1^+ = 7{,}680{,}828.$ (Profit constraint)

$51 * x_1 + 60.4 * x_2 + d_2^- - d_2^+ = 61{,}548{,}600.$ (cost constraint)

$57.83 * x_1 + 66.96 * x_2 + d_3^- - d_3^+ = 69{,}229{,}428.$ (sales constraint)

$0.000558 * x_1 + 0.001225 * x_2 + d_4^- - d_4^+ = 4{,}500.$ (time constraint)

$$1.25 * x_1 + 1.25 * x_2 + d_5^- - d_5^+ = 1{,}423{,}875. \qquad \text{(material constraint)}$$

$$x_1 + x_2 + d_6^- - d_6^+ = 1{,}139{,}100. \qquad \text{(production capacity constraint)}$$

$$\left.\begin{array}{c} x_3 - d_7^+ = 0.6 \\ x_4 - d_8^+ = 0.82 \\ x_5 - d_9^+ = 0.7 \\ x_6 - d_{10}^+ = 0.8 \\ x_7 - d_{11}^+ = 0.6 \\ x_8 - d_{12}^+ = 0.75 \\ x_9 - d_{13}^+ = 0.8 \\ x_{10} - d_{14}^+ = 0.5 \\ x_{11} - d_{15}^+ = 0.4 \\ 0.4 * \frac{x_3}{0.6} + 0.45\frac{x_4}{0.82} - d_{16}^+ = 1.14 \\ 0.25 * \frac{x_5}{0.7} + 0.45\frac{x_6}{0.8} + 0.4 * \frac{x_7}{0.6} + 0.45\frac{x_8}{0.75} - d_{17}^+ = 1.9 \\ 0.75 * \frac{x_9}{0.8} + 0.15\frac{x_{10}}{0.5} + 0.45\frac{x_{11}}{0.4} - d_{18}^+ = 0.76 \end{array}\right\}. \quad \text{(Ergonomics constraint)}$$

$$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+, d_5^-, d_5^+, d_6^-, d_6^+,$$
$$d_7^+, d_8^+, d_9^+, d_{10}^+, d_{11}^+, d_{12}^+, d_{13}^+, d_{14}^+, d_{15}^+, d_{16}^+, d_{17}^+, d_{18}^+ \geq 0.$$

By considering strategic goals of the case company with the given/planned target values and the priorities of goals, the PI of the KPAs' of the ergonomics sub-system, the performance objectives of each KPAs with its respective weight, OV, and each performance objectives with their respective PV; the objective function and constriants has been developed as follows so as to improve the productivity of the case company.

3.2 | Result Analysis

Q2

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1			GOAL PROGRAMING:EDGET YARN AND SEWING THREAD SHARE COMPANY															
2																		
3			COUNT 10	COUNT 21	X3	X4	X5	X6	X7	X8	X9	X10	X11	d-	d+			
4			771600	367500	1.04	0.82	0.7	0.8	2.76	0.75	0.8	0.5	0.4					
5																CONSTRAINT		
6																TOTAL		
7	GOAL CONSTRAINTS															LHS	CONSTRA	RHS
8	PROFIT		6.83	6.56										0	0	7680828		7680828
9	SALES		57.83	66.96										3.027E-09	0	69229428		69229428
10	COST		51	60.4										0	0	61548600		61548600
11	TIME		0.000558	0.001225										3619.2597	0	4500		4500
12	MATERIAL		1.25	1.25										0	8.77E-11	1423875		1423875
13	CAPACITY		1	1										1.714E-11	0	1139100		1139100
14	ERGONON	x3			1									0	0.435	0.6		0.6
15		x4				1								0	0	0.82		0.82
16		x5					1							0	0	0.7		0.7
17		x6						1						0	0	0.8		0.8
18		x7							1					0	2.16	0.6		0.6
19		x8								1				0	0	0.75		0.75
20		x9									1			0	0	0.8		0.8
21		x10										1		0	0	0.5		0.5
22		x11											1	0	0	0.4		0.4
23	ERGONOMICS KPAs		PERSONAL CAPABILITY											0	0	1.14		1.14
24			WORKING CONDITION											0	0	1.9		1.9
25			OHERS											0	0.24	0.76		0.76
26																		

Fig. 1. Excel solver optimal solution sheet.

The answer report of the excel solver have given details of the optimal solutions with cell value of $x_1 =$ 771600 kg of yarn with count 10, $x_2 = 367500$ kg of yarn with count 21. These values are the maximum amount to be produced for each product. To get the optimal PV of the performance objectives in KPAs of the ergonomics sub-system sequential approach to attempt to obtain a better solution have been accomplished. For instance, by having cell O14 as the target cell and $N8 = 0$, $N10 = 0$, $O9 = 0$, $O11 = 0$, $O13 = 0$ and $O15 = 0$ as a constraint again solve for the third time but the answer became the same with the first and second solution. That means the solution did not provide a better optimal result without sacrificing the goal achievement at the higher priority levels. Thus, $x_1 = 771600$, $x_2 = 367500$, $x_3 = 1.035$, $x_4 = 0.82$, $x_5 = 0.7$, $x_6 = 0.8$, $x_7 = 2.76$, $x_8 = 0.75$, $x_9 = 0.8$, $x_{10} = 0.5$, and $x_{11} = 0.4$ are better solutions with deviational values of $d_2^- = 3.027\text{E-}09$, $d_4^- = 3619.2597$, $d_6^- = 1.714\text{E-}11$, $d_5^+ = 8.77\text{E-}11$, $d_7^+ = 0.435$, $d_{11}^+ =$

2.16, $d_{18}^{+}=0.24$. The report also indicates that all constraints are binding, so all are utilized in the final solution because all constraints have been adjusted to equality signs.

The sensitivity report of the excel solver have shown the GP model is good, for example, the shadow price for profit goal constraint is zero (0), and if the value of x_1 is increased by 1 (from 771600 to771601), the corresponding value at the optimal solution of profit will not be increased. Similarly, if the x_1 is decreased by 1 (from 771600 to 771599), the respective profit value at the optimal solution will not be decrease. In addition to this, the sensitivity report details shown how changes in the coefficients of the objective function affect the solution. For instance, if the coefficient on x3 is raised to 1+1 = 2, or decreased to 1-1 = 0, the optimal solution remains unchanged. Similarly, if the coefficient on d_3^{+} is raised to 1+1 = 2, or decreased to 1-1 = 0, the optimal solution remains unchanged.

According to the interpretation of the answer report, sensitivity report as well as the optimal solution sheet of the excel solver in *Fig.1* the results of the optimal (suggested) PV of each performance objectives those should attain to provide comfortable and safe work environment to works are summarized.

Table 4. Suggested solutions of PV of performance objectives.

	X3	X4	X5	X6	X7	X8	X9	X10	X11
OV	0.6	0.82	0.7	0.8	0.6	0.75	0.8	0.5	0.4
PV	0.4	0.53	0.56	0.65	0.4	0.67	0.6	0.45	0.25
Optimal (Suggested) value	1.035	0.82	0.7	0.8	2.76	0.75	0.8	0.5	0.4

* Source: OV and PV from Table 2. and suggested value from Fig.1.

Using the optimal (suggested) PV of the performance objectives the PI of KPAS under ergonomics sub-system using *Eq. (12)* became:

I. For levels of personal fitness to the work, $(PI)_{vu} = 0.4*(1.035 \div 0.6) + 0.45*(0.8 \div 0.82) = 1$.
II. For workplace environment, $(PI)_{vu} = 0.25*(0.7 \div 0.7)+0.25*(0.8 \div 0.8)+0.25*(0.2.76 \div 0.6)+ 0.25*(0.75 \div 0.75) = 1.9$.
III. For other issues, $(PI)_{vu} = 0.75*(0.8 \div 0.8) +0.15*(0.5 \div 0.5) +0.1*(0.4 \div 0.4) = 1$ Then, using *Eq. (13)* the PI of the ergonomics sub-system has been improved and became; $(PI)_u = 0.3*1 + 0.5*1.9+ 0.2*1 = 1.492$.

Finally, using the three sub systems' (production, marketing, and technology) PI and their respective weight as they are during the productivity assessment, and the recalculated/improved PI of the ergonomics sub-system with its weight as it is, the improved PI of the system have been determined.

Table 5. PI of the sub-systems.

System-Sub	Relative Weight	PI
Production	12%	0.7379
Technology	40%	0.7882
Marketing	20%	0.661
Ergonomics	6%	Existing durinng assessment = 0.7156 Improvd after optimal (suggested) pvof the performance objectivesof the ergonomics sub-system = 1.492

*Source: [14] and the recalculated PI of ergonomics sub-system using Eq. (13).

Therefore, using *Eq. (14)* and the information in *Table 5* productivity of the system became;

$$PI = 0.12*0.7379 + 0.4*0.7882 + 0.2*0.6661 + 0.16*1.492 = 0.776$$

4 | Conclusion

Productivity of the system, Edget Yarn and Sewing Thread Share Company, have been measured by using the PO-P approach. Hence, the existing system productivity level is determined from the productivity of potential subsystems and is 0.652 [14]. By having these potential sub system and strategic goal of the case company GP have been formulated to show by how much percent does the ergonomics subsystem alone improves the overall PI. For this it is required to have optimal solution of PV of the performance objectives of KPAs under the ergonomics sub-system. This optimal solution brings the PV values of the performance objectives x3 = 1.035, x4 = 0.82, x5 = 0.7, x6 = 0.8, x7 = 2.76, x8 = 0.75, x9 = 0.8, x10 = 0.5, and x11 = 0.4. Having these optimal (suggested) PVs of performance objectives, the PI of the ergonomics sub-system has been recalculated and became 1.492, in effect increases the overall PI of the system (case company) from 0.652 to 0.776.

The following suggestions can be drawn from the results of this paper. The workplace environment design should be carried out using ergonomic guidelines, acts and recommendations and environment must be given adequate consideration. Strategies should be formulated and implemented to introduce ergonomics systematically through ergonomic programs in the company to improve productivity, safety and health and environment. The decision maker in ergonomics sub system of the company should implement GP technique to set out the planned output of performance objectives of the ergonomic subsystems. This should be done by integrating ergonomic sub system with potential subsystems.

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Parametric Optimization (GMAW) for the Improvement of Mild Steel Weld Strength Using Response Surface Technique

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Abstract

In every welding operation, the Ultimate Tensile Strength (UTS) of the weld in comparison to the parent metal is the most desirable strength metric. It is necessary that the parameters of the welding process be continually examined and improved due to the growing demand for stronger weld connections in structural and industrial materials. This study's objective is to investigate the flaws in the welding procedure that the investigated industrial company employs and to come up with alternative, specially designed, and enhanced process parameters to replace the existing procedure welding protocol. If successful, this will result in improved weld results and a higher UTS. The Response Surface Methodology (RSM) was then utilized in order to optimize the suggested process parameters on the basis of a comparison to the previously published research.

The tensile strength of 200 mm x 20 mm GMAW welding plates was evaluated through the use of testing procedures. The results of the experiments were evaluated using the RSM approach, and the findings demonstrated that the current, voltage, and travel speed were the primary factors that determined the final strength of the weld. The results also show that there is a significant correlation between the values that were measured and those that were anticipated for the UTS. Maximum UTSs of 425, 450, and 475 MPa. Were achieved when welding voltages were set at 28 volts, currents were set at 240 amperes, and travel rates were set at 0.012 meters per second.

Keywords: Optimization, GMAW welding, Ultimate tensile strength, Response surface method, Contour plot, Surface plot.

1 | Introduction

The measure of mild steel weld products is critical to the manufacturing, fabrication, and construction processes. Because of their high coefficient of thermal expansion, these materials are prone to deformation [1]. The welding process parameters established by modern industries and included as part of their distinctive processes have a significant impact on the success or failure of such finished products. The demand for stronger, more dependable welds with better quality control is continually increasing. Most manufacturers, on the other hand, followed the same welding techniques and specifications [2].

Gas Metal Arc Welding (GMAW) technique is a fast and cheap method of joining two materials permanently. It is more suitable for design flexibility and construction of the plan structure. This

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process is use in almost all metal manufacturing process, such as in jet engines, pipelines, automobiles, ships and buildings [3].

Mild steel accounts for a significant share of total steel output [4]. They are the most important steel utilized in the petroleum and petrochemical industries, accounting for more than 98% of construction materials [5]. Mild steel has a wide range of applications, including petrochemical facilities, oil and gas storage tanks, and transportation pipelines, due to its moderate strength, good weldability, and formability [6].

Sound weld is a key factor for industries to maintain a universal competition in the present day fast-rising environment, traditional welding process must be more adaptable, efficient and flexible [7]. GMAW is the most commonly used welding process over others because of ease of operation, simple, less expensive and has an efficient output. Its operation cut across automobiles, ships, oil and gas, petrochemical and building application. The weld strength of a GMAW is directly influenced with the amount of current, voltage, rate of gas flow and wire diameters. Other factors such as torch angle and plate thickness are also critical in achieving a sound weld, as a result it is necessary researchers identify these idea parameter standard values for optimum weld quality [8], [9].

The GMAW welding technique is the idea welding process for overcoming the limitations of employing short electrode lengths and the incapacity of the submerged-arc welding procedure to weld in a variety of positions. This process has made it possible to weld joints in the thickness range of 1-13 mm in all welding situations by properly modifying the process parameters [10], [11]. This process is use in welding several engineering materials such as carbon steels, low alloy and high alloy steels, stainless steels, aluminum, and copper alloys, as well as titanium, zirconium, and nickel alloys [12], [13].

Optimized parameters result in the production of flawless welds with enhanced mechanical and metallurgical properties. In order to evaluate elusive components using a reliable experimental model, there is a tendency toward employing measurable systems, such as the Response Surface Methodology (RSM), which is one of the fundamental uses of Design of Experiments (DOE) [14], [15]. Using RSM, it is feasible to assess and improve the input parameters for weld characteristics and obtain the desired outcomes. Chikhale et al. [16], who investigated the mechanical performance of AA 6061-T6 via metal inert gas welding and considered welding current, arc voltage, and wire feed speed as welding parameters, found that welding current has the greatest effect on the Tensile strength, depth of penetration, and toughness of weld joint. Rizvi et al. [17] used the Taguchi method to MIG welding during the bonding of IS2062 steel, and their results suggested that welding voltage and welding current had the most impact on the tensile strength of the welded joint, while gas flow rate had the least impact.

Hooda et al. [18] developed a response surface model to evaluate the tensile strength of a joint comprised of inert gas metal arc welded AISI 1040 medium carbon steel. Several input factors, including welding voltage, current, wire speed, and gas flow rate, were considered. To organize the experiment, a Central Composite Design (CCD) matrix was used. According to the results of the experiment, the optimal values of process parameters such as welding voltage (22.5 V), wire speed (2.4 m/min), and gas flow rate (12 l/min) for maximum yield strength (in both the transverse and longitudinal directions) are 22.5 V, 2.4 m/min, and 12 l/min, but the current value is 22.5 V, 2.4 m/min, and 12 l/min (190 A and 210 A). Various mechanical tests are used to assess the strength or other properties of engineering materials.

A tensile test may determine mechanical characteristics such as yield stress, ultimate tensile stress, modulus of elasticity, and ductility. It includes applying a tensile tension to a sample of material and dragging it along a single axis until it breaks. For tensile testing metals, the American Society for Testing and Materials (ASTM) recommends using either a cylinder or a flat specimen. Typically, the shape and size of testing specimens are determined by the product form in which the materials will be employed or by the amount of material available for sampling. When the end product will be a plate or sheet, the shape of the specimen should reflect this. For specimens having a circular cross section, extruded bars, forgings, and castings are optimal. Sada [19] predicted and adjusted the weld strength parameters (tensile strength and hardness) of a gas tungsten arc welded 10mm thick mild steel plate using RSM. The author analyzed the mechanical properties of the weld input parameters and their relationship to the bead geometry in order to identify which values would provide the requisite weld quality. Current and gas flow rate had the biggest influence on tensile strength, whereas gas flow rate and filler rod had the most significant effect in determining hardness.

Etin-Osa and Ebhota [20] used RSM to predict the weld tensile strength of TIG mild steel welds in order to get the best potential outcomes. Several inputs are considered, including current, voltage, and gas flow rate. Using the ideal process parameters of 120.00 Amp of current, 20.00 V of voltage, and 12.00 L/min of gas flow rate, the weld tensile test yielded 596.218 MPa with a desirability value of 95.70 percent. Imtiaz et al. [21] investigated the mechanical properties of a friction stir welded butt joint arrangement of Polycarbonate, and then optimized the combination of process parameters (traverse speed, rotational speed, and tool shape). The major objective is to demonstrate how modifying the process parameters increases the overall strength of the joint. The highest Ultimate Tensile Strength (UTS) of 51,299 MPa was attained by butt joints created with a traverse speed of 14 mm/min, a rotating speed of 1700 RPM, and a basic cylindrical conical tool form, as shown by the data. Jafari and Hajikhani [22] evaluated a multi objective decision making for impregnability of needle mat using design of experiment technique and RSM while Prastyo et al. [23] sought to lower the cost of Milkuat LAB 70 ml bottles using optimal parameter setting and the Taguchi method. Onyekwere et al. [24] used experimental design and optimization techniques to determine the ideal processing parameters for bamboo fiber polyester composites. With a value of 158.23J/cm, the impact strength was found to be ideal with mercerization treatment and 30wt% fibre content. Using the ideal parameter settings of the mercerization procedure at a fibre content of 50 wt%, a flexural strength of 62.7 MPa was attained. Ogbeide et al. [25] predicted the tensile strength of butt joint of mild steel weldment using Tungsten Inert Gas (TIG) and RSM.

The result revealed that the current and load has a very strong influence on the tensile strength.The maximum tensile strength was attained at 450 Mpa with a welding Voltage (V) of 24 V, current 170 A and gas flow rate 0f 13 lit/min respectively. To get the best potential tensile strength, the mercerized-acetylation procedure should be used to a material containing 50 wt% fibers. Tensile strength of 72,96 MPa, there was no statistically significant difference between mercerized and mercerized-acetylated fiber composites in terms of flexural strength, tensile strength, and impact strength ($P>0.05$). Several prospective routes for future investigation of welded joints and their effect on materials have been studied.

The European Federation for Welding, Joining, and Cutting (EWF) and other international engineering and welding organizations are eager to engage in research and development to create better processes for creating acceptable weldments [26], [27]. Artificial neural networks, fuzzy logic, finite elements, Taguchi, and evolutionary algorithms, among others, have all been utilized by experts to optimize process parameters because it has been found that employing the best process parameters significantly affects the final quality of the weldment [28]-[35].

The GMAW technique was utilized in this study to join steel pipes in a multinational industrial firm that operates in the upstream and downstream of Nigeria's oil sector. For more than two decades, the company had always used their established protocol with the same process parameters for its pipeline welding procedures, but they were always constrained by the fact that the welded structures could not achieve their specified life span due to unjustifiable structural breakdowns [2]. The cause of these failures was discovered to be low weld strength in comparison to the source metal. Following a thorough brainstorming session with specialists, management determined that the established process was insufficient, emphasizing the need for stronger and more durable welds. They established that the need for improved weld strength can be reached by managing welding process factors at the source and changing their established procedures, which is why this research was conducted [2].

This study examines mild steel weld strength optimization using the response surface approach. The method has been shown to be a powerful tool for enhancing the quality of the entire process by cost-effectively minimizing variance while also optimizing the welding process parameters.

2 | Materials and Methods

This study created weld deposits using the GMAW technique. Ferrous and nonferrous metals are usually welded using this welding technique. Weld deposits were created using mild steel electrodes that were 350 mm long and 4.5 mm in diameter on the GMAW equipment, which can be modified to different welding conditions as necessary. These weld deposits were shaped on the lathe machine to provide tensile specimens of 200 mm in length with a diameter of 20 mm for all the tensile tests specimen. To determine the steel stress-strain curve, standard specimens are subjected to tensile tests, as shown in *Fig 1*. The measurements in *Fig. 1*. (in mm) that were used for the tensile testing were machined from all-weld metal deposits.The stress-strain curve was used to determine each weld specimen's UTS.

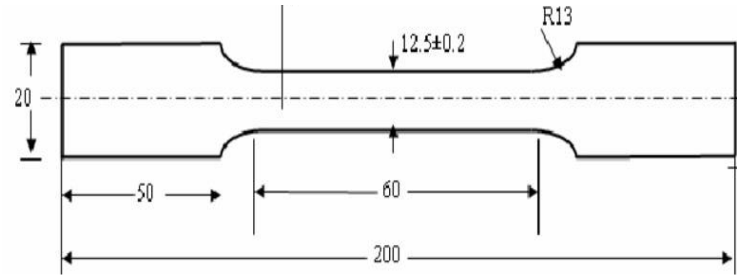


Fig. 1. Tensile test specimen.

The range of the process parameters is shown in *Table 1*. The table illustrate the varying current, time, travel speed and voltage at different leveling codes which was used to generate the experimental runs.

Table 1. Process parameters and their levels.

Sr No	Parameters	Notation	Codes	Units	Level Coded		
					1	2	3
1	Current	I	A	A	170	196	240
2	Time	t	B	min	1	1.7	2
3	Travel Speed	TS	C	m/s	0.0062	0.092	0.012
4	Voltage	V	D	v	23	25	28

The variables used were current (x1), travel speed (x2) and voltage (x3) each at level codes 1, 2, and 3. These limits were set based on the pilot study carried out prior the experimental runs. The actual levels of the variables for CCD experiments were selected based on the initial levels as the center points. A total of 27 experimental trials generated by the design expert 11.1.0.1 software adopting the CCD were performed. The data of the UTS is illustrated as show in *Table 2*. This data where obtained at varying current, time, Travel speed and voltage.

Table 2. Experimental trials data for the composite design experiments.

Run Order	Current (A)	Travel Speed (m/s^2) (C)	Voltage (V) (D)	Ultimate Tensile Strength (Mpa)
1	3	3	3	376
2	3	1	3	342
3	3	3	1	385
4	2	2	2	381
5	1	3	1	412
6	3	1	1	342
7	2	2	2	365
8	2	1	2	352
9	3	3	3	356
10	2	3	2	341

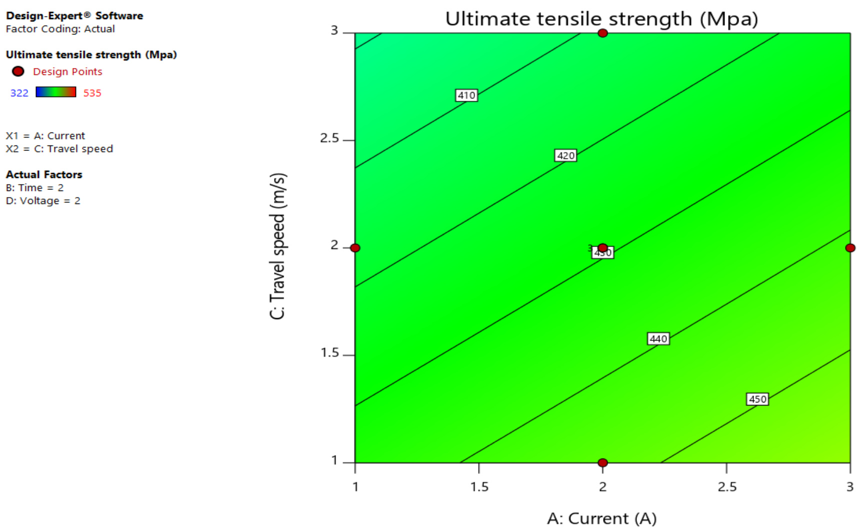
Table 2. Continued.

Run Order	Current (A)	Travel Speed (m/s^2) (C)	Voltage (V) (D)	Ultimate Tensile Strength (Mpa)
11	1	2	2	386
12	1	3	3	385
13	3	1	3	381
14	2	2	1	371
15	3	3	1	378
16	2	2	2	384
17	1	3	1	322
18	2	2	2	388
19	1	3	3	413
20	2	2	3	341
21	3	2	2	384
22	1	1	3	396
23	1	1	1	322
24	3	1	1	416
25	1	1	3	408
26	1	1	1	383
27	2	2	2	416

3 | Result and Discussion

The *Figs. 2*, *3* and *4* presents the contour plots(a) and the 3D response surface plots(b) between the varying parameters such as current, travel speed and the voltage response to the UTS within the experimental conditions established by the RSM matrix. The influence of current and travel speed on the slice of gas flowrate is shown in *Fig. 2*. The slice has three center points, which are denoted by a dot in the middle of the contour plot. The estimated optimization region of the weld UTS can be observed at max. 450 MPa as depicted in *Fig. 2*. It also demonstrated that as the weld travel speed increased, the weld current had a significant effect on the tensile strength. *Fig. 2* depicts a 3D surface plot that depicts the relationship that exists between the input variables (current and travel speed). As the current and travel speed increased, so did the tensile strength until a point when additional increases in current and travel speed resulted in a drop in the material's UTS. The green region is an indication of the tensile strength area of higher optimization. The maximum value UTS attained at this point is 425 MPa.

The contour plot in *Fig. 3* shows the predicted optimization region of the weld ultimate tensile test. The green region indicates that current and voltage had a stronger effect on the tensile strength. As a result, an optimal weld ultimate test value of 450 MPa was established. The progressive increase of the input variables increases the tensile strength of the material but as it reaches a certain point, the material UTS begins to decrease.



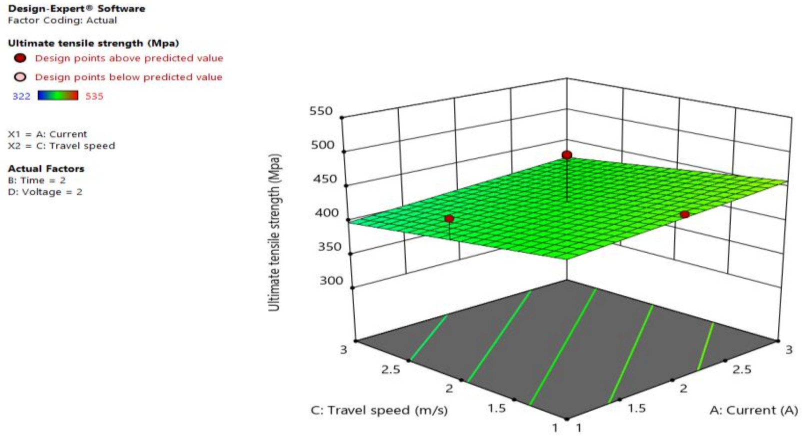


Fig. 2. Contour plot and response surface plot showing the effect of current and travel speed to the UTS.

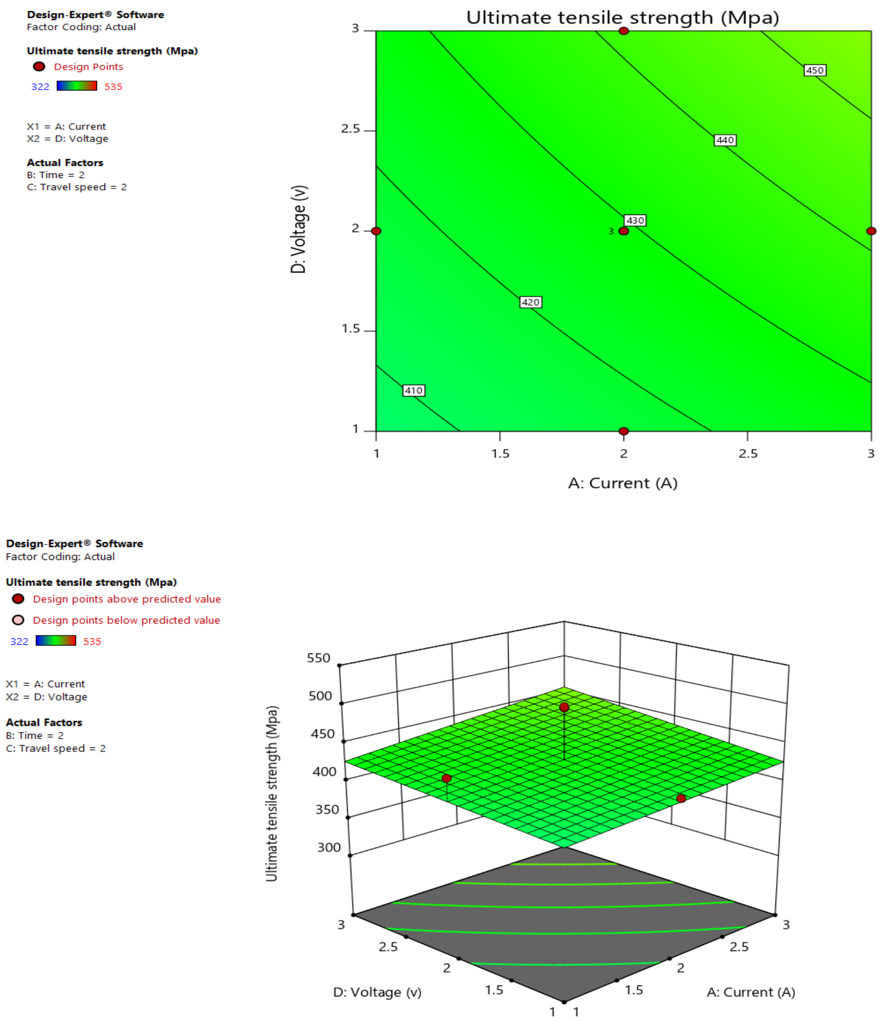


Fig. 3. Contour plot and response surface plot showing the effect of current and voltage to the UTS.

Fig. 4 depicts a three-dimensional interacting surface plot of voltage and travel speed against tensile strength. The plot *Fig. 4* shows that the tensile strength initially increases up to a certain limit when the values of the corresponding parameters increase. The plot also shows that when the voltage is low and the travel speed is fast, a larger value of UTS is obtained. In contrast, at high voltage and travel, the material does not settle adequately, resulting in porosity in the weld joints. At maximum voltage and travel speed, the ideal UTS was 475 MPa.This result has earlier been reported in the study by [2], [36], [37] which are congruent with our investigation,this finding shows that there is a significant improvement using the new optimal process parameters obtained from applying the RSM.

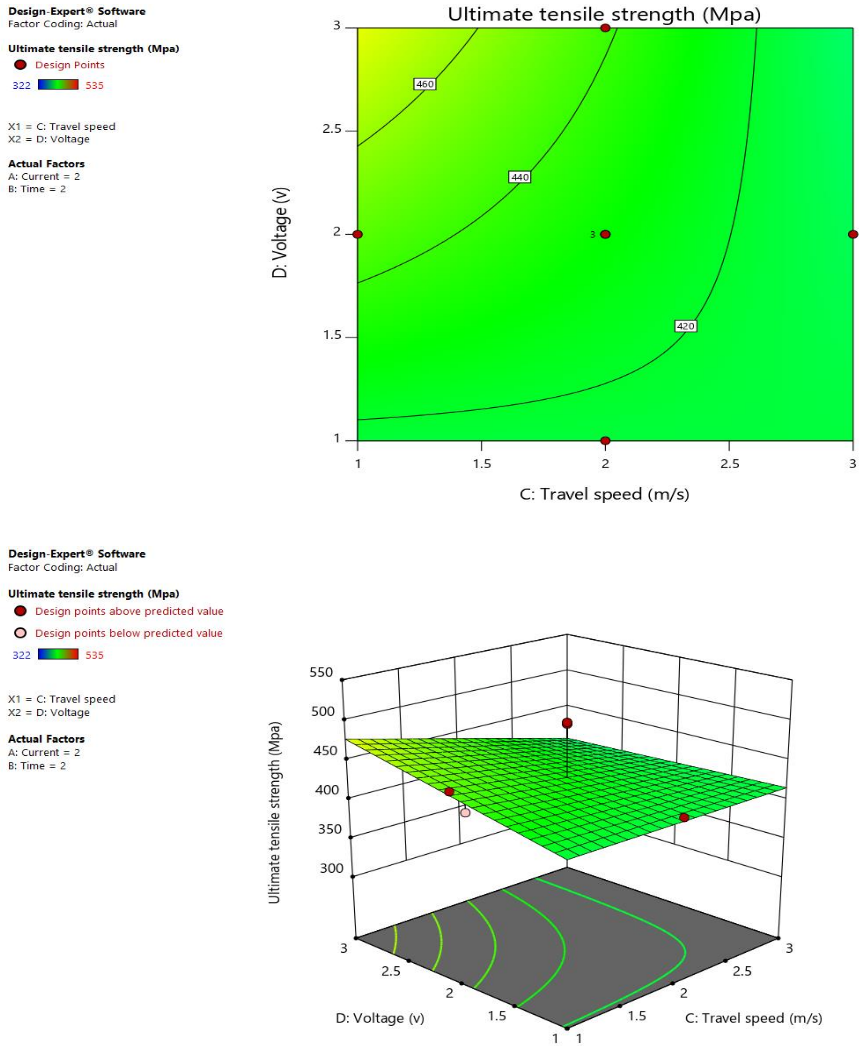


Fig. 4. Contour plot and response surface plot showing the effect of voltage and travel speed to the UTS.

Fig. 5 is use to illustrate the response of predicted and actual values of the UTS, the result indicates a strong correlation between the experimental and predicted values of the UTS. The regression analysis with R^2 of 0.9998 demonstrate the strength of response surface method and its ability to maximize the weld tensile strength.

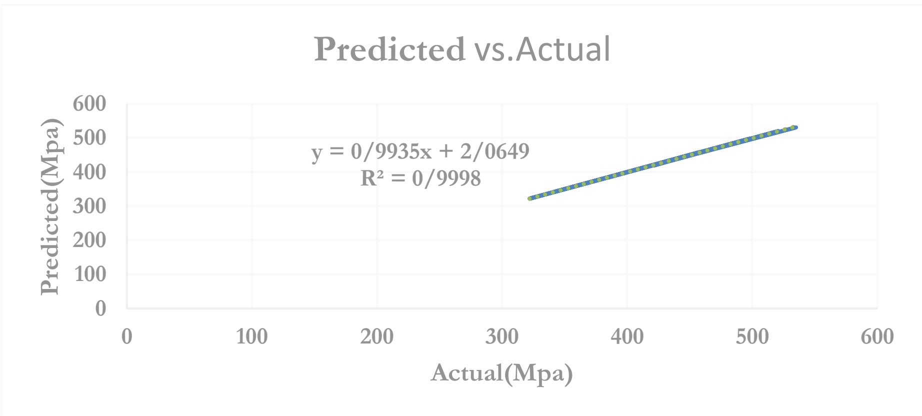


Fig. 5. Predicted against actual for a UTS response (MPa).

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4 | Conclusion

In this study, the UTS of the weld was optimized and predicted on mild steel welded samples using the GMAW welding procedure. The response surface technique was used to determine the material's UTS. The results reveal a simultaneous increase in UTS when all of the parameters (current, voltage, and travel speed) increase. However, after a specific limit, a downward trend with subsequent simultaneous increases in the values of the examined parameters was seen. As a result, when the welding voltage is 28 v, the current is 240 A, and the travel speed is 0.012 m/s, the UTS reaches optimum values of 425, 450, and 475 MPa.

Conflicts of Interest

Authors do not have any conflicts of interest.

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A Genetic Algorithm for Curve Fitting by Spline Regression

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Abstract

Curve fitting is a computational problem in which we look for a base objective function with a set of data points. Recently, nonparametric regression has received a lot of attention from researchers. Usually, spline functions are used due to the difficulty of the curve fitting. In this regard, the choice of the number and location of knots for regression is a major issue. Therefore, in this study, a Genetic Algorithm (GA) simultaneously determines the number and location of the knots based on two criteria. Those are the least square error and capability process indices. The proposed algorithm performance has been evaluated by some numerical examples. Simulation results and comparisons reveal that the proposed approach in curve fitting has satisfactory performance. Also, an example illustrated a sensitivity analysis of the number of knots. Finally, simulation results from a real case in Statistical Process Control (SPC) show that the proposed GA works well in practice.

Keywords: Capability process index, Genetic algorithm, Least square error, Spline regression.

1 | Introduction

With the development of technology in computation and measurement, scientists usually encounter providing information by curve fitting. If the pattern of a link between the predictor variable and response variable isn't known, or if there is no complete past information on the shape of a data pattern, nonparametric regression models are used. In situations in which there is a complex shape for measured data, piecewise polynomial functions or splines are the most important methods for smoothing in curve fitting. In the spline technique, the spline function must be continuous to higher derivatives at different points in the domain of function f. In this method, it is assumed that function f can be estimated by a continuous sequence of knots. Note that choosing the number and location of the knots is a challenge in data interpolation through spline regression.

As mentioned in Dierckx [1], the distribution of knots is a nonlinear optimization problem. To solve these problems, as one of the first works, Dimatteo et al. [2] used a Bayesian model in Markov Chain Monte Carlo (MCMC) in spline regression. Some studies carried out some computations based on

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nonlinear optimization such as Ahmed et al. [3]. Also, Zhao et al. [4] proposed an adaptive knot placement using a generalized mix model-based continuous optimization algorithm based on a B-Spline curve approximation. Gazioglu et al. [5] developed penalized regression spline methodology which uses all the data and improves the precision of estimation. Also, Lai and Wang [6] applied the asymptotic behavior of penalized spline estimators using bivariate splines over triangulations and an energy functional as the penalty. After that, Seo et al. [7] proposed an outlier detection method in penalized spline regression models.

Furthermore, Schwarz and Krivobokova [8] developed a unified framework to investigate the properties of all periodic spline-based estimators, including regression, penalized, and smoothing splines. Moreover, Montoril [9] suggested a spline estimation of the functional-coefficient in regression models for time series with correlated errors. In addition, for time series nonparametric regression models with discontinuities, Yang and Song [10] used polynomial splines to estimate locations and sizes of jumps in the mean function. Papp and Alizadeh [11] applied a shape-constrained estimation using nonnegative splines. Moreover, Ma et al. [12] proposed a new method in spline regression in the presence of categorical predictors. In recent years, Zhou et al. [13] proposed the polynomial spline method to estimate a partial functional linear model. Recently, Daouia et al. [14] developed a novel constrained approach to the boundary curve achieved from the smoothness of spline approximation.

Usually, in most of these techniques, firstly, spline coefficients are estimated, and then the knots are selected. These methods display a relatively satisfactory performance; however, they are statistically complicated, and sometimes results fall in local solutions. Hence, some researchers have employed omission and addition techniques to estimate the knots. In this regard, Powell [15] produced extra knots in one variable, and Jupp [16] required an initial estimation of the location of the knots that is not feasible in practice. Similarly, Dierckx [1] needed an error tolerance or a smoothing factor to estimate the location of the knots at first. Ma [17] obtained a plug-in formula for the optimal number of interior knots based on the theoretical results of asymptotic optimality and strategies for choosing them in the spline estimator. Wang [18] treated the number and locations of knots as free parameters and used reversible jump MCMC to obtain posterior samples of knot configurations. In this work, second-order programming is used to estimate the remaining parameters based on the number and location of the knots.

On the other hand, metaheuristic algorithms are computational intelligence paradigms especially used for sophisticated solving optimization problems. For example, Engin and İşler [19] proposed a parallel greedy algorithm to solve the fuzzy hybrid flow shop problems with setup time and lot size. Also, Goli et al. [20] proposed a comprehensive model of demand prediction based on hybrid artificial intelligence and metaheuristic algorithms in the dairy industry. Moreover, Shahsavari et al. [21] suggested a novel GA for a flow shop scheduling problem with fuzzy processing time. On this subject, Sanagooy Aghdam et al. [22] proposed a heuristic method of GA and Simulated Annealing (SA) for the purpose of placing readers in an emergency department of a hospital. Recently, Khalili and Mosadegh Khah [23] presented a new mathematical optimization model using queuing theory to determine the hotel capacity in an optimal manner. On this subject, Rezaee and Pilevari [24] presented a mathematical model of sustainable multilevel supply chain using a meta-heuristic algorithm approach. Also, Alizadeh Firozi et al. [25] used an uncapacitated single allocation hub location problem for uncapacitated single allocation hub location problem.

In the field of application of GA in curve fitting, Irshad et al. [26] proposed a technique to capture the outline of planar objects based on two rational cubic functions for approximating the boundary curve using GA. It is worth mentioning that GA is an approach for an optimal selection of the number and location of the knots. This issue was introduced by Holland [27] for the first time. Afterward, Lee [28] changed the search space of the GA to a discontinuous type and used one-hot encoding to show the knots. In addition, Yoshimoto et al. [29] proposed a coded GA in curve fitting. In this regard, Pittman [30] showed the knots by integer coding. In his method, the number of the knots is assumed to be fixed

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and only their location must be optimized. In addition, Tongur and Ülker [31] estimated curve knot points, which are found for curves by using Niched Pareto GA. Garcia et al. [32] proposed a hierarchical GA to counter the B-Spline curve interpolation problem. Their proposed approach helps identify the number and location of the knots, and it is capable of simultaneous determination of coefficients of the B-Spline function. Gálvez et al. [33] introduced an adapted elitist clonal selection algorithm for automatic knot adjustment of B-Spline curves that determines the number and location of knots to obtain accurate data. Garcia et al. [32] applied a hierarchical GA to tackle the B-Spline curve-fitting problem. Fengler and Hin [34] proposed a simple and general approach to fitting the discount curve under no-arbitrage constraints based on a penalized shape-constrained B-spline. Liu et al. [35] suggested jump-detection and curve estimation methods for the discontinuous regression function. Wu et al. [36] surveyed the problem of fitting scattered data points with ball B-Spline curves and then proposed a corresponding fitting algorithm based on the particle swarm optimization algorithm.

On this subject, Karadede and Özdemir [37] suggested a hierarchical soft computing model for estimating the parameter of curve fitting problems consisting of three stages. Afterward, Ramirez et al. [38] applied a parallel hierarchical Genetic Algorithm (GA) and B-splines to solve the curve-fitting problem of noisy scattered data using a multi-objective function. Recently, Li and Lily [39] proposed an approach based on an extreme learning machine algorithm to solve nonlinear curve fitting problems. Also, Yeh et al. [40] provided a new algorithm for curve fitting by a B-Spline of arbitrary order to determine the knot vector. They utilized a feature function that describes the amount and spatial distribution of the input curve.

Generally, the distribution of knots in splines is a nonlinear optimization problem. To solve this problem, researchers used some methods such as the Bayesian model, MCMC, generalized mix model-based continuous optimization algorithm, and penalized regression spline, the constrained approach to the boundary curve. Recently, some works used the GA algorithm to counter the spline curve interpolation problem. Choosing the number and location of the knots is an important challenge in data interpolation through spline regression. As aforementioned, a lot of attention has been given to estimating the number and location of the knots. Hence, in this study, a new GA has been employed based on three approaches, including Least Squares Error (LSE), Capability Process Index (CPI), and a combination of these two functions for curve fitting. In the rest of the paper, at first, the proposed GA is discussed in detail.

In the third section, the performance of the proposed approaches is evaluated, and three estimation methods of the proposed algorithm are compared. Afterward, a sensitivity analysis of the number of knots is illustrated by an example. Section 4 provides one of the applicability of the proposed method applied in change point estimation in the monitoring curve of the cooling equipment sales. Finally, the conclusion and further researches are given in the last section.

2 | Proposed Method

Consider a vector $x = [x_1, x_2, \ldots, x_n]$ fitted within different intervals with different response variables $y = [y_1, y_2, \ldots, y_p], p \le n$. This paper focuses on the estimation of the regression parameters. Assume that $\Delta = \{a = x_0 < x_1 < \ldots < x_n = b\}$ is a partition on $I = [a, b]$ interval in which distances between points are not necessarily equal. A spline is a function that is constructed piecewise from polynomial functions. To provide a visual interpretation, a schematic concept of spline regression is shown below:

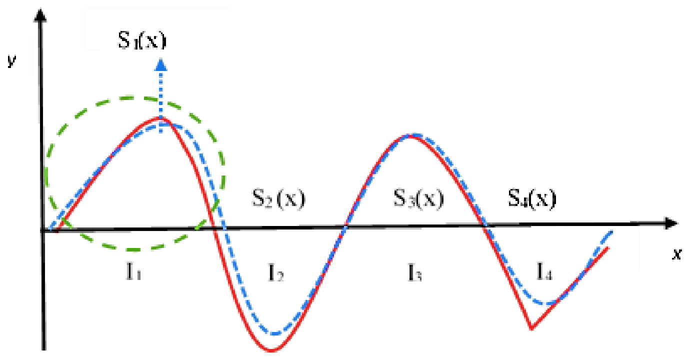

Fig. 1. A demonstration of spline regression for curve fitting.

"In general, the setup of fixed knots is an arbitrary restriction of the set of available spline curves" [29]. Therefore, it is first considered that fixed knots to solve the problem. It is worth mentioning that the proposed method is a flexible model for normal data in which residuals are normally distributed. To construct the chromosomes showing knots vector, Haupt and Haupt [41] is appllied. In the GA scheme, initially, a population of chromosomes is randomly produced in which each chromosome is an answer vector for the knots vector. After that, the selected chromosomes in the initial population are replaced with new chromosomes obtained from mutation and crossover operators. We estimate the regression parameters in each interval of x. Then, for population, the objective function is calculated using three approaches including least squared error and CPI and the combination of them, which are explained briefly in the following. Then, a certain number of the parent chromosomes are selected from the initial population. The selection and replacement processes keep on till the completion of the algorithm.

The coefficients of the spline functions can be estimated by least squares regression. This method is used when the type of distribution is exclusively normal. In this method, a certain value for x is the best-predicted value for y and $f(x)$.

$$y = f(x) + \text{noise}. \quad (1)$$

In which the function f is called regression. Now, the parameters of the distribution are based on the minimizing sum of $(f(x)-y)^2$ for all observations. It is also important to verify, in a residual analysis that if the assumptions of the white noise residuals are satisfied, we will be sure that the model well fitted.

On another side, the detection and the examination of outliers are important parts of data analysis because some outliers in the data may have a detrimental effect on statistical analysis. Many authors have discussed outlier detection methods. In this regard, we utilized CPI method. In this method, the estimated regression parameters are obtained by applying CPI to the residual. In other words, using this index, the process compares the output of the controlled process with the quality specification limits. The comparison is made by the ratio of the standard variation of samples from the residuals to 6 times of the standard variation residual. There are several statistics can be used to measure the capability of a process: Cp, Cpk, and Cpm. For the sake of simplicity, the CPI of Cp is used as one of the objective functions of GA. Assume that there is a two-sided specification, and USL and LSL are the upper and lower specification limits value, respectively. In Statistical Process Control (SPC), Cp is calculated as follows:

$$C_p = \left(\frac{USL - LSL}{6\sigma}\right). \quad (2)$$

As can be seen in simulation studies, using applying separately two mentioned objective functions leads to satisfactory results. It is worth mentioning that considering simultaneously these approaches have more desirable answers than separately. Applying the least-squares criterion may remove a chromosome that has only a few outliers. On the other hand, GA based on the objective function of CPI may give an answer in which all response variables are near to the control limit, while total error is unneglectable. According to this concept and conducting some simulation results, it can be easily concluded two approaches act against each other. Hence combining them with a weighting method leads to a better solution. The proposed method based on the two estimation functions is as follows:

$$\alpha\left(f\left(x\right)-y\right)^{2}-\beta\left(\frac{USL-LSL}{6\sigma}\right). \tag{3}$$

Where two parameters of α and β are the weights for two objective functions of least squares criterion and the CPI, respectively.

2.1 | Proposed GA Pseudo-Code to Estimate the Spline Regression

Succinctly, the recommended pseudo-code of the GA algorithm is given in the following.

I. Determining the input parameters.
II. Producing the primary population from 0 and 1 values.
III. Transforming the 0 and 1 values to D vector or knots vector. (D vector is defined clearly in [34]).
IV. Estimating regression parameters using LSE for each interval of D vector of the population.
V. Calculating the fitting function according to *Eq. (3).*
VI. Comparing the minimum function as the best answer with the best answer in the previous replication.
VII. Creating a new population according to the following method:

- *Select two vectors from D vectors from the current population using the selection operator with the occurrence probability of pc.*
- *Transforming the selected vectors D to 0 and 1 vectors and applying the crossover operator to create new vectors.*
- *Select a vector from D vectors using the selection operator with the occurrence probability of pm.*
- *Transforming the selected D vectors to 0 and 1 vectors and applying mutation operator on the new vector.*
- *Adding the new population to the initial population, as well as pr times the initial population.*

3 | Performance Evaluation of the Proposed Method

In this subsection, we present some simulation results to evaluate the performance of the proposed method. In this regard, we use some multiple linear regression examples. In this method, we should obtain parameters such as percentage of crossover, and mutation operators to enhance the efficiency of the proposed GA. To achieve this goal, the trial and error method is employed to adjust parameters. In this regard, the given parameter including crossover operation percentage is tuned 65 percent and mutation operation is 20 percent (pm=0.2, pc=0.65). Similarly, the rate of selecting superior answers from the initial population is 5 percent, (pr=0.05). The chromosomes of the population are assumed 100. Genes in each chromosome and the particles in each gene are equal to 20 and 7, respectively. In addition, the replications in each run are equal to 3000. The assumed functions with determined knots are shown in *Table 1*. In this regard, we minimize the total error based on only the least squared error. Afterward, it is similarly assumed that maximizing the CPI is the objective function. Then, the combination of the two functions is considered. It should be noted that we use a Mean Squared Error (MSE) criterion to appraise and compare proposed methods with different objective functions

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Table 1. The assumed functions in each interval created by knots.

Number	Functions
1	$Y_1=x_1+3x_2+5x_3+8x_4$
2	$Y_2=x_1+8x_2+7x_3+3x_4$
3	$Y_3=2x_1+4x_2+6x_3+6x_4$
4	$Y_4=2x_1+3x_2+1x_3+9x_4$
5	$Y_5=2x_1+5x_2+7x_3+3x_4$
6	$Y_6=2x_1+3x_2+6x_3+5x_4$
7	$Y_7=x_1+4x_2+2x_3+8x_4$
8	$Y_8=x_1+2x_2+7x_3+2x_4$
9	$Y_9=4x_1+8x_2+9x_3+8x_4$
10	$Y_{10}=x_1+3x_2+6x_3+6x_4$
Knot vector	[17,36,43,43,54,58,62,69,93,100]

Objective functions based on the LSE and the CPI separately may have satisfactory results. However, they may not achieve the appropriate fitting. Because, as expected, in the least squared error, the emphasis is on the total deviations. On the other hand, in some cases, we may witness excessive error while in the majority of points; the fitting has been well achieved. Therefore, in this situation, this approach is not able to select an appropriate model for curve fitting. On the contrary, when the CPI is used, may there be considerable errors in the majority of points with fewer outliers. With fewer outliers. As a result, combining two functions and employing them simultaneously is acceptable to achieve more appropriate fitting and lower MSE criterion. As mentioned before, the assumed knot vector is considered in *Table 1*. Also, the knot vector obtained from the proposed method is illustrated as an estimated knot vector in 11 examples in *Tables 2, 3*, and *4*.

In *Tables 2* and *3*, an example has been provided with a determined input variable in each run to obtain the optimal solution for one of the objective functions (CPI and LSE, respectively) and the other objective function calculated with the optimal population. In this regard, its final population has been assumed as the population of another objective function to perform once again. Moreover, the three approaches including objective function based on the LSE, CPI, and the combination of them are applied to the mentioned method in *Table 4*.

Comparing the results in *Tables 2, 3,* and *4* shows that the obtained vector of the solution is close to the initial knot vector. We can confirm that considering simultaneous two objective functions improves substantially the performance of the algorithm. In summary, the simulation results indicate that the proposed method is capable of handling behaviors of a wide range of observations on the sub-intervals.

Table 2. Superior performance of CPI approach to the LSE approach.

	CPI Function	Corresponding LSE Function
MSE	58.70	69.90
Knot points	[17, 36, 43, 43, 54, 58, 62, 69, 93, 100]	[17, 25, 43, 55, 60, 70, 78, 87, 91, 100]
MSE	299.70	305.40
Knot points	[17, 26, 58, 65, 67, 89, 97, 100, 100, 100]	[15, 25, 59, 68, 69, 82, 100, 100, 100, 100]
MSE	121.60	769.90
Knot points	[1, 6, 22, 46, 48, 60, 86, 91, 100, 100]	[12, 60, 67, 87, 91, 92, 100, 100, 100, 100]

Table 3. Superior performance of the LSE approach to the CPI approach.

	LSE Function	Corresponding CPI Function
MSE	152.20	243.10
Knot Points	[33, 35, 39, 52, 55, 80, 90, 100, 100, 100]	[33, 44, 58, 63, 69, 78, 86, 90, 100, 100]
MSE	147.50	194.10
Knot Points	[1, 9, 12, 28, 45, 68, 74, 82, 92, 100]	[1, 9, 12 28, 34, 45, 69, 85, 92, 100]
MSE	64.40	86.80
Knot Points	[12, 20, 39, 45, 55, 76, 77, 100, 100, 100]	[12, 34, 45, 54, 69, 73, 82, 83, 86, 100]

Table 4. Comparison of the proposed methods.

	CPI Function	LSE Function	CPI+LSE
MSE	79.90	0.1	0
Knot points	[8, 20, 27, 36, 68, 71, 85, 87, 95, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 91, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 90, 100]
MSE	41.60	0.3	0
Knot points	[15, 40, 41, 44, 59, 69, 71, 93, 94, 100]	[17, 25, 35, 43, 56, 61, 70, 87, 91, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 90, 100]
MSE	26.70	0.1	0
Knot points	[9, 25, 29, 39, 54, 58, 71, 79, 81, 100]	[17, 25, 35, 43, 55, 60, 70, 86, 90, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 90, 100]
MSE	970.90	2.7	0.1
Knot points	[12, 68, 84, 89,91, 92, 97, 100, 100, 100]	[17, 25, 34, 38, 55, 60, 70, 87, 91,100]	[17, 25, 35, 43, 55, 60, 70, 87, 91, 100]
MSE	67.50	0.1	0
Knot points	[31, 33, 36, 40, 58, 59, 61, 70, 85, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 91, 100]	[17, 25, 35, 43, 55, 60, 70, 87, 90, 100]

Table 5. The effect of the number of knots on total square error (MSE values).

Number of Knots	CPI Function	LSE Function	Combining the Two Functions
2	297.00	249.60	220.40
3	256.20	266.70	200.60
4	184.30	189.00	166.20
5	172.40	184.0	92.30
6	162.80	147.70	86.10
7	102.10	81.60	68.50
8	97.30	60.90	59.70
9	45.90	48.50	36.50
10	26.70	0.1	0

3.1 | Sensitivity Analysis of the Number of Knots

First, we use simulations to demonstrate that our method is not sensitive to some knots. We assume the numerical example and the mentioned parameters in the previous section, the results of *Table 5* indicate that the combined method has better performance than the other methods. As we expected, as the number of knots increases, the performance of all the proposed methods increases. In addition, as shown in *Fig. 4*, the more the number of knots is assumed, the fewer differences between the methods LSE and CPI. Note that when the number of knots is more than one, the proposed method can be used.

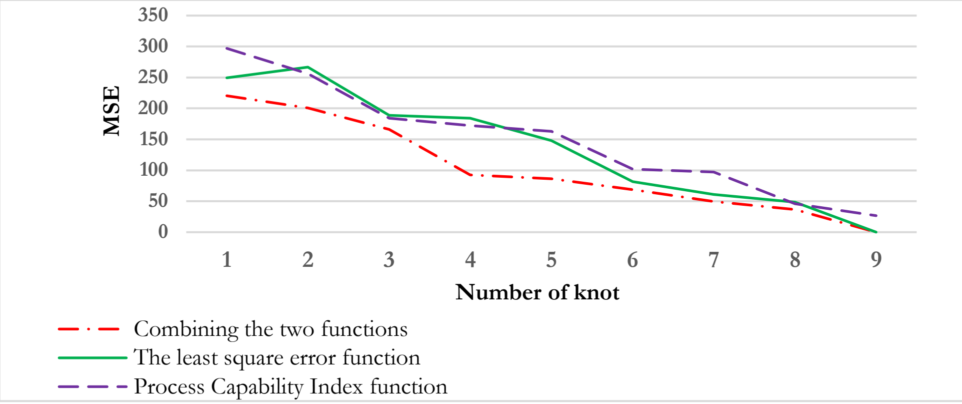

Fig. 4. Comparison of the performance of the proposed methods.

Real world numerical data is usually difficult to analyze. To this end, the idea of the applying GA in spline is developed. As shown in *Tables 2-4*, simulation results confirm that proposed GA help substantially to spline curve fitting. Using the proposed algorithm, a series of unique polynomials are fitted between each of the data points, with the stipulation that the curve obtained be continuous and appear smooth. There are many cases in which spline plays an important role in data analysis. Wherever spline is used, the proposed algorithm can be attractive and help improve splines. Hence, the proposed method can be used in various fields from a managerial point of view.

4 | A Comparative Study

Due to the lack of an analytic expression for optimal knot locations, different methodologies in the specialized literature have been demonstrated for the selection and optimization of knot vectors. Some fast deterministic methods employ. However, in the case of complex point clouds, the results are far away from the optimum. Alternatively, metaheuristic methods especially the GA algorithm yield knot vectors which are very close to the optimum, but only converge slowly and are, therefore, time- and computing power-consuming. Furthermore, the performance of these algorithms is seriously affected by the occurrence of data gaps. Recently, Bureick et al. [42] proposed an elitist GA to solve the knot adjustment problem for B-Spline curves despite the possible occurrence of data gaps. It is worth mentioning that we focused on the determination of knot location and knot vector size. In reality, we try to realize model selection and knot vector determination simultaneously. By contrast, Bureick et al. [42] focused solely on knot vector determination.

To evaluate the efficiency of proposed algorithm, our method and the elitist GA are applied to a test function. To evaluate the capability of the proposed algorithm, the test functions are introduced in Yoshimoto et al. [29] according to *Eq. (4)*. The chosen parameters for both algorithms to obtain the subsequent results are gathered mainly from the literature.

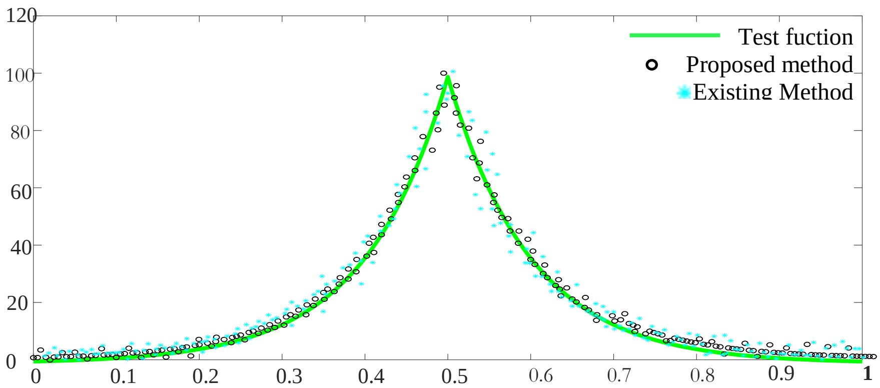

Fig. 5. Comparison results for test function with given parameters.

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$$y = \frac{100}{e^{|10x-5|}} + \frac{(10x-5)^5}{500}. \tag{4}$$

Generally, the simulation results show that the proposed GA algorithm is a simple method and performs slightly better than comparative methods. However, elitist GA solves the knot adjustment problem in a faster manner than the proposed approach.

5 | Application

The estimation of locations of the knots in spline functions can be used in different applications. Recently, Toutounji and Durstewitz [43] have utilized this concept and detected multiple change points using adaptive regression splines with application to neural recordings. One another application is in SPC. In this respect, control charts are one of the most important tools in monitoring a process, but most control charts delay warning alarm of a change in the process. The real-time in which the process changes is called a change point. To save time and cost, its estimation is an important issue in SPC. In this regard, if the knots are assumed as the change points, the multiple change points in monitoring the qualitative characteristic can be estimated through estimation of the number and location of the knots. Hence, multiple change points can be considered an interesting application. So far, some studies have been conducted to estimate the multiple change points that are restricting assumptions such as fixity in the number of change points.

In this subsection, we specifically illustrate the implementation of our method in the estimation of multiple change points. Note that the knot numbers obtained from the proposed method are illustrated as the estimated change point vector. To validate the algorithm in this example, we consider the multiple change point vectors within the given ranges as the determined change point vector in *Table 6*. As can be seen, different functions of the simple linear regression model are assumed in this table. Now, simulation results are calculated using the proposed algorithm and the values of pm=0.2 and pc=0.65 are obtained by adjusting the algorithm parameters. The MSE for the CPI, the least squared error, and the combination of the two functions are equal to 72.40, 39.20, and 37.6, respectively. The change points are illustrated in *Table 6* to show the applicability of the proposed method in this real example. As shown in this table, the estimations of change points obtained by the proposed method are close to the determined change points.

Table 6. A real example of the multiple change points.

	Simple Linear Profile Functions within Different Ranges of the Independent Variable
1	$y_1 = 3 + x$
2	$y_2 = 8 + 6x$
3	$y_3 = 4 + 2x$
4	$y_4 = 2 + 3x$
5	$y_5 = 5 + 2x$
6	$y_6 = 3 + 2x$
7	$y_7 = 4 + x$
8	$y_8 = 2 + 7x$
9	$y_9 = 8 + 4x$
10	$y_{10} = 3 + 9x$
	Determined change points
	[17, 25, 35, 43, 55, 60, 70, 87, 90, 100]
	The estimations of change points by the proposed method
	[7, 19, 31, 47, 56, 62, 69, 81, 91, 100]

6 | Conclusion

Among nonparametric, a spline model is one of the regression models with considerable statistical interpretation. However, this method requires the identification of knots. In this regard, we proposed a regression spline based on a GA that is intuitively appealing and simple. The proposed algorithm is provided to estimate the number and the location of the knots simultaneously. The proposed algorithm has the specified ability to handle data with changeable behaviors on certain sub-intervals. The proposed GA is based on the LSE considering CPI. The performance of the proposed method was evaluated using several numerical examples. Also, it was shown that the more the number of knots is assumed, the fewer differences between the methods LSE and CPI. Note that this algorithm can be used for Normal-type of observations with normal residuals. In the end, the applicability of the proposed algorithm was shown using a real example.

For further researche, functions and methods defined in spline regression may be applied in the objective function to minimize total error. The dependence of the proposed method on residuals distribution may also be eradicated by applying other nonparametric regression. In addition, a new GA can be provided for non-Normal data.

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Conflicts of Interest

All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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A Neutral DEA Model for Cross-Efficiency Evaluation

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Abstract

The cross-efficiency method in Data Envelopment Analysis (DEA) has widely been used as a suitable utility for ranking decision-making units. In this paper, to overcome the issue of the existence of multiple optimal solutions in cross-efficiency evaluation, we use the neutral strategy to design a new secondary goal. Unlike the aggressive and benevolent formulations in cross-efficiency evaluation, the neutral cross-efficiency evaluation methods have been developed in a way that is only concerned with their own interests and is indifferent to other DMUs. The proposed secondary goal introduces a new cross-efficiency score by maximizing the sum of the output weights. The first model is then extended to a cross-weight evaluation, which seeks a common set of weights for all the DMUs. Finally, we give two numerical examples to illustrate the effectiveness of the proposed neutral models and the potential applications in ranking DMUs by comparing their solutions with those of alternative approaches.

Keywords: Data envelopment analysis, Cross-efficiency evaluation, Ranking.

1 | Introduction

Data Envelopment Analysis (DEA) was introduced to assess the relative efficiency of a homogeneous group of Decision-Making Units (DMUs), such as banks, industries, police stations, hospitals, tax offices, schools, and university departments [1]-[7]. The traditional DEA methods allow each DMU to generate a set of relative weights. These weights maximize the ratio of aggregated weighted outputs to aggregated weighted inputs while ensuring that the same ratio does not exceed one for all DMUs. The maximum ratio is regarded as the efficiency score for the evaluated DMU. The traditional DEA approaches can separate efficient DMUs from inefficient DMUs, but they cannot discriminate the efficient DMUs with the efficiency score one [8]. In the face of this issue, Sexton et al. [9] suggested the cross-evaluation method as a ranking method in DEA that involves self-evaluation efficiency and peer-evaluation efficiency. The standard cross-efficiency method in the self-evaluation section uses traditional DEA models such as the CCR and BCC models that are constructed based on linear programming.

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These models usually have alternate optimal solutions, so each DMU is assigned a self-evaluation efficiency score and several peer-evaluation efficiency scores. So, regarding the ultimate cross-efficiency score that is calculated based on self-evaluation and peer-evaluation scores for each DMU, the ranking of each DMU can be changed [9]. To overcome this issue and considering that the evaluation strategy and attitude among DMUs significantly impact the weight selection and hence the cross-efficiency scores, Doyle and Green [10] proposed the aggressive and benevolent models which these ideas are widely used in cross-efficiency evaluation. Both models attempt that maximize the efficiency of the DMU under evaluation, but simultaneously the benevolent model maximizes the average efficiency of other DMUs and the aggressive model minimizes the average efficiency of other DMUs. Liang et al. [11] proposed benevolent game cross-efficiency. In this model, a unique set of weights is determined based on the Nash equilibrium and the benevolent strategy. Using the symmetric weight assignment technique, Jahanshahloo et al. [12] suggested a new secondary goal for the evaluation cross-efficiency score. Li et al. [8] considered the reciprocal behaviors among DMUs to address the cross-efficiency evaluation and used a novel threshold value to determine positive or negative reciprocal behaviors by comparing the peer-evaluated efficiency with the threshold value-based efficiency. Chen et al. [13] introduced a meta-frontier analysis framework into a cross-efficiency method to develop a new efficiency evaluation method. Chen and Wang [14] innovatively proposed the definition of cross-efficiency and developed two new target-setting approaches for individual DMU and global optimization to improve the cross-efficiency of DMUs in different decision-making situations. Chen et al. [15] introduced prospect theory to describe the subjective preference of decision-makers in the aggregation process when they face gains and losses, then a new method is constructed to aggregate cross-efficiency. Contreras et al. [16] proposed a new cross-efficiency model based on bargaining problems and the Kalai-Smorodinsky solution. Wu et al. [17] proposed an innovative composite method for ranking DMUs by calculating the Shannon entropy of the obtained cross-efficiency scores derived from the perspectives of satisfaction and consensus.

Another strategy for cross-efficiency evaluation is the neutral strategy that was first proposed by Wang and Chin [18]. Unlike aggressive or benevolent models, the neutral cross-efficiency method attempts to specify a set of weights for the inputs and outputs of each DMU from its profit perspective. Wang et al. [19] proposed a neutral method for cross-efficiency evaluation based on the distance of each DMU from the best DMU (IDMU) or the worst DMU (ADMU). Based upon the method of Wang et al. [19], Carrillo and Jorge [20] proposed a neutral model that determines an optimal set of weights that maximize the efficiency score of the ADMU and minimize the efficiency score of the IDMU simultaneously while keeping the efficiency of the evaluated unit unchanged. Shi et al. [21] utilized an ideal and anti-ideal frontier as evaluation criteria and proposed a new method for evaluating cross-efficiency scores. Using IDMU and ADMU, Liu et al. [22] introduced a prospect value based on prospect theory. They proposed a new secondary goal based on a neutral strategy for evaluating cross-efficiency scores.

Kao and Liu [23] studied two basic network systems, series and parallel, and developed a relational model to measure the cross-efficiencies of the systems and divisions. Based on this model, Örkcü et al. [24] proposed a new neutral model for cross-efficiency evaluation of the basic two-stage network systems. This model can be ranked each DMU based on the efficiency score of sub-stages and the overall efficiency score. In this model, the overall efficiency is the product of those of the stages. Liu et al. [25] proposed the neutral cross-efficiency evaluation method for general parallel systems. Shi et al. [26] proposed a neutral cross-efficiency evaluation method based on the prospect theory, which reflects the bounded rationality of DMUs when facing gain and loss as secondary goals. In addition to developing theoretical models, cross-efficiency has been applied in evaluating efficiency in various fields. For example, Wang et al. [27] conducted a cross-efficiency assessment of energy efficiency in the construction industry. Amin and Hajjami [28] generated cross-efficiency matrices by combining multiple optimal solutions to produce stock portfolios with lower risk and higher expected returns.

This paper proposes a new neutral secondary goal for cross-efficiency evaluation. This model can guarantee the maximum self-evaluation efficiency of the DMU being evaluated and the maximum sum of the output weights. The following model is an extension of the first model to cross-weight evaluation. The remainder of this paper is arranged as follows. In Section 2, we address the cross-efficiency evaluation approach. The new models for evaluating the efficiency score are introduced in Section 3. In Section 4, using two data sets, we compare the results of the proposed models with cross-efficiency models and demonstrate the effectiveness of the proposed models. Concluding is discussed in Section 5.

2 | Cross-Efficiency Evaluation

We consider n DMUs that each $DMU_j (j=1,2,\ldots,n)$ produces s different output indexes $Y_j=(y_{1j},y_{2j},\ldots,y_{sj})\in\mathbb{R}_+^s$ from m different input indexes $X_j=(x_{1j},x_{2j},\ldots,x_{mj})\in\mathbb{R}_+^m$, where $\mathbb{R}_+^s$ and $\mathbb{R}_+^m$ are two sets of nonnegative numbers. The efficiency of DMU_j is as follows:

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}, \tag{1}$$

where $u_r (r=1,2,\ldots,s)$ and $v_i (i=1,2,\ldots,m)$ are the rth output and ith input weights respectively.

The cross-efficiency evaluation process is often two-step, called self-evaluation and peer-evaluation. Each DMU's efficiency score is evaluated against the weights of all DMUs, not just its own. Suppose $DMU_p=\left(X_p,Y_p\right)$ be the DMU under evaluation. In the first phase of the cross-efficiency process, self-evaluation, the relative efficiency of DMU_p to other DMUs can be calculated using the traditional DEA model, such as the CCR model [1] that has the following form:

$$\begin{aligned}
E_{pp}^{*} &= \text{Max} \sum_{r=1}^{s} u_r^p y_{rp}, \\
\text{s.t.} \quad & \sum_{r=1}^{s} u_r^p y_{rj} - \sum_{i=1}^{m} v_i^p x_{ij} \le 0, \quad j=1,2,\ldots,n, \\
& \sum_{i=1}^{m} v_i^p x_{ip} = 1, \\
& u_r^p \ge 0, \quad r=1,2,\ldots,m, \\
& v_i^p \ge 0, \quad i=1,2,\ldots,s,
\end{aligned} \tag{2}$$

where E_{pp}^{*} is referred the relative efficiency of DMU_p. Let $u_r^{p*}(r=1,2,\ldots,s)$ and $v_i^{p*}(i=1,2,\ldots,m)$ be the optimal solution of the *Model (2)* for evaluation DMU_p, then in the second phase of the cross-efficiency method, peer-evaluation, the cross-efficiency score of DMU_j, using $u_r^{p*}(r=1,2,\ldots,s)$ and $v_i^{p*}(i=1,2,\ldots,m)$, calculates as follows:

$$E_{pj}=\frac{\sum_{r=1}^{s} u_r^{p*} y_{rj}}{\sum_{i=1}^{m} v_r^{p*} x_{ij}}, \ \left(j=1,2\ldots,n\right). \tag{3}$$

In this case, $\bar{E}_j = \frac{1}{n}\sum_{p=1}^{n} E_{pj}$ is the final score of $DMU_j (j=1,2,\ldots,n)$ for ranking.

Model (2) usually generates alternative optimal solutions, so we have different cross-efficiency scores for each DMU. Sexton et al. [9] introduced a secondary goal in cross-efficiency evaluation to overcome this vagueness. In this regard, Doyle and Green [10] presented new secondary goals called benevolent and aggressive models. As mentioned in the last section these models maximize the efficiency of DMU_p while minimize (maximize) the average cross-efficiency of other DMUs. The benevolent and aggressive formulations are as follows:

$$
\begin{aligned}
&\text{Min} \sum_{r=1}^{s} u_r^p \left(\sum_{j=1, j\neq p}^{n} y_{rj} \right), \\
&\text{s.t.} \quad \sum_{i=1}^{m} v_i^p \left(\sum_{j=1, j\neq p}^{n} x_{ij} \right) = 1, \\
&\qquad \sum_{r=1}^{s} u_r^p y_{rp} - E_{pp}^{*} \times \sum_{i=1}^{m} v_i^p x_{ip} = 0, \\
&\qquad \sum_{r=1}^{s} u_r^p y_{rj} - \sum_{i=1}^{m} v_i^p x_{ij} \leq 0, \quad j = 1,2,\ldots,n, \ \ j \neq p, \\
&\qquad u_r^p \geq 0, \quad r = 1,2,\ldots,m, \\
&\qquad v_i^p \geq 0, \quad i = 1,2,\ldots,s.
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
&\text{Max} \sum_{r=1}^{s} u_r^p \left(\sum_{j=1, j\neq p}^{n} y_{rj} \right), \\
&\text{s.t.} \quad \sum_{i=1}^{m} v_i^p \left(\sum_{j=1, j\neq p}^{n} x_{ij} \right) = 1, \\
&\qquad \sum_{r=1}^{s} u_r^p y_{rp} - E_{pp}^{*} \times \sum_{i=1}^{m} v_i^p x_{ip} = 0, \\
&\qquad \sum_{r=1}^{s} u_r^p y_{rj} - \sum_{i=1}^{m} v_i^p x_{ij} \leq 0, \quad j = 1,2,\ldots,n, \ \ j \neq p, \\
&\qquad u_r^p \geq 0, \quad r = 1,2,\ldots,m, \\
&\qquad v_i^p \geq 0, \quad i = 1,2,\ldots,s.
\end{aligned} \tag{5}
$$

Models (4) and *(5)* are accounted as the aggressive and benevolent models for cross-efficiency evaluation, respectively. Due to the different nature of the two models, two models provide different weights. As a result, the two methods usually will produce different rankings. Aiming to avoid aggressive and benevolent strategy in evaluating cross-efficiency score performance, Wang and Chin [18] proposed the following neutral model as a secondary goal to evaluate cross-efficiency in DEA:

$$
\begin{aligned}
&\text{Max} \ \ \delta = \min_{r=1,2,\ldots,s} \left\{ \frac{u_r^p y_{rp}}{\sum_{i=1}^{m} v_i^p x_{ip}} \right\}, \\
&\text{s.t.} \qquad E_{pp}^{*} = \frac{\sum_{r=1}^{s} u_r^p y_{rp}}{\sum_{i=1}^{m} v_i^p x_{ip}},
\end{aligned} \tag{6}
$$

$$\frac{\sum_{r=1}^{s} u_r^p y_{rj}}{\sum_{i=1}^{m} v_i^p x_{ij}} \leq 1, \quad j=1,2,\dots,n, \quad j \neq p,$$

$$u_r^p \geq 0, \quad r=1,2,\dots,s,$$
$$v_i^p \geq 0, \quad i=1,2,\dots.,m.$$

For DMU_p, *Model (6)* finds an optimal set of weights to maximize each of its output's efficiency, $\frac{u_r^p y_{rp}}{\sum_{i=1}^{m} v_i^p x_{ip}} (r=1,2,\dots,r)$, as much as possible while its relative efficiency is kept. In this paper, we proposed a new secondary goal based on the neutral cross-efficiency evaluation idea.

3 | Proposed Model for the Cross-Efficiency Evaluation

In this section, we proposed the following neutral DEA model for the cross-efficiency evaluation of $DMU_p (p=1,2,\dots,n)$:

$$\begin{aligned} Z_{pu}^* &= \text{Max} \sum_{r=1}^{s} u_r^p, \\ \text{s.t.} \quad & \sum_{r=1}^{s} u_r^p y_{rj} - \sum_{i=1}^{m} v_i^p x_{ij} \leq 0, \quad j=1,2,\dots,n, \\ & \sum_{r=1}^{s} u_r^p y_{rp} = E_{pp}^*, \\ & \sum_{i=1}^{m} v_i^p x_{ip} = 1, \\ & u_r^p \geq 0, \quad r=1,2,\dots,m, \\ & v_i^p \geq 0, \quad i=1,2,\dots,s, \end{aligned} \tag{7}$$

where E_{pp}^* is obtained from *Model (2)* for evaluation DMU$_P$. In this model, the sum of output weights is maximized while the efficiency of DMU$_P$ is kept. In other words, the value of each of the output weights in the objective function is considered the same, and this causes the production of non-zero output weights to decrease. On the other hand, the efficiency of each of the outputs of DMU$_P$ increases regardless of the amount of these outputs, while in the *Model (6)*, the selection of optimal weights is influenced by the lowest output value of DMU$_P$. *Model (7)* has fewer constraints than Model *(6)*, as a result, its computational complexity is less than *Model (6)*, and based on numerical results, it has the same performance as *Model (6)*. The proposed model discusses a new secondary goal in a way that reduces the influences of the existence of multiple optimal solutions. These secondary goals have nothing to do with the cross-efficiency of other DMUs, so they can be categorized as neutral secondary goals rather than aggressive and benevolent.

3.1 | Extension to the Cross-Weight Evaluation

Similar to cross-efficiency models, *Model (7)* must solve n times, and each time the efficiency of a DMU must be maintained unchanged, so we have n sets of input and output weights. If these weights are comparable, we can form a cross weights matrix and obtain a set of input and output weights using the arithmetic mean to calculate the efficiency of DMU. For this purpose, we propose the following model for the cross-efficiency evaluation of $DMU_p(p=1,2,...,n)$ based on which n sets of generated weights are comparable:

$$
\begin{aligned}
& Z_{pu}^{*} = \text{Max} \sum_{r=1}^{s} u_r^p, \\
& \text{s.t.} \ \sum_{r=1}^{s} u_r^p y_{rj} - E_{jj}^{*} \sum_{i=1}^{m} v_i^p x_{ij} \le 0, \quad j=1,2,...,n, \\
& \sum_{r=1}^{s} u_r^p y_{rp} - E_{pp}^{*} \sum_{i=1}^{m} v_i^p x_{ip} = 0, \\
& \sum_{j=1}^{n} \sum_{i=1}^{m} v_i^p x_{ij} = 1, \\
& u_r^p \ge 0, \quad r=1,2,...,m, \\
& v_i^p \ge 0, \quad i=1,2,...,s.
\end{aligned} \tag{8}
$$

Theorem 1. *Model (8)* has a feasible solution.

Proof: Suppose $v_i^{p*}(i=1,2,...,m)$ and $u_r^{p*}(r=1,2,...,s)$ be the optimal solution of the *Model (7)* for evaluation DMU_p. We define $\left(\hat{v}_i^p(i=1,2,...,m), \hat{u}_r^p(r=1,2,...,s)\right)$ as follows:

$$
\hat{v}_i^p = \frac{v_i^{p*}}{\sum_{i=1}^{m} v_i^{p*}\left(\sum_{j=1}^{n} x_{ij}\right)}, \quad i=1,2,...,m,
$$

$$
\hat{u}_r^p = \frac{u_r^{p*}}{\sum_{i=1}^{m} u_r^{p*}\left(\sum_{j=1}^{n} x_{ij}\right)}, \quad r=1,2,...,s,
$$

Therefore, we have

$$
\sum_{r=1}^{s} u_r^{p*} y_{rj} - \sum_{i=1}^{m} v_i^{p*} x_{ij} \le 0, \rightarrow E_{pj} = \frac{\sum_{r=1}^{s} u_r^{p*} y_{rj}}{\sum_{i=1}^{m} v_i^{p*} x_{ij}} = \frac{\sum_{r=1}^{s} \hat{u}_r^p y_{rj}}{\sum_{i=1}^{m} \hat{v}_i^p x_{ij}} \le E_{jj}^{*}, \ j=1,2,...,n,
$$

$$
\sum_{r=1}^{s} u_r^{p*} y_{rp} = E_{pp}^{*}, \sum_{i=1}^{m} v_i^{p*} x_{ip} = 1 \rightarrow \sum_{r=1}^{s} \hat{u}_r^p y_{rp} - E_{pp}^{*} \sum_{i=1}^{m} \hat{v}_i^p x_{ip} = 0,
$$

$$
\sum_{j=1}^{n} \sum_{i=1}^{m} \hat{v}_i^p x_{ij} = 1.
$$

The proof is completed.

Let $\left(\bar{u}_r^p(r=1,2,...,s), \bar{v}_i^p(i=1,2,...,m)\right)$ be the optimal solution of *Model (8)* for the cross-efficiency evaluation of $DMU_p(p=1,2,...,n)$, thus the cross-weight matrix is as follows.

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Table 1. Cross-weight evaluation for n DMUs.

Target DMU	Input Weights				Output Weights			
	$\bar{v}_1^p$	$\bar{v}_2^p$	$\cdots$	$\bar{v}_m^p$	$\bar{u}_1^p$	$\bar{u}_2^p$	$\cdots$	$\bar{u}_s^p$
1	$\bar{v}_1^1$	$\bar{v}_2^1$	$\cdots$	$\bar{v}_m^1$	$\bar{u}_1^1$	$\bar{u}_2^1$	$\cdots$	$\bar{u}_s^1$
2	$\bar{v}_1^2$	$\bar{v}_2^2$	$\cdots$	$\bar{v}_m^2$	$\bar{u}_1^2$	$\bar{u}_2^2$	$\cdots$	$\bar{u}_s^2$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$			$\vdots$
n	$\bar{v}_1^n$	$\bar{v}_2^n$	$\cdots$	$\bar{v}_m^n$	$\bar{u}_1^n$	$\bar{u}_2^n$	$\cdots$	$\bar{u}_s^n$

According to information in *Table 1*, the final values of input and output weights are as follows:

$$
\begin{aligned}
v_i^* &= \frac{1}{n}\sum_{j=1}^{n}\bar{v}_i^j, \quad i = 1,2,\ldots,m, \\
u_r^* &= \frac{1}{n}\sum_{j=1}^{n}\bar{u}_r^j, \quad r = 1,2,\ldots,s.
\end{aligned}
\tag{9}
$$

Then we can calculate the final score of $DMU_j\,(j = 1,2,\ldots,n)$ using *Eqs. (9)* and *(1)*.

4 | Numerical Example

In this section, to evaluate the performance of the proposed process, we consider two numerical examples that were used in previous studies in the DEA literature. *Models (4)-(6)* and the proposed models are applied to rank all DMUs and compare their performance.

Example 1. Consider the case of 14 airlines as DMUs with three inputs and two outputs which is adapted from [12], Tofallis [29] and Chiang et al. [30]. The airlines data are summarized in *Table 2*.

Table 2. Data for 14 passenger airlines.

Airline (DMU)	Inputs			Outputs	
	x_1	x_2	x_3	y_1	y_2
1	5723	3239	2003	26677	697
2	5895	4225	4557	3081	539
3	24099	9560	6267	124055	1266
4	13565	7499	3213	64734	1563
5	5183	1880	783	23604	513
6	19080	8032	3272	95011	572
7	4603	3457	2360	22112	969
8	12097	6779	6474	52363	2001
9	6587	3341	3581	26504	1297
10	5654	1878	1916	19277	972
11	12559	8098	3310	41925	3398
12	5728	2481	2254	27754	982
13	4715	1792	2485	31332	543
14	22793	9874	4145	122528	1404

The CCR efficiency scores for 14 passenger airlines are revealed in the second column of *Table 3*. According to the results of the CCR model, 7 of 14 airlines are identified as efficient DMUs. In this case, it is not possible to recognize their superiority over each other; so, we use the results of *Models (4)-(6)* and the proposed models to rank them, which are shown in the third through the twelfth columns of *Table 3*, respectively.

Table 3. Results of Models (4)-(6) and proposed models in Example 1.

DMU	CCR Model (2)	Aggressive Model (4)	Rank	Benevolent Model (5)	Rank	Neutral Model (6)	Rank	Model (7)	Rank	Model (8)	Rank
1	0.8684	0.5990	12	0.7543	12	0.7179	11	0.7200	11	0.7543	12
2	0.3379	0.1652	14	0.1894	14	0.1988	14	0.1956	14	0.1894	14
3	0.9475	0.6226	11	0.7678	9	0.7278	10	0.7332	10	0.7678	9
4	0.9581	0.6734	7	0.8222	6	0.7748	8	0.7796	8	0.8222	6
5	1	0.7983	1	0.8912	3	0.8730	4	0.8802	4	0.8912	3
6	0.9766	0.6385	9	0.7554	11	0.7000	13	0.7078	13	0.7554	11
7	1	0.6478	8	0.8214	7	0.7887	7	0.7869	7	0.8214	7
8	0.8588	0.5855	13	0.7242	13	0.7135	12	0.7107	12	0.7242	13
9	0.9477	0.6309	10	0.7590	10	0.7659	9	0.7611	9	0.7590	10
10	1	0.6813	6	0.7803	8	0.8129	5	0.8114	6	0.7803	8
11	1	0.7742	2	0.9193	1	0.9048	2	0.9048	1	0.9193	1
12	1	0.7314	5	0.8850	4	0.8825	3	0.8815	3	0.8850	4
13	1	0.7503	3	0.9190	2	0.9058	1	0.9041	2	0.9190	2
14	1	0.7316	4	0.8659	5	0.8128	6	0.8205	5	0.8659	5
sum		9.0300		10.8544		10.5791		10.5975		10.8544	

As can be seen in *Table 3*, the sum of efficiencies in the *Model (7)* is higher than the *Model (6)*. The sum of efficiencies in the *Models (8)* and *(5)* is the same. Also, the sum of efficiencies in the *Model (6)* and also the *Model (7)* (neutral models) is higher than *Model (4)* (aggressive model) and lower than the *Model (5)* (benevolent model), which all above results are reasonable with respect the structures of models.

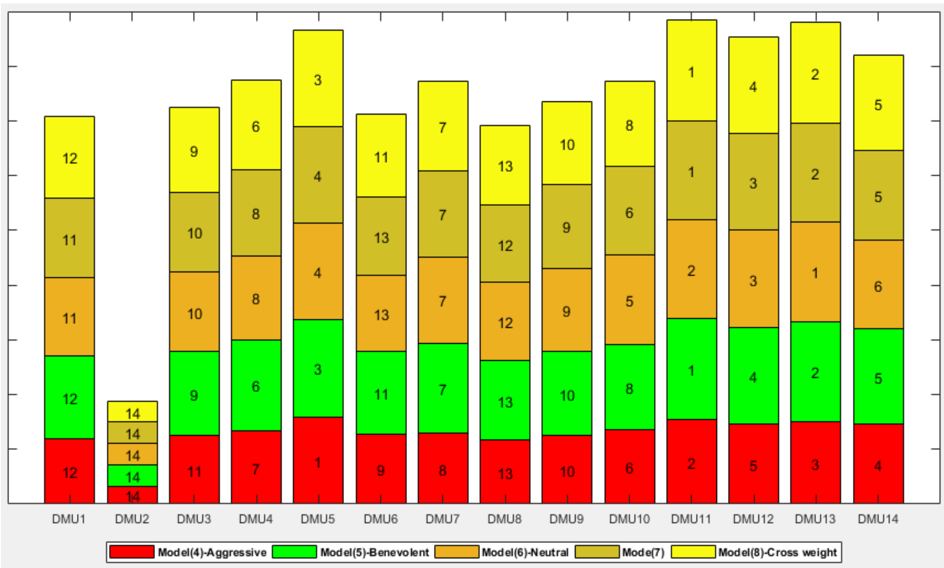

Fig. 1. Illustrative comparison between the ranking results of Models (4)-(6) and proposed models in Example 1.

Fig. 1 provides an illustrative comparison among *Models (4)-(6)* and the proposed models in *Example 1* according to the ranking results shown in *Table 3*. As can be seen, DMU_{11} took first place in *Models (5)*, *(7)* and *(8)*, whereas it gained the second rank in *Models (4)* and *(6)*. Also DMU_{13} and DMU_5 took first place in *Model (6)* and *Model (4)*, respectively. Note that DMU_2 has the worst performance in all methods.

Table 4. Ranking models correlation test in Example 1.

	Spearmen's Rho	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)
Model (4)	Correlation	1.0000	0.9516	0.9033	0.9165	0.9516
	Sig.(bilateral)		0	0	0	0
Model (5)	Correlation	0.9516	1.0000	0.9429	0.9604	1.0000
	Sig.(bilateral)	0		0	0	0
Model (6)	Correlation	0.9033	0.9429	1.0000	0.9912	0.9429
	Sig.(bilateral)	0	0		0	0
Model (7)	Correlation	0.9165	0.9604	0.9912	1.0000	0.9604
	Sig.(bilateral)	0	0	0		0
Model (8)	Correlation	0.9516	1.0000	0.9429	0.9604	1.0000
	Sig.(bilateral)	0	0	0	0	

Table 4 shows the value of Spearman's rank correlation coefficients of the five models in *Table 2* to assess the similarities between the rankings induced from the corresponding values. In all the cases, the values are statistically significant at the 0.0001 level. The test values correlations among *Models (4)-(8)* are all above 0.9. Note that *Model (7)* has the highest correlation with the *Model (6)* (green) and the *Model (8)* has the highest correlation with the *Model (5)* (green). Also, the *Model (7)* has the lowest correlation with the *Model (4)* (red) and the *Model (8)* has the lowest correlation with the *Model (6)* (red).

Example 2. This example is taken from Shi et al. [21] and is about the efficiency evaluation of 20 machinery manufacturing enterprises (DMUs) in 2014 with four inputs and four outputs. The manufacturing data are documented in *Table 5*.

Table 5. Data for 20 machinery manufacturing enterprises.

Enterprises (DMUs)	x_1	x_2	x_3	x_4	y_1	y_2	y_3	y_4
1	15	1361	222	27	3012	926.51	89	4.2
2	12.2	520	435	205	2144	1146	318	5.6
3	16.54	226.31	226.31	7	2799.76	1118.97	158.63	8.4
4	40	595	74.16	7	198	1554.96	220.35	11.5
5	11.18	0.396	317.3	9	3100	603.6	107.37	3.7
6	12.61	224.6	224.8	119	3436.8	581.6	1177	4.9
7	4.91	349	187	6	3801	1404	193	4.3
8	100	273	285	198	2533	1716	167	8.7
9	12.22	398.89	398.89	8	5192.85	1955.78	125.79	8.8
10	11	532.86	532.86	391	3472.98	3550.89	528.22	9.1
11	11.87	566	566	2	2937	5197	400	0.2
12	14.66	1044.5	961.62	232	11142	4362	827.14	18.8
13	11.48	173.71	173.7	4	1975	1508.96	43.8	12.4
14	24.56	346.04	223.3	11	2605.94	771	173.67	13.5
15	21.18	179.39	179.39	2	1858.3	504	70	5.9
16	10.32	454.71	454.71	31	3300.33	1382.91	532.36	4.9
17	5.33	328	41	4	5549.02	368	987	2.5
18	10.78	547.99	518.68	11	5837	2619.39	285.45	6.4
19	15.48	613.72	573.81	13	4820.71	2621.4	404.94	10.4
20	12.55	615.88	316.79	11	9018.71	384.22	64.99	1.5

The CCR efficiency scores and their rankings for 20 DMUs in the second column in *Table 6* show that 10 of 20 DMUs are efficient, so we cannot find any difference between them for ranking. Thus, we use cross-efficiency for further distinction. The results of *Models (4)-(8)* for evaluations of 20 enterprises are shown in the third through the twelfth columns in *Table 6*.

Table 6. Results of Models (4)-(6) and proposed model in Example 2.

DMU	CCR Model (2)	Aggressive Model (4)	Rank	Benevolent Model (5)	Rank	Neutral Model (6)	Rank	Model (7)	Rank	Model (8)	Rank
1	0.4544	0.1503	20	0.2064	20	0.1778	20	0.1996	20	0.2060	20
2	0.4722	0.2083	18	0.3318	18	0.2670	18	0.2833	18	0.3318	18
3	0.7530	0.4278	10	0.6345	10	0.5365	12	0.5519	12	0.6345	10
4	1	0.3483	15	0.3835	17	0.4367	14	0.4186	14	0.3835	17
5	1	0.5218	5	0.7910	5	0.6067	7	0.6360	8	0.7910	5
6	1	0.4207	12	0.6253	12	0.5417	11	0.5812	10	0.6263	12
7	1	0.5982	4	0.8397	4	0.7031	4	0.7659	4	0.8392	4
8	0.7708	0.1707	19	0.3307	19	0.2182	19	0.2688	19	0.3318	19
9	0.9723	0.5209	6	0.7667	6	0.6174	5	0.6616	5	0.7665	6
10	1	0.4237	11	0.7211	9	0.5531	9	0.5907	9	0.7211	9
11	1	0.6135	3	0.8672	3	0.7458	3	0.8239	3	0.8672	3
12	1	0.4925	8	0.7380	8	0.6139	6	0.6376	7	0.7379	8
13	1	0.7306	2	0.9685	2	0.8862	2	0.8835	2	0.9685	2
14	0.8037	0.3557	13	0.4494	15	0.4409	13	0.4153	15	0.4494	15
15	1	0.3514	14	0.4118	16	0.4172	16	0.3972	16	0.4119	16
16	0.6840	0.3404	16	0.4992	13	0.4350	15	0.4531	13	0.4993	13
17	1	0.7711	1	0.9927	1	0.9915	1	0.9927	1	0.9927	1
18	0.9476	0.5017	7	0.7387	7	0.6018	8	0.6484	6	0.7385	7
19	0.7987	0.4520	9	0.6302	11	0.5468	10	0.5755	11	0.6301	11
20	0.8108	0.2785	17	0.4946	14	0.3124	17	0.3569	17	0.4940	14
sum		8.6780		12.4208		10.6498		11.1415		12.4211	

As can be seen in *Table 6*, the sum of efficiencies in the *Model (7)* is higher than the *Model (6)*. The sum of efficiencies in the *Model (8)* is higher than the *Model (5)*. Also, the sum of efficiencies in the *Model (6)* and also the *Model (7)* (neutral models) is higher than *Model (4)* (aggressive model) and lower than *Model (5)* (benevolent model). Note that in this example, *Model (8)* with the same performance as the *Model (5)* produces the sum of efficiencies than *Model (5)*.

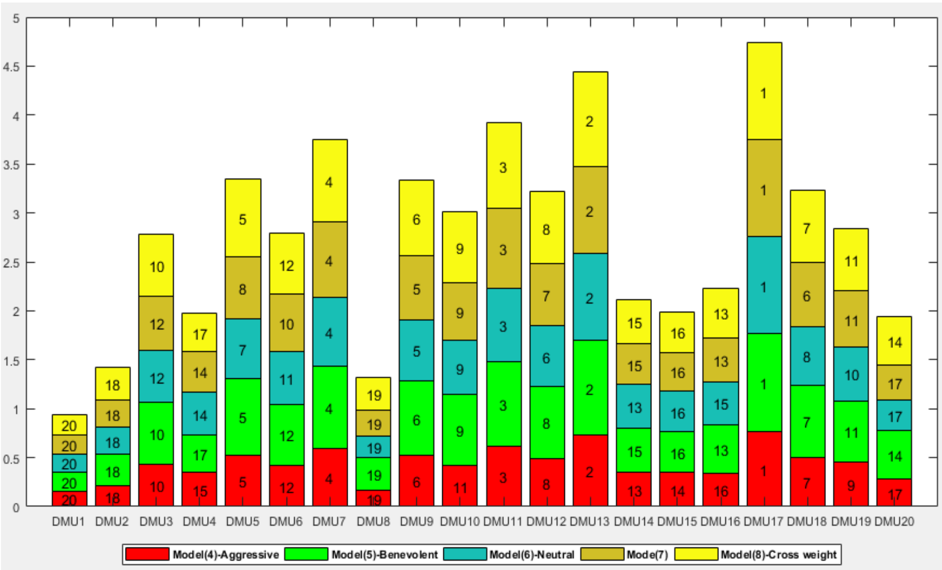

Fig. 2. Illustrative comparison between the ranking results of Models (4)-(6) and proposed models in Example 2.

Fig. 2 provides an illustrative comparison between the results of the *Models (4)-(6)* and the proposed model for ranking of DMUs in *Example 2* according to the rankings that are shown in *Table 6*. As can be seen in *Fig. 2*, in all models, DMU1, DMU8, and DMU2 (inefficient DMUs) are ranked 20th, 19th, and 18th, respectively. Moreover, the DMU17 and DMU13 as efficient DMU have the first and the second rank in the five models, respectively.

Table 7. Ranking models correlation test in Example 2.

	Spearmen's Rho	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)
Model (4)	Correlation	1.0000	0.9714	0.9805	0.9654	0.9714
	Sig.(bilateral)		0	0	0	0
Model (5)	Correlation	0.9714	1.0000	0.9684	0.9714	1.0000
	Sig.(bilateral)	0		0	0	0
Model (6)	Correlation	0.9805	0.9684	1.0000	0.9880	0.9684
	Sig.(bilateral)	0	0		0	0
Model (7)	Correlation	0.9654	0.9714	0.9880	1.0000	0.9714
	Sig.(bilateral)	0	0	0		0
Model (8)	Correlation	0.9714	1.0000	0.9684	0.9714	1.0000
	Sig.(bilateral)	0	0	0	0	

Table 7 shows the value of Spearman's rank correlation coefficients of the five models in *Table 6*. After the Spearman test, the test values of correlations among *Models (4)-(8)* are all above 0.9. In all the cases, the values are statistically significant at the 0.0001 level. Similar to *Example 1*, the *Model (7)* and the *Model (8)* have the highest correlation with the *Model (6)* and *Model (5)*, respectively. Also, the *Model (7)* has the lowest correlation with the *Model (4)* and the *Model (8)* has the lowest correlation with the *Model (6)*.

5 | Conclusion

Cross-efficiency evaluation is a utility to enhance the power of discriminating efficient DMUs in DEA. Although this method is widely used, it also has some drawbacks, such as the existence of multiple optimal weights for DEA models. Secondary goals are proposed based on aggressive, benevolent, and neutral points of view for overcoming this issue. In this paper, we proposed two models. Based on the neutral strategy in DEA, the first model seeks input and output weights that not only undertake the maximum self-assessment efficiency of DMU under evaluation but also maximize the sum of output weights. Therefore, increasing non-zero weights increases the efficiency of each DMU output under evaluation. The second model produces a set of comparable weights. According to these weights and using the matrix of cross weights, input and output weights are generated to calculate the efficiency of the DMUs. We compare the performance of the proposed models by three well-known models with an optimistic, pessimistic and neutral view using two numerical examples. It was found that the first proposed model with the same performance has less computational complexity. Also, the second model (matrix of cross-weights) has the same performance as the optimistic compared model. Existing literature proves that few studies have considered ranking DMUs with network structure using cross-efficiency evaluation. Therefore, the proposed models can be effectively applied to rank DMUs with network structure in DEA.

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