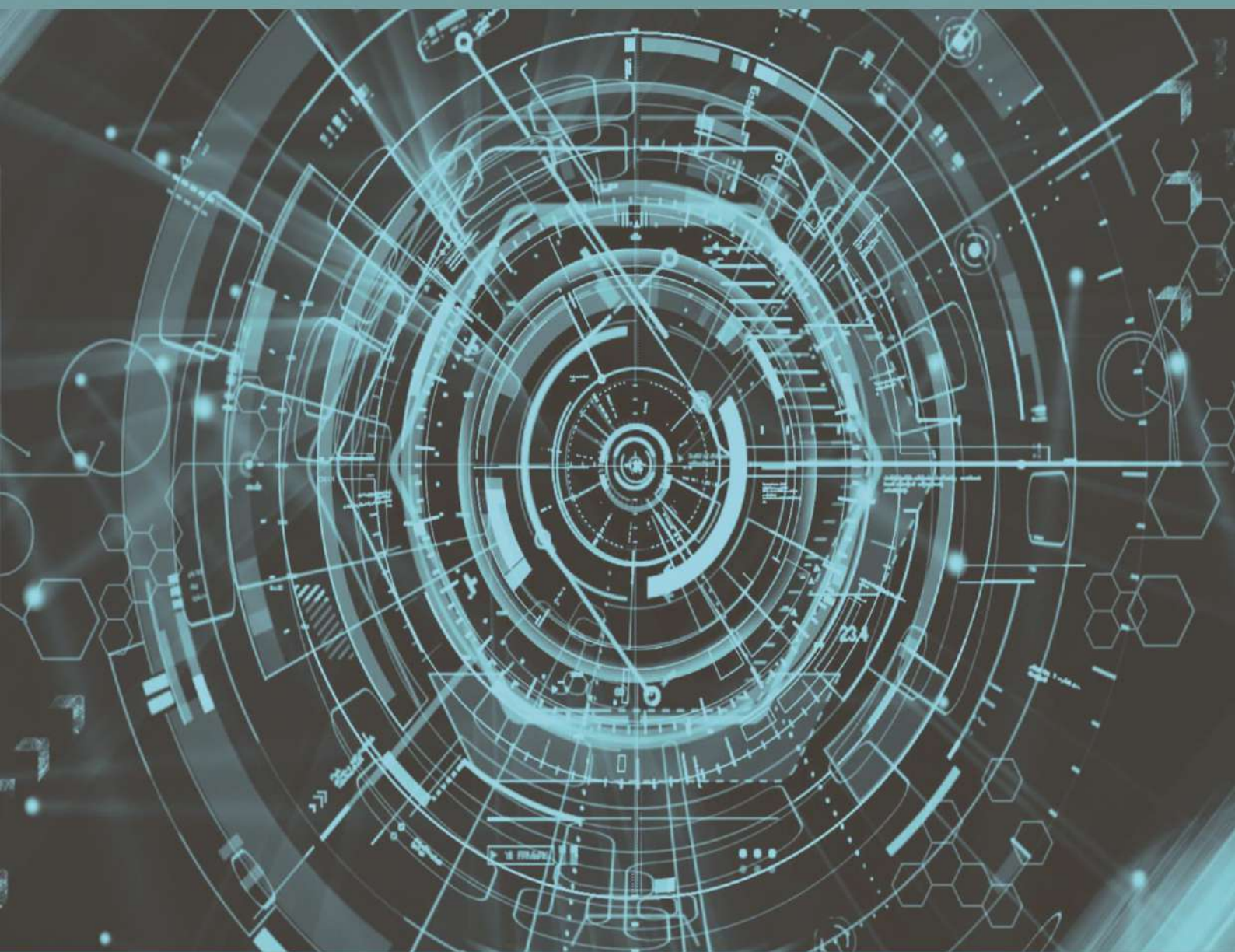




INTERNATIONAL JOURNAL OF RESEARCH IN INDUSTRIAL ENGINEERING



<http://www.riejournal.com/>

Print ISSN: 2783-1337

Online ISSN: 2717-2937

Director-in-Charge Mohammad Fallah Department of Industrial Engineering, Ayandegan Institute of Higher Education, Tonekabon, Iran.		
Editor-in-Chief Farhad Hosseinzadeh-Lotfi Department of Applied Mathematics, Islamic Azad University, Science and Research Branch, Tehran, Iran.		
Scientific & Executive Manager Seyyed Ahmad Edalatpanah Department of Industrial Engineering, Ayandegan Institute of Higher Education, Tonekabon, Iran.		
Editorial Board		
Z. Xu Business School, Sichuan University, Chengdu, China.	A. Kusiak Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, USA.	L. Liang School of Management, University of Science and Technology of China, China.
M. Abdel-Basset Faculty of Computers and Informatics, Zagazig University, Zagazig 44519, Egypt.	D. Pamučar Department of Operations Research and Statistics, Faculty of Organizational Sciences, University of Belgrade, Belgrade, Serbia.	J. L. Verdegay Department of Computer Science and Artificial Intelligence, University of Granada, Granada, Spain
J. Shang Katz Graduate School of Business, University of Pittsburgh, Pittsburgh, PA 15260, USA.	M. Rabbani Department of Industrial Engineering, University of Tehran, Tehran, Iran.	E.B. Tirkolaee Department of Industrial Engineering, Istinye University, Istanbul, Turkey.
P. F. Wanke COPPEAD Graduate Business School, Federal University of Rio de Janeiro, Rua Paschoal Lemme, 355, 21949-900, Rio de Janeiro, Brazil.	J. Wallenius Department of Information and Service Economy, Aalto University, Helsinki, Finland.	P. Stanimirovic Faculty of Sciences and Mathematics, University of Niš, višegradska 33, 18000 Niš, Serbia.
S. Broumi Laboratory of Information Processing, Faculty of Science Ben M'Sik, University Hassan II, Casablanca, Morocco.	A. Goli Department of Industrial Engineering, University of Isfahan, Isfahan, Iran.	S. A. Edalatpanah Department of Industrial Engineering, Ayandegan Institute of Higher Education, Tonekabon, Iran.
M. Yazdani School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia.	P. Ifinedo Goodman School of Business, Brock University, Canada.	M. E. Bruni Department of Mechanical, Energy and Management Engineering, University of Calabria, Italy.
M. Nikkhaheh Bahrami Department of Mechanical Engineering, Ayandegan Institute of Higher Education, Tonekabon, Iran.	A. Bianchini Department of Industrial Engineering, University of Bologna, Bologna, Italy.	J. Jablonsky Department of Econometrics, Faculty of Informatics and Statistics, University of Economics. W. Churchill Sq. 4, 130 67 Praha 3, Czech Republic, Prague.
H. Saberi Najafi Department of Applied Mathematics, Lahijan Branch, Islamic Azad University, Lahijan, Iran.	M. Salahi Department of Applied Mathematics, Faculty of Science, University of Guilan, Rasht, Iran.	
Advisory Board		
R. V. Rao Department of Mechanical Engineering, Birla Institute of Technology and Science (BITS) Pilani, Dubai Campus, United Arab Emirates.	A. Makui Department of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran.	M. J. Tarokh Department of Industrial Engineering, Khajeh Nasir Toosi University of Technology, Tehran, Iran. P. Agarwal Department of Mathematics, Anand International College of Engineering, Jaipur, 303012, Rajasthan, India.
H. Shirouyehzad Department of Industrial Engineering, Islamic Azad University, Najafabad Branch, Isfahan, Iran.	S. Shadrokh Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran.	P. Peykani School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran.
S. E. Najafi Department of Industrial Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.	S. Kumar Das National Institute of Technology Jamshedpur, 831014 Jamshedpur, India.	A. Alam-Tabriz Department of Industrial Management, Faculty of Management & Accounting, Shahid Beheshti University, Tehran, Iran.
M. T. Taqhvai Fard Department of Industrial Management, Allameh Tabataba'i University, Tehran, Iran.	R. Kumar School of CS and IT, Bangalore, Karnataka, India.	M. R. Taghizadeh Yazdi Department of Industrial Management, Faculty of Management, University of Tehran, Tehran, Iran.
M. R. de Almeida Finance & Operations Research and DEA at Federal University of Rio Grande do Norte, Brazil.	N. Zarrinpoor Faculty of Industrial Engineering, Shiraz University of Technology, Shiraz, Iran.	Z. Moghaddas Department of Mathematics, Qazvin Branch, Islamic Azad University, Qazvin, Iran.
L. Neralic Department of Mathematics, Faculty of Economics and Business, University of Zagreb, Croatia.	J. Trewn Wayne State University, 5050 Anthony Wayne Dr, Detroit (MI) 48202, USA.	R. Sh. Keyser Southern Polytechnic College of Engineering and Engineering Technology, Kennesaw State University, Marietta, Georgia 30060, USA.
T. Rao Padi Department of Statistics, and Dean, Faculty of Mathematical Sciences, Pondicherry University, India.		
Manager		
M. Imeni Department of Accounting, Ayandegan Institute of Higher Education, Tonekabon, Iran.	Technical Manager	
	J. Pourqasem Ayandegan Institute of Higher Education, Tonekabon, Iran.	

TABLE OF CONTENTS

Improvement of overall equipment efficiency with root cause analysis and TPM strategy: a case study

Ahsanul Abedin 205-220

ChatGPT for healthcare sector: SWOT analysis

Mobasshira Zaman 221-233

Hybrid metaheuristic artificial neural networks for stock price prediction considering efficient market hypothesis

Milad Shahvaroughi Farahani; Hamed Farrokhi-Asl; Saeed Rahimian 234-272

Designing an innovative closed-loop supply chain network considering economic and environmental aspects

Maryam Rahmaty 273-286

Measuring effective indicators for waste disposal in order to assess the sustainable environment: application of fuzzy approach

Mohammad Hossein Kabgani 287-305

The impact of digital transformation on sustainability: a case of the Iranian telecom industry

Jamal Aghayari; Changiz Valmohammadi; Mahmood Alborzi 306-320

Improving classic hungarian algorithm considering uncertainty by applying for grey numbers

Shahram Ariaifar; Seyed Hamed Moosavirad; Ali Soltanpour 321-336



Paper Type: Research Paper



Improvement of Overall Equipment Efficiency with Root Cause Analysis and TPM Strategy: a Case Study

Ahsanul Abedin* ¹ Khulna University of Engineering and Technology, Khulna9203; abedin.ipe.kuet@gmail.com.

Citation:



Abedin, A. (2023). Improvement of overall equipment efficiency with root cause analysis and TPM strategy: a case study. *International journal of research in industrial engineering*, 12(3), 205-220.

Received: 04/02/2023

Reviewed: 06/03/2023

Revised: 14/04/2023

Accepted: 26/05/2023

Abstract

Nowadays, industrial businesses are more aware of the value of machine maintenance, and more especially, the adoption of an effective maintenance strategy. Total Productive Maintenance (TPM), which involves everyday chores involving the entire workforce, increases equipment efficiency, prevents breakdowns, and promotes autonomous operator maintenance. TPM is a fantastic technique for maintaining buildings and machines. This article provides research and a review of TPM implementation in an RMG Industry to help enhance Overall Equipment Effectiveness (OEE). Data from the past have been studied, and the findings obtained in terms of motivated employees, improved OEE, and a decrease in the number of rejects/accidents on the production line are fairly positive. The methodology calls for gradually applying lean principles, Autonomous Maintenance (AM), 5S, and planned maintenance. After TPM deployment on the critical machine, improvements in availability, performance, and quality are seen boosting the overall efficacy of the equipment. A comparison of OEE before and after implementation demonstrates the effectiveness of TPM deployment throughout the industry.

Keywords: Overall equipment effectiveness, RCA, Total productive maintenance, 5S.

1 | Introduction

For businesses in the manufacturing and industrial sectors to succeed, equipment productivity and efficiency must be maximized. Implementing Total Productive Maintenance (TPM) is one method for doing this. TPM involves all staff members in maintenance tasks to increase the equipment's overall effectiveness. TPM involves all employees in improving product quality while boosting equipment uptime and reducing maintenance expenses. TPM strives to prevent equipment breakdowns through proactive maintenance techniques such as regular inspections, cleaning, and lubrication. TPM also takes into account continuing efforts to increase productivity, simplify the production process, and reduce waste. By using this technique, the equipment's general efficacy is increased and less reactive maintenance is necessary, which can help save time and money. The company needs to undergo a culture change so that everyone, from operators to executives, participates in maintenance activities to implement TPM. Management must also completely commit to TPM and adopt a disciplined approach to continuous improvement.



International Journal of Research in Industrial Engineering. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).



Corresponding Author: abedin.ipe.kuet@gmail.com


<https://doi.org/10.22105/riej.2023.393216.1388>

A key element of TPM is employee involvement in identifying and fixing equipment issues since it promotes their sense of ownership and involvement. TPM has several benefits, some of which include improved product quality, cheaper maintenance costs, more production, and increased equipment uptime. Implementing TPM can help businesses reach their sustainability objectives by reducing waste, improving energy efficiency, and reducing the environmental impact of operations. Businesses that have implemented TPM report higher production, cheaper maintenance costs, and more productive machinery. There have been instances when TPM has been utilized to achieve sustainability goals, such as waste reduction and improved energy efficiency. The following is what the letter TPM stands for Total denotes a complete analysis of all maintenance-related tasks and their impact on equipment availability. Unlike what is usually supposed, the term "productive" refers to the effort's ultimate objective, which is efficient production rather than just efficient maintenance. The program's emphasis on establishing dependable operations and maintaining production is known as maintenance. In today's highly dynamic and continuously changing environment, increased expectations of industrial organizations are a result of global business competition. Manufacturers must deliver a variety of products in the quickest possible period at prices and of acceptable quality. Overall Equipment Effectiveness (OEE) is used to calculate the performance gap between a manufacturing unit's current performance and its anticipated performance. Three metrics are included in OEE for tracking performance, availability, and quality. By categorizing the significant losses that affect the production process, these helps determine the plant's effectiveness. Downtime can be quickly decreased by using OEE to get visibility into machine status and do root-cause investigation of problems [1], [2].

Applying the methodology increased productivity and quality based on performance indicators, as well as improved organizational climate and a decrease in risks that were highlighted in the workshop. TPM aims to decrease the six significant equipment losses, to zero, which have been acknowledged as essential to the company's survival. TPM is a distinctive plant management method from Japan that was created from the concept of preventive maintenance. To achieve equipment improvement goals, this strategy places a strong emphasis on the importance of collaboration, small-group activities, and employee participation [3]. Breakdowns caused by machine failures are a common source of waste for manufacturing companies, and the implementation of strategies for strategic maintenance management is the best method to reduce them [4], [5].

In this study, a critical production line's availability is improved using the TPM technique and lean maintenance tools. After the problems are identified, a plan of action is made and put into effect to use 5S tools, visual management, and maintenance progress to find the root cause of the high frequency of errors and defects in one piece of equipment on the line. This study suggests a framework that combines the generic OEE model with problem-solving techniques to reduce three significant losses for knitting machines, boosting overall output, machine availability, and product quality. The foundation of process improvement in firms is the 5S methodology, which strives to get rid of all waste. Organizational practices like classification, cleanliness, standardization, and discipline help businesses make the most use of their resources. Higher productivity will be attained through increased production and improved resource management.

1.1 | Aim and Objective

The research was conducted to uphold specific tenets. The following list includes the research's primary goals:

- *To identify major losses by root cause analysis.*
- *To reduce major losses through the identification and elimination of root causes with TPM.*
- *To evaluate the effectiveness by analyzing OEE.*

2 | Literature Review

The TPM concept provides a quantifiable measure of OEE for evaluating the productivity of the equipment in a production line. Companies must restructure themselves and drastically increase their level of competition to meet this market need. Businesses must eliminate all production-related waste to achieve this. In the process industry, increasing production efficiency is a key component. Numerous studies have looked into the problems with an injection molding process in a company making vehicle parts. The participation of the entire organizational structure, from the CEO to the remaining employees, who must be always dedicated to the goals specified and with the responsibilities allocated to each, is a necessary step for the TPM's success.

The TPM maximizes productivity and equipment availability while fostering a stimulating atmosphere to encourage employee engagement and outperform competitors in terms of quality, reliability, cost-effectiveness, and inventiveness [6]. The personnel are in charge of maintaining the equipment with which they work daily. The operations have been well-planned and structured from the start. One of the key aspects of the TPM originated as the idea of "Autonomous Maintenance (AM)" [7]. Preventive maintenance and AM are used in this methodology. To prevent production downtime and manage the machine's service life, cleaning, inspection, component replacement, and planned repairs are all a part of AM [8].

On the other hand, the TPM can be defined as strategy-based care teams designed to maximize equipment effectiveness by developing production systems' comprehensive maintenance that covers the entire life of the equipment, which includes all equipment-related fields (planning, use, and maintenance) and involves everyone in the organization [9]. The OEE is a tried-and-true method and a particularly potent instrument that can be used to compare production units across industries and to carry out diagnostics. As long as the corrective actions are structural and simple to perform, the OEE might approve either long-term planned actions or short-term reactive actions [10], [11].

TPM is essentially a new maintenance approach created to gather the evolving maintenance requirements. TPM is an American method of meticulous maintenance that has been improved upon and tailored to work in the Japanese industrial setting. It is now acknowledged in the Japanese business and other Western nations as well [2], [12]. The TPM can be summed up using the definition below. Total productive manufacturing, also known as ordered equipment-centric nonstop enhancement, aims to maximize production effectiveness by identifying, and eliminating equipment and efficiency losses throughout the life cycle of the production system and by recruiting the active participation of team-based employees at all levels of the operating network of control [13]. Numerous studies in the literature show that TPM programs have a significant influence on organizations when they are properly implemented. Gupta and Vardhan [14] looked into the application of TPM in a well-established Indian tractor manufacturing company. According to their research, TPM reduced production costs and improved OEE, which resulted in a threefold gain in profit over three years and a doubling of sales revenue. The high defect rate prompted the organization to incur considerable costs due to product loss and poor product quality.

Using TPM, four primary reasons for failures were identified: human error, subpar raw materials, underperforming equipment, and work practices [12], [15]. Additionally, by focusing on the engine damage to the machines, they began to gather data and analyze it using Pareto charts and descriptive statistics. As a result, there were fewer machine breakdowns and mistakes, which in turn led to fewer flaws in the gloves. The majority of TPM implementation situations are found in the manufacturing industry. McKone et al. [16] looked at the connection between TPM and manufacturing performance in 2001. They showed that low-cost, high-quality standards and effective delivery performance are all significantly and positively connected with TPM. Gupta et al. [17] said that OEE is a powerful tool for identifying and eliminating losses, thereby developing an efficient production system for achieving world-class manufacturing. Rove its business performance to meet the ever-growing expectations of customers. TPM is one such methodology that has a strong potential to enhance productivity, and quality and reduce product cost [18],

[19]. The OEE value can be increased by minimizing the breakdowns and changeover losses which are associated with availability and by minimizing the defects and setup scraps losses which are associated with quality [20].

TPM generally accepts organizations in manufacturing as the most effective maintenance strategy to improve maintenance performance. Previous research showed that TPM had a direct impact on the performance improvement of production equipment [21].

3 | Methodology

Primary and secondary data for inquiry are shown in *Fig. 1*. To acquire primary data, observation of the production process, equipment monitoring, and interviews are used. During the interview process, targeted questions are directed at the pertinent company stakeholders. According to the observations of the manufacturing process on the production line, a certain machine or piece of equipment was disrupted during the production process. Secondary statistics, such as the amount of downtime, total production, the number of faults per day, and the amount of non-productive time, were obtained using historical data from both before and after the installation of TPM. Finding OEE values is the initial stage in the calculation process and it involves combining data for availability, performance, and quality. The key errors that impacted availability, performance, and quality are then identified from the six primary losses. Setup and adjustment losses, breakdown losses, and idle losses make up the availability factor. The yield or scrap losses, rework losses, minor stoppage, and reduced speed losses make up the performance component. The strategy for machine maintenance was put into place to solve the problem of low OEE values that didn't meet international standards. This strategy focused on the six major widely used factors that reduce machine efficacy.

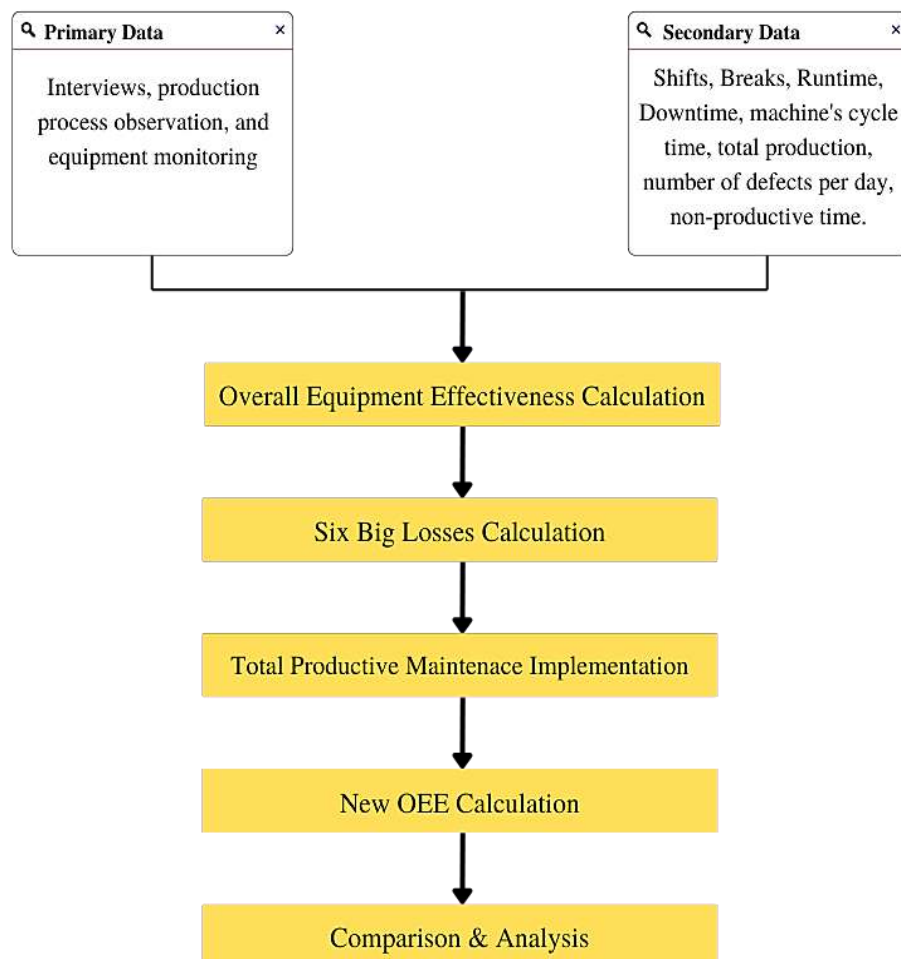


Fig. 1. Research framework.

3.1 | Overall Equipment Effectiveness Calculation

OEE is a simple tool that will help in assessing how effective their machinery is. OEE is the result of the three main factors that contributed to the six large considerable losses shown in *Table 1*.

Table 1. Six big losses.

Sl. No.	Six Major Loss Category	OEE Factor	OEE Loss Category	Example of Loss Category
01	Machine Breakdowns	Availability	Downtime	Equipment breakdowns, tool damage, and unplanned maintenance.
02	Machine setups and adjustment	Availability	Downtime	Process acclimatization, machine swaps, and material storage
03	Minor Stops	Performance	Speed	Product fraud, component blockage, and product flow obstruction
04	Machine Reduced Speeds	Performance	Speed	Level of machine operator training, tool wear, and equipment age
05	Production Rejects	Quality	Quality	Adjusting tolerance, the warming-up process, and damage
06	Rejects on start-up	Quality	Quality	Improper assembly, rejects, and rework

$$OEE = \text{Availability (A)} \times \text{Performance Rate (P)} \times \text{Quality Rate (Q)}. \quad (1)$$

The OEE's strength as a measurement instrument lies in the way it unifies various crucial manufacturing processes into a single tool. The maintenance effectiveness, production efficiency, and quality efficiency perspectives are included in the OEE tool. OEE is therefore dependent on three factors: availability (A), performance rate (P), and quality rate (Q) as *Fig. 2*.

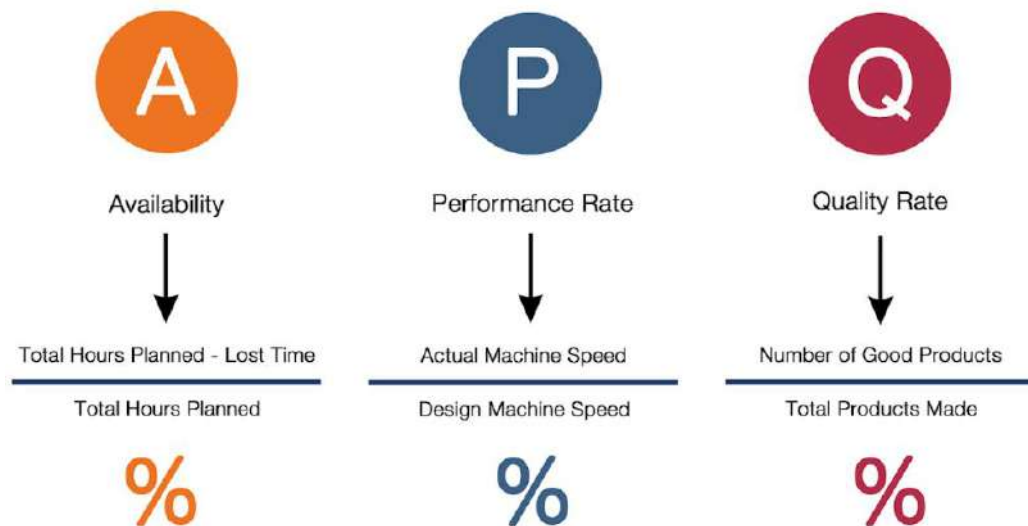


Fig. 2. OEE equations.

3.2 | OEE Calculation before TPM Implementation

Using *Eq. (1)*, the OEE of the selected production line is calculated. Here, the company's shift = 9 hours or 540 min. Lunch break = 1 hour or 60 min. So, the planned production time is 8 hours or 480 min, extra break = 20 min.

The downtime in this case encompasses startup, idling, small stoppages, speed loss, defects (scarp and rework), and equipment failure. The OEE condition of the chosen production line on the chosen level is represented in *Table 2* below:

Table 2. OEE calculation before TPM.

Machine Name	Availability (%)	Performance (%)	Quality (%)	OEE (%)
Flat lock (front neck top)	86.04	83.93	99.52	71.06
Flat lock (sleeve hem)	87.08	88.15	98.1	75.3
Flat lock (side seam)	85.20	82.46	97.78	68.69
Flat lock (body hem)	86.45	83.12	99.1	71.21
Lock stitch (neck rib tuck)	88.12	85.56	99.56	75.07
Over lock (shoulder join)	85.83	83.18	99.08	70.74
Band knife	92.08	94.46	99.56	86.60
Metal detector	91.25	87.31	100	79.67
Thread suction	90.83	93.38	100	84.82
Iron machine	90.62	93.82	99.46	84.56
Production line OEE %	82.35	83.53	85.21	67.77

So, the production Line OEE was found 76.77%. A comparison of this value with world-class standards is shown in Fig. 3.

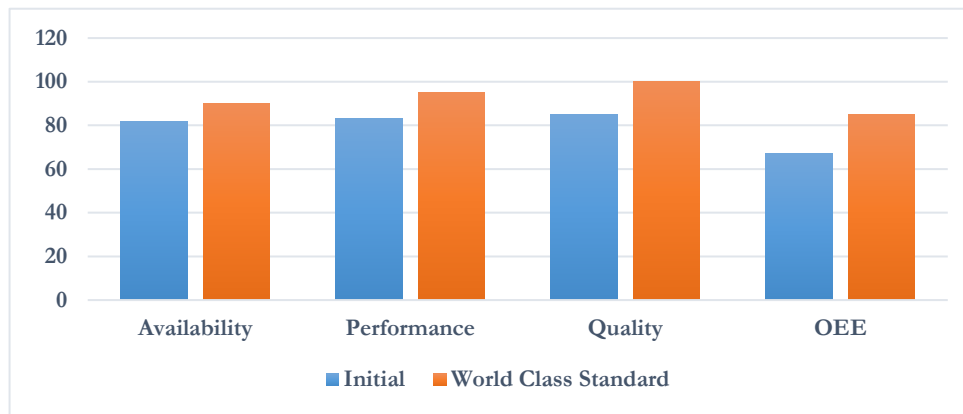


Fig. 3. OEE comparison with world-class standard.

4 | Root Cause Analysis

Root cause analysis is a systematic approach that aims to identify the underlying cause(s) of an event or problem, rather than just addressing its symptoms. It is a critical tool used in various fields, including engineering, medicine, aviation, and business management. The process of root cause analysis typically involves gathering data, identifying possible causes, evaluating evidence, and tracing the problem back to its fundamental cause(s). This process helps to uncover the root cause(s) and determine corrective actions that can prevent the problem from recurring. There are various techniques used for root cause analysis, such as the fishbone diagram, 5 whys, and Failure Modes and Effects Analysis (FMEA). The Fishbone Diagram, also known as the Ishikawa diagram, is used to identify the potential causes of a problem, while the 5 whys technique involves asking "why" questions repeatedly until the root cause(s) are identified. FMEA, on the other hand, is a proactive approach that involves identifying potential failure modes and evaluating their impact. Root cause analysis is a crucial process that helps organizations to learn from their mistakes and improve their processes. It can help to prevent similar problems from occurring in the future, improve efficiency, and increase productivity. By identifying the root cause(s) of a problem, organizations can make informed decisions on how to mitigate and prevent the problem from reoccurring.

4.1 | Fishbone Diagram

A fishbone diagram is a visual tool as Fig. 4, used to identify the potential causes of a problem or issue, also known as an Ishikawa diagram or cause-and-effect diagram. In this case, the problem or issue is low OEE on a selected production line. The major categories of potential causes are typically labeled on the diagram's branches. Each major category can be broken down further into sub-categories to identify more specific potential causes. Creating a fishbone diagram typically involves brainstorming potential causes with a team of relevant personnel to ensure that all possible causes are identified.

By mapping out all potential causes in a fishbone diagram, the root causes of low OEE can be identified, and solutions to address them. The fishbone diagram for the selected production line is shown below:

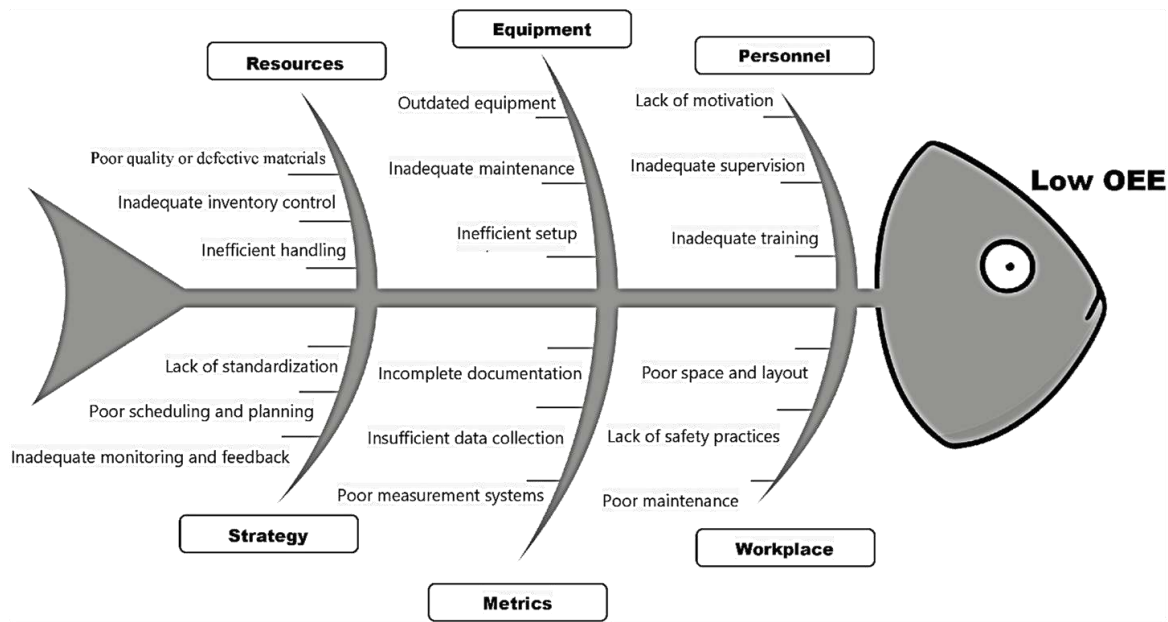


Fig. 4. Fishbone diagram for low OEE.

The following causes were found to be the root causes that resulted in low OEE for that production line:

I. Resources:

- *Material availability: insufficient or inconsistent supply of materials, or low-quality materials.*
- *Energy supply: inadequate or unreliable energy supply, which can lead to equipment breakdowns or reduced productivity.*
- *Capital investment: insufficient funding for new equipment, technology, or maintenance.*

II. Equipment:

- *Maintenance: inadequate or infrequent maintenance, which can lead to breakdowns, reduced capacity, or poor calibration.*
- *Technology: outdated or inefficient equipment, or lack of automation, which can lead to low productivity or reduced quality.*
- *Capacity: insufficient or mismatched equipment capacity, which can lead to bottlenecks or slow production.*

III. Personnel:

- *Training: insufficient or inadequate training, which can lead to errors, inefficiencies, or safety hazards.*
- *Staffing: insufficient or inexperienced staff, which can lead to overworked employees or poor quality.*
- *Motivation: poor morale or motivation, which can lead to decreased productivity or absenteeism.*

IV. Strategy:

- *Planning: inadequate or inflexible production planning, which can lead to inefficiencies or poor capacity utilization.*
- *Product design: poorly designed products or inadequate consideration of production requirements, which can lead to production problems or inefficiencies.*
- *Supply chain management: inadequate or unreliable supply chain management, which can lead to disruptions or delays in production.*

V. Metrics:

- *Data collection: insufficient or unreliable data collection, can lead to inaccurate or incomplete OEE measurements.*
- *Performance measurement: inadequate or inappropriate performance metrics, which can lead to incorrect assessment of OEE or production problems.*
- *Analysis: inadequate or incomplete analysis of OEE data, can lead to missed opportunities for improvement or incorrect diagnosis of production problems.*

VI. Workplace:

- *Environment: poor or inadequate workplace environment, such as noise, temperature, or lighting, which can lead to safety hazards, decreased productivity, or absenteeism.*
- *Organization: poor organization or layout of the workplace, which can lead to inefficiencies, safety hazards, or decreased productivity.*
- *Cleanliness: poor or inadequate workplace cleanliness, which can lead to safety hazards, quality issues, or decreased productivity.*

The effectiveness of the entire plant is impacted by the fact that all of the aforementioned problems are lowering the overall equipment efficacy of the machines on the production floor. A thorough productive maintenance strategy needs to be implemented to address the aforementioned problems and improve OEE.

4.2 | Pareto Chart

A Pareto chart is a graphical representation of data that highlights the relative importance of different categories or factors. It is named after Vilfredo Pareto, an Italian economist who observed that 80% of the wealth in Italy was held by 20% of the population. In a Pareto chart, categories are arranged in descending order of importance, with the largest category on the left and the smallest on the right. The chart also includes a cumulative percentage line that shows the cumulative percentage of the total represented by each category.

The Pareto chart is often used in quality control and process improvement to identify the most significant causes of problems or defects. By focusing efforts on the few categories that account for the majority of the issues, organizations can make the most efficient use of their resources and achieve the greatest impact.

The Pareto analysis is a quality control tool used to identify the most significant issues affecting the quality of a product or service. The Pareto principle, also known as the 80/20 rule, states that 80% of the problems are caused by 20% of the causes.

One specific application of the Pareto chart is in identifying equipment failure. To do this, data is collected on all equipment failures over a certain period, and the causes of those failures are classified. The categories might include factors like design flaws, inadequate maintenance, operator error, or environmental factors. Once the categories have been established, they are arranged in order of frequency or severity, and a Pareto chart is created. The chart allows analysts to quickly see which categories account for the majority of the equipment failures, and to prioritize efforts to address those issues. By addressing the top few categories of equipment failure, organizations can reduce downtime, increase productivity, and improve safety.

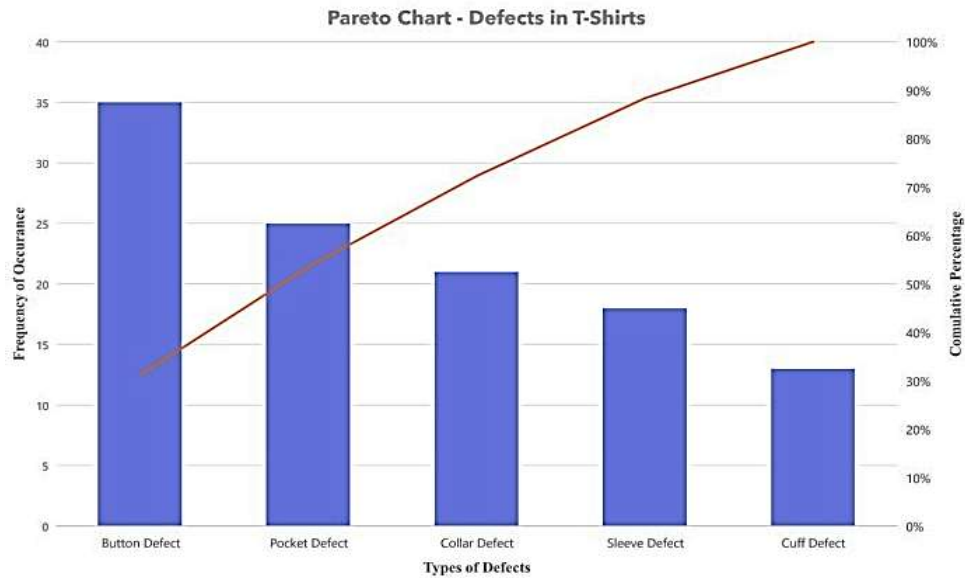


Fig. 5. Pareto analysis.

Pareto analysis of the selected production line is depicted in *Fig. 5* including button defect, pocket defect, collar defect, sleeve defect, and cuff defect with their frequency of occurrence and cumulative percentage.

Here are the defects and their frequency of occurrence for the production line:

- Button defect: 25 occurrences.
- Pocket defect: 18 occurrences.
- Collar defect: 12 occurrences.
- Sleeve defect: 10 occurrences.
- Cuff defect: 5 occurrences.

To perform the Pareto analysis, we need to calculate the cumulative percentage of the defects. The cumulative percentage is calculated by adding up the percentage of each defect to the percentage of the previous defects in *Table 3*.

Table 3. Defects analysis.

Defect	Frequency	Percentage	Cumulative Percentage
Button defect	25	36.2%	36.2%
Pocket defect	18	26.1%	62.3%
Collar defect	12	17.4%	79.7%
Sleeve defect	10	14.5%	94.2%
Cuff defect	5	7.2%	100%

From *Table 3*, we can see that the button defect and pocket defects account for over 60% of the total defects, which means they are the most significant issues affecting the quality of the production line. Therefore, the management should prioritize addressing these two issues first to improve the overall quality of the product. Here are some possible processes to reduce the rate of defects in each category:

I. Button defects:

- Implement a process to test the buttons for durability and strength during production.
- Increase the training and monitoring of the workers responsible for attaching the buttons.
- Improve the quality of the buttons used in the production process.

II. Pocket defects:

- Increase the training and monitoring of the workers responsible for sewing the pockets.
- Implement a process to test the strength and durability of the pockets during production.
- Use higher-quality fabric and thread for the pockets.

III. Collar defects:

- Increase the training and monitoring of the workers responsible for sewing the collar.
- Implement a process to test the strength and durability of the collar during production.
- Use higher-quality fabric and thread for the collar.

IV. Sleeve defects:

- Increase the training and monitoring of the workers responsible for sewing the sleeves.
- Implement a process to test the strength and durability of the sleeves during production.
- Use higher-quality fabric and thread for the sleeves.

V. Cuff defects:

- Increase the training and monitoring of the workers responsible for sewing the cuffs.
- Implement a process to test the strength and durability of the cuffs during production.
- Use higher-quality fabric and thread for the cuffs.

In general, to reduce the rate of defects, it is essential to improve the quality control process at each step of the production line. This can involve increasing the training and monitoring of the workers responsible for each step, implementing quality checks during production, and using higher-quality materials where possible. Additionally, it is essential to track and analyze the defects to identify any patterns or common issues that can be addressed systematically to prevent future occurrences. TPM is a maintenance strategy aimed at maximizing equipment effectiveness and minimizing downtime. 5S is a workplace organization method that helps improve efficiency and productivity by creating a clean and organized work environment. Together, these strategies can help identify and eliminate this waste, reduce downtime, and improve OEE. Here are some possible steps to take for implementing TPM and 5S in the production line:

- I. Create a team: assemble a team of employees who will be responsible for implementing TPM and 5S. This team should include representatives from all areas of the production line.
- II. Conduct a thorough analysis: identify the root causes of the problems you have observed in your production line. Use tools like fishbone diagrams and Pareto charts to determine the most common causes.
- III. Develop an action plan: based on your analysis, develop a plan for implementing TPM and 5S. This plan should include specific goals, timelines, and responsibilities for each team member.
- IV. Implement 5S: start by implementing the 5S methodology. This involves creating a clean and organized work environment by sorting, simplifying, sweeping, standardizing, and sustaining. Make sure to involve all team members in this process and ensure that everyone understands the importance of maintaining a clean and organized workspace.
- V. Implement TPM: once 5S is in place, begin implementing TPM. This involves creating a proactive maintenance program that focuses on preventing equipment breakdowns and improving OEE. Develop a maintenance schedule and ensure that all team members are trained to perform maintenance tasks.
- VI. Monitor progress: regularly monitor progress to ensure that TPM and 5S are being implemented effectively. Use metrics like equipment downtime, productivity, and employee feedback to measure success.

These are ongoing processes that require continuous improvement and commitment from all team members.

5 | TPM Implementation

5.1 | Industrial Overview of the TPM Approach

- I. Top Management has come to understand how the TPM tactics will benefit them.
- II. Employing training, and spreading awareness of TPM among employees.
- III. Establishing departmental and TPM committees, and specialist subcommittees, creating an organizational structure that will handle quality and AM.
- IV. Fixing TPM's guiding principles, objectives, and operational process.
- V. Creating a strategy for implementing TPM.
- VI. To maximize the benefits of TPM, the production floor implements its eight pillars.
- VII. To maintain progress over the long term, there must be constant monitoring and control.

5.2 | TPM Implementation

TPM should be applied properly and step-by-step to be successful. In *Fig. 6*, each step calls for the implementation of one TPM pillar per the needs of the business. The following diagram illustrates the progressive implementation.

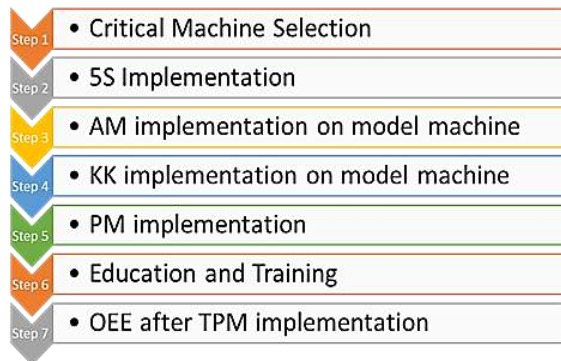


Fig. 6. TPM implementation steps.

5.3 | Pillar-Wise Steps to Adopt TPM

The introduction of the TPM program is based on the systematic application of a number of the eight TPM pillars. This would maximize plant and equipment efficiency by creating a flawless rapport between people and machinery. The *Fig. 7* below shows a typical TPM structure.

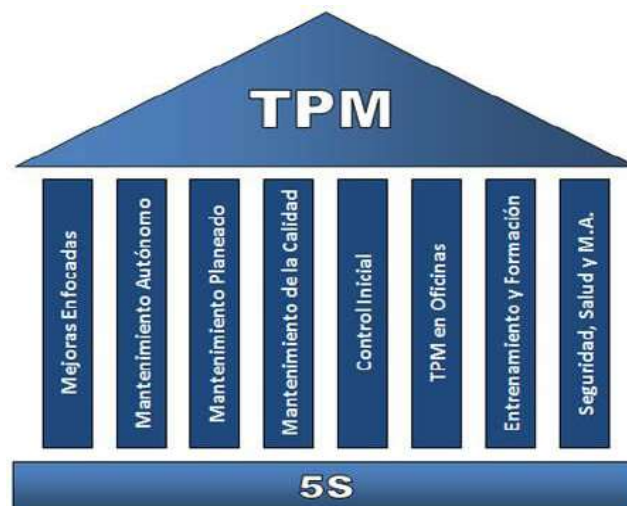


Fig. 7. TPM's 8 pillars.

Table 4. 5S implementation.

5S Terms	Actions
Seiri (sort)	A list of the things that are not regularly used. Priority must be given to objects that are used frequently, and less frequently used items should be removed. Items that are not needed must be kept in a red-tagged area where they can be located when needed.
Seiton (set in order)	Initially, make sure that all extraneous items have been removed, and arrange the necessities such that they are accessible for use. The allocation of specific locations for necessary objects and the selection of sites based on frequency of use.
Seiso (clean)	Preserving a clean, clutter-free, and dust-free workplace. involving everyone in cleaning their machines, chairs, tables, etc.
Seiketsu (standardize)	Standardizing the activities that are carried out during the first three stages. In the plant, this can be accomplished by using color coding and standard operating procedures.
Shitsuke (sustain)	Providing people with various incentives and training to encourage appropriate housekeeping practices using a 5S tagline and poster to spread awareness among the public, as well as hosting monthly 5S meetings.

Table 4 elaborates the 5S terminologies and the effect can be seen in Fig. 8 below:



Fig. 8. Scenery after 5S implementation on the factory floor.

5.5 | Implementation of AM on the Model Machine

After 5S, the model machine will go through an AM phase. This pillar is based on the notion that by delegating routine maintenance tasks to operators, skilled maintenance staff will have more time to concentrate on more complex tasks and technical repairs. Personnel must follow daily cleaning, lubrication, inspection, and tightening standards because of this CLIT instrument. Before a machine is unable to be properly identified due to a lack of maintenance, AM is performed. It increases quality and availability, avoids malfunctions, foresees failures, and prolongs equipment life. The business carried out AM by using run-to-failure mode regulation to allow the machine to run until it malfunctioned. One tool used on the assembly line to identify the machine component that appears to be malfunctioning is fugue mapping.

Machine abnormalities that put the operator in danger are referred to as fugue. Fuguai Tagging (F-Tagging) is a card with three categories—red, yellow, and blue—that is used to "tag" areas where machine anomalies exist. To understand the fundamental operations of the machine and locate the root cause, operators should receive machine function training and a component breakdown sheet. Determine the specific equipment that has a function for each component and how the components would fail using failure mode equipment analysis. The machines with the greatest risk are the axis and spindle subsystems. The five-axis system, which is the machine's critical area, should undergo AM, along with general cleaning, inspection, and F-Tagging. To show which abnormalities have been fixed and

which have not, AM boards should be filled in. Machine function and likely causes of failure should be described on machine component sheets.

5.6 | Focused Improvement

The issues in WP-ATB 08 must now be resolved by all staff or employees, from the operator level to the top management. Starting with small group activities (a group made up of several operators), the problem is addressed by creating a report that will serve as the basis for discussion.

5.7 | Planned Maintenance

This phase attempts to keep an eye on the machine's malfunctioning parts. Components like a cutter, sensors, and pusher lock can all be maintained. The business might switch its preventive maintenance program from periodic to routine maintenance.

5.8 | Quality Maintenance

Planning a maintenance system that delivers a high-quality, error-free product is the activity at this point (zero defects). The engineering team can now talk with quality control about the problems with the product quality. The maintenance staff should be aware of the maintenance activities, and standard operating procedures should be adequately documented.

5.9 | Education and Training

At this point, the staff or employees will be familiar with the machine. Before the implementation of OEE, businesses will need to develop several components, including awareness training, a clear definition of the operators' role, awareness of equipment losses, and basic equipment handling. A manager is in charge of ensuring that each maintenance worker has received the required training. They would become more knowledgeable, skilled, and capable as a result, improving their ability to make wise decisions when performing maintenance tasks. Later, I created a training program to advance our students' aptitude and knowledge in troubleshooting mechanical issues.

5.10 | Safety, Health, and Environment

All staff members will now receive training on workplace, environmental, and health safety. This knowledge includes wearing personal protection equipment, such as masks, shoes, and work attire when entering manufacturing areas. It also includes knowing how to evacuate in an emergency. Another skill might be upholding workplace environmental hygiene, such as refraining from bringing cosmetics or other foreign objects that contravene the operational standards of the company.

5.11 | Office TPM

At this stage, the company can develop TPM as a topic to be discussed regularly at every meeting in the company's activities.

5.12 | Development Management

The TPM department is currently designing an office to assist with administrative tasks that locate and eliminate waste to support production processes. Running AM, focused improvement, planned maintenance, and quality maintenance completes this level.

5.13 | OEE Calculation after TPM Implementation

After implementing the TPM methodology by the company, some new data from a certain production line was collected to calculate the OEE. The company has a 9-hour shift (8 AM to 5 PM), where the scheduled lunch break time is 1 hour/60 min. So, the planned production time is 8 hours/480min. Extra break = 20min. *Table 6* shows the new OEE calculation along with availability, performance, and quality.

Table 5. OEE calculation after TPM implementation.

Machine Name	Availability (%)	Performance (%)	Quality (%)	OEE (%)
Flat lock (front neck top)	90.00	94.00	99.00	83.00
Flat lock (sleeve hem)	89.16	91.22	99.00	80.82
Flat lock (side seam)	88.54	89.92	99.00	79.00
Flat lock (body hem)	90.00	86.00	99.00	77.00
Lock stitch (neck rib tuck)	91.25	89.00	99.80	81.05
Over lock (shoulder join)	90.62	89.37	99.50	80.00
Band knife	92.00	95.00	99.00	87.00
Metal detector	93.13	93.69	100	87.00
Thread suction	92.70	96.84	100	89.00
Iron machine	92.70	92.07	99.86	85.00
Production line OEE %	91.01	91.551	99.434	82.887

6 | Result and Discussion

Although implementing TPM successfully in any industrial setting is a difficult endeavor, the industry mentioned in the case study made every effort to complete the journey. According to the data gathered from the surveys, the industry has improved its performance in every area that concerns them, from January 2022 to February 2023. The corrective action plan increased the OEE value due to a decrease in the contributions of three major losses, confirming the plan's success. A comparison of the industrial environment scenario before and after TPM installation is shown in *Fig. 9*.

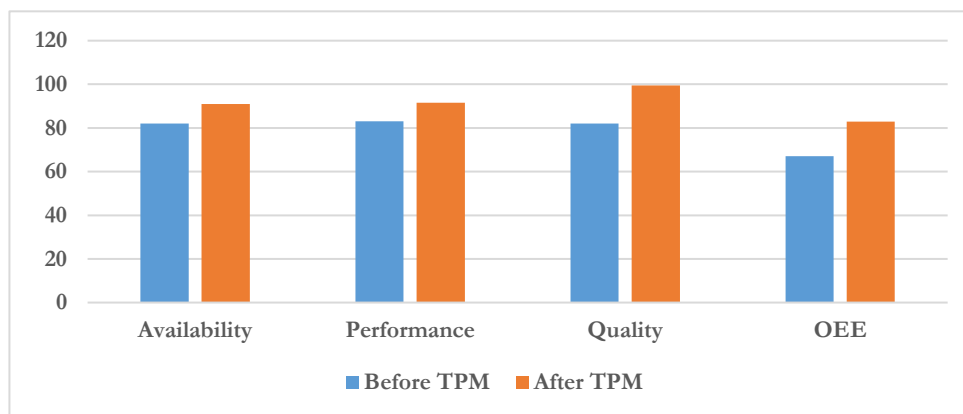


Fig. 9. OEE comparison.

By executing the TPM journey, the industry has reportedly made improvements in all relevant areas, including availability, performance efficiency, quality rate, OEE, breakdowns/accidents, customer complaints, etc. Additionally, an increasing number of managers and employees are currently expressing a desire to be hired by the industry, which is now regarded as a favorable omen for the future.

The current status of that production line is also compared with the world-class standard. This comparison is shown in the bellow chart:

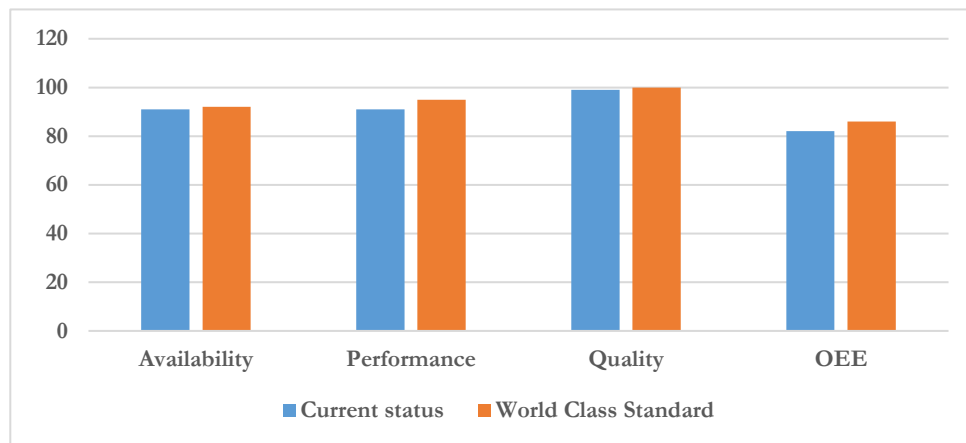


Fig. 10. OEE comparison with the world-class standard.

The industry-wide OEE is thus calculated based on the information shown in *Fig. 10*, and it is significantly lower than the global OEE level for process industries, which remains at about 85%. Hence, a successful TPM implementation can hold the industry's present OEE level closer to the worldwide average.

7 | Conclusions and Recommendation

7.1 | Conclusion

OEE was developed to reduce losses and increase value in the knitted textile sector. The following is ensured by the effective application of this sophisticated strategy:

- The rate of availability rose to 2.66% as a result of the drop in setup and adjustment loss.
- The performance rate increases to 4.021% as a result of a decrease in minor stoppage loss.
- As a result of lower shortcomings and rework loss, the rate of quality rises to 0.224%.
- The OEE rate has increased to 6.117% due to higher availability, performance, and quality rates.

The use of modern equipment and plant maintenance techniques is crucial in the age of globalization if you want to compete with other sectors. TPM is the best way for industries to keep up their effectiveness and competitiveness in terms of an organization's overall effectiveness. Continuous improvement is essential for industrial sectors to thrive and gain an advantage over rival industries. The textile spinning plant's OEE depends on both the efficiency of its machinery and the consistency of its processes because it is a continuous processing unit.

7.2 | Recommendation

Machines, as it offers logical suggestions to lower the proportion of each big loss attributed to OEE This study developed the OEE model to provide a comprehensive maintenance plan for the reduction of short stoppages, quality faults, and rework, setup, and adjustment loss. For each OEE loss, it is necessary to conduct a baseline investigation, analyze data using a Pareto chart and cause-and-effect diagrams, apply corrective action using checklists, collect data following the execution of the action plan, and compare the data. The proposed OEE model produces superior outcomes for enhancing the overall functionality of knitting causes.

- [1] Ahuja, I. P. S., & Khamba, J. S. (2008). Total productive maintenance: literature review and directions. *International journal of quality & reliability management*, 25(7), 709–756. DOI: 10.1108/02656710810890890
- [2] Bataineh, O., Al-Hawari, T., Alshraideh, H., & Dalalah, D. (2019). A sequential TPM-based scheme for improving production effectiveness presented with a case study. *Journal of quality in maintenance engineering*, 25(1), 144–161. DOI: 10.1108/JQME-07-2017-0045
- [3] Correia Pinto, G. F., José Gomes Da Silva, F., Octávio Garcia Fernandes, N., Carla Barros Casais, R., Baptista Da Silva, A., & Jorge Vale Carvalh, C. (2020). Implementing a maintenance strategic plan using TPM methodology. *International journal of industrial engineering and management*, 11(3), 192–204.
- [4] Dal, B., Tugwell, P., & Greatbanks, R. (2000). Overall equipment effectiveness as a measure of operational improvement-A practical analysis. *International journal of operations & production management*, 20(12), 1488–1502. DOI: 10.1108/01443570010355750
- [5] Ferreira, S., Silva, F. J. G., Casais, R. B., Pereira, M. T., & Ferreira, L. P. (2019). KPI development and obsolescence management in industrial maintenance. *Procedia manufacturing*, 38, 1427–1435.
- [6] Foulloy, L., Clivillé, V., & Berrah, L. (2019). A fuzzy temporal approach to the Overall Equipment Effectiveness measurement. *Computers & industrial engineering*, 127, 103–115.
- [7] Gapp, R., Fisher, R., & Kobayashi, K. (2008). Implementing 5S within a Japanese context: an integrated management system. *Management decision*, 46(4), 565–579. DOI: 10.1108/00251740810865067
- [8] Guariente, P., Antonioli, I., Ferreira, L. P., Pereira, T., & Silva, F. J. G. (2017). Implementing autonomous maintenance in an automotive components manufacturer. *Procedia manufacturing*, 13, 1128–1134. DOI: <https://doi.org/10.1016/j.promfg.2017.09.174>
- [9] Herdiwan, A., & Widiyanesti, S. (2015). An analysis of machine effectiveness on the production line by using overall equipment effectiveness (OEE) method based on total productive maintenance (TPM) principle (a study case of ball tea machine in PT Kabepe Chakra). *Journal of corporate governance, insurance, and risk management*, 2(1), 106–118. DOI: 10.56578/jcgirm020108
- [10] Hooi, L. W., & Leong, T. Y. (2017). Total productive maintenance and manufacturing performance improvement. *Journal of quality in maintenance engineering*, 23(1), 2–21.
- [11] Lameijer, B. A., Pereira, W., & Antony, J. (2021). The implementation of Lean Six Sigma for operational excellence in digital emerging technology companies. *Journal of manufacturing technology management*, 32(9), 260–284. DOI: 10.1108/JMTM-09-2020-0373
- [12] Lee Cooke, F. (2000). Implementing TPM in plant maintenance: some organisational barriers. *International journal of quality & reliability management*, 17(9), 1003–1016.
- [13] Sharma, R. (2019). Overall equipment effectiveness measurement of TPM manager model machines in flexible manufacturing environment: a case study of automobile sector. *International journal of productivity and quality management*, 26(2), 206–222. DOI: 10.1504/IJPQM.2019.097767
- [14] Gupta, P., & Vardhan, S. (2016). Optimizing OEE, productivity and production cost for improving sales volume in an automobile industry through TPM: a case study. *International journal of production research*, 54(10), 2976–2988. DOI: 10.1080/00207543.2016.1145817
- [15] Pačaiová, H., & Ižariková, G. (2019). Base principles and practices for implementation of total productive maintenance in automotive industry. *Quality innovation prosperity*, 23(1), 45–59.
- [16] Mckone, K. E., & Weiss, E. N. (1998). TPM: planned and autonomous maintenance: bridging the gap between practice and research. *Production and operations management*, 7(4), 335–351.
- [17] Gupta, P., Vardhan, S., & Haque, M. S. Al. (2015). Study of success factors of tpm implementation in indian industry towards operational excellence: an overview. *2015 international conference on industrial engineering and operations management (IEOM)* (pp. 1–6). IEEE.
- [18] Ng Corrales, L. D., Lambán, M. P., Hernandez Korner, M. E., & Royo, J. (2020). Overall equipment effectiveness: systematic literature review and overview of different approaches. *Applied sciences*, 10(18), 6469. <https://doi.org/10.3390/app10186469>
- [19] Singh, J., Singh, H., & Sharma, V. (2018). Success of TPM concept in a manufacturing unit-a case study. *International journal of productivity and performance management*, 67(3), 536–549.
- [20] Ur Rehman, A., Usmani, Y. S., Umer, U., & Alkahtani, M. (2020). Lean approach to enhance manufacturing productivity: a case study of saudi arabian factory. *Arabian journal for science and engineering*, 45(3), 2263–2280.
- [21] Wang, F. K. (2006). Evaluating the efficiency of implementing total productive maintenance. *Total quality management & business excellence*, 17(5), 655–667. DOI: 10.1080/14783360600588232



Paper Type: Research Paper



ChatGPT for Healthcare Sector: SWOT Analysis

Mobasshira Zaman* 

Department of Industrial and Systems Engineering, Northern Illinois University, United States; zaman.mobasshira@gmail.com.

Citation:

Zaman, M. (2023). ChatGPT for healthcare sector: SWOT analysis. *International journal of research in industrial engineering*, 12(3), 221-233.

Received: 01/04/2023

Reviewed: 03/05/2023

Revised: 19/06/2023

Accepted: 01/07/2023

Abstract

This research paper presents a comprehensive SWOT analysis of ChatGPT in healthcare, examining its strengths, weaknesses, opportunities, and threats. The paper highlights the potential benefits of ChatGPT, such as improved patient engagement and support for medical education, as well as its limitations, including the risk of inaccurate data and inability to summarize non-text reports. The paper also identifies opportunities for ChatGPT, such as enabling personalized healthcare delivery and supporting remote patient monitoring. However, the paper also highlights potential threats, such as self-treatment among patients and the risk of an AI-driven infodemic. The significance of this research paper lies in its valuable insights into the ethical and safe use of ChatGPT in healthcare, providing healthcare professionals and policymakers with important considerations for its use. The SWOT analysis also serves as a framework for future research and development of ChatGPT and other large language models in healthcare. This research paper is a significant contribution to the ongoing discussion on the use of ChatGPT in healthcare and its potential impact on patient care and public health.

Keywords: ChatGPT usability, Healthcare systems, SWOT analysis, OpenAI trial version.

1 | Introduction

 Licensee
International Journal of Research in Industrial Engineering. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).

The chatbot ChatGPT (Open AI, San Francisco, CA, USA) has become incredibly popular. ChatGPT, which will be made available to the general public in November 2022, is an Artificial Intelligence (AI) system that was trained using data taken from the internet that was created by people, including chats [1]. Deep learning models, known as transformers, are used in ChatGPT. Through the use of a large dataset of text, the model learns patterns and generates human-like responses. Using a conversational model, ChatGPT produces relevant and coherent responses based on context and input from users. An AI-powered chatbot is capable of Natural Language Processing (NLP), personalization, customer service, sales and marketing, task automation, 24/7 availability, etc. [2]. ChatGPT has taken internet searching to the next level; the program provides quick and thorough comprehension of complicated subjects and creates personalized conversational solutions to the precise topic posed while remembering its own past responses. ChatGPT has demonstrated outstanding performance across several use scenarios while still only being a research preview.



Corresponding Author: zaman.mobasshira@gmail.com

<https://doi.org/10.22105/riej.2023.391536.1373>

Healthcare professionals and researchers have also been very interested in and divided about ChatGPT. An AI-powered chatbot also can handle tasks like patient triage, the virtual consultations, medication administration, mental health support, chronic illness management, and more in the healthcare industry [3], [4]. Through NLP and personalization, ChatGPT can help improve healthcare efficiency and accessibility. While AI-powered chatbots can have many advantages for the healthcare, industry, there are also a number of drawbacks to taking into account, such as dependency, misdiagnosis, bad advice, lack of human touch, legal and ethical issues, and worries about privacy [5].

1.1 | Working Principle of ChatGPT

The ChatGPT system uses GPT-3.5 architecture for deep learning. A transformer neural network is trained on large amounts of text data to learn patterns and predict next words based on context. By using a combination of self-attention and feed-forward neural networks, ChatGPT can identify relationships between words. Encoding entails dividing the input text into tokens, assigning a numerical representation for each token [6]. Tokens are then passed through transformer layers, creating contextualized representations. Input text words are weighed by self-attention mechanisms, and each token has a probability of being the next word, depending on its context and training. It is possible to determine output response randomness and diversity using sampling techniques, such as temperature-based sampling. The ChatGPT system can be customised for specific datasets or domains, enhancing performance in specific tasks. The ChatGPT system combines these steps to comprehend user queries and provide relevant and coherent responses, resulting in an interactive conversation experience.

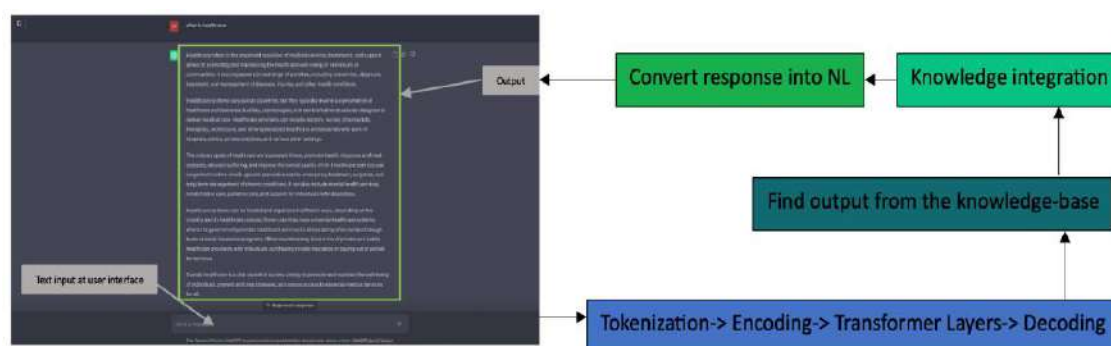


Fig. 1. ChatGPT's working principle.

To enhance its responses, ChatGPT can also rely on a knowledge base. Knowledge bases are structured collections of information available during a conversation [7]. The model is capable of retrieving relevant answers, facts, or references from a knowledge base in order to respond appropriately. This enables ChatGPT to provide accurate and reliable responses based on verified facts and data when a user query requires factual information or specifics. Human experts can create a knowledge base based on high-quality sources such as encyclopedias, databases, or industry-specific knowledge. In order to integrate the retrieved information into the generated response, ChatGPT can utilize the knowledge base. Using this integration, the model can provide contextually relevant answers, thereby improving its conversational capability.

1.2 | Example of ChatGPT's Application in Healthcare

Several medical fields have utilized Generative Pre-trained Transformer (GPT) models for treatment purposes. As part of mental health treatment, GPT models were developed to develop virtual conversational agents. Personalized and accessible treatment options are provided, offering support, guidance, and resources to treat mental health concerns. In GPT models, guidelines are used to build interactive systems that provide personalized recommendations, reminders, and feedback to encourage positive lifestyle changes. To support individuals managing chronic diseases, GPT models can provide

personalized treatment plans and medication reminders, symptom tracking, and educational resources for self-care. The field of precision medicine explores GPT models to tailor treatment to an individual's unique characteristics. Data from genomics, clinical records, and treatment outcomes can be analyzed by these models to make personalized recommendations. Rehabilitation and physical therapy use GPT modeling to develop interactive tools that can guide individuals through personalized exercise routines, provide feedback on form and technique as well as track progress. Models like GPT have been used in palliative care settings to enhance communication, assist with end-of-life decision-making, and provide information about treatments and prognoses. A chatbot, such as ChatGPT developed by OpenAI, can speed up the creation of evidence-based clinical practice guidelines by searching and selecting relevant evidence from a variety of databases in an efficient manner. However, ChatGPT should be understood to complement and enhance healthcare professionals, not to replace their expertise [8]. Chen et al. [9] evaluated the performance of ChatGPT in providing cancer treatment recommendations aligned with NCCN guidelines, finding that while it provided NCCN-concordant recommendations for most prompts, a significant portion also included non-concordant recommendations, indicating limitations in its reliability and robustness for providing accurate cancer treatment information. Arslan [10] suggests ChatGPT may be useful for obesity treatment, since it can provide personalized nutritional, exercise, and psychological support, making the treatment more effective; however, ethical and security concerns must be addressed to ensure its responsible application.

Sinha et al. [11] evaluated the capability of ChatGPT, a NLP model, in solving higher-order reasoning questions in pathology. The results showed that ChatGPT demonstrated a relational level of accuracy in providing meaningful responses, scoring approximately 80%. This suggests that the program can be utilized by academicians and students as a helpful tool for reasoning-type questions. Further research is needed to assess its accuracy in future versions of the program [7]. An exploratory case study on the use of ChatGPT for simplifying radiology reports showed promising potential in improving patient-centered care, although concerns regarding the accuracy and potential harm were identified and further research is needed [12]. According to Bhattacharya et al. [13], ChatGPT, an advanced large language model developed by OpenAI, offers impressive capabilities in generating human-like text and stimulating conversations. However, it is crucial to consider both the benefits and drawbacks of such models, as they have the potential to impact evidence-based medicine.

ChatGPT and similar GPT tools have contributed to mental and physical health treatment [14]. These models provide personalized guidance, resources, and recommendations, which improve therapy outcomes. Precision medicine analyzes genomics and clinical data to make tailored recommendations. Chronic disease management includes tailored treatment plans, medication reminders, symptom tracking, and educational resources. During rehabilitation and physical therapy, they guide individuals through personalized workout routines, track progress, and provide feedback. Furthermore, ChatGPT offers the potential to improve patient-centered care in physical and mental health treatments. While more research is needed, ChatGPT shows promise. ChatGPT is a new platform that is still developing and we can expect to see more empirical relevant research in this field in the near future.

1.3 | SWOT Analysis

The identification and analysis of internal and external elements that may have an impact on an organization's or project's success are made using the strategic planning tool known as the SWOT analysis [15]. Strengths, Weaknesses, Opportunities, and Threats are referred to by the abbreviation SWOT. The usage of ChatGPT in healthcare can benefit from SWOT analysis in a variety of ways. A SWOT analysis can provide light on ChatGPT's advantages, disadvantages, opportunities, and threats in the context of the healthcare industry. This may be used to create plans for maximizing the usage of ChatGPT in the healthcare industry, such as enhancing context awareness to deliver more accurate medical guidance. A SWOT analysis can show areas where changes can be made to better help patients and healthcare workers by highlighting ChatGPT's shortcomings related to healthcare, such as a lack of empathy.

Moreover, a SWOT analysis may assist in analyzing and minimizing these risks by identifying possible threats to ChatGPT's usage in healthcare, such as privacy issues, to guarantee patient safety and data protection. A SWOT analysis can assist in exploiting ChatGPT's strengths that are particular to the healthcare industry, such as its extensive medical expertise, to improve healthcare services for patients. A SWOT analysis can assist in investigating and extending the possible uses of ChatGPT in healthcare by finding possibilities particular to that industry, such as offering remote medical consultations.

1.4 | Significance

This article's goal is to present all sides of ChatGPT's application in healthcare, from positive to negative. A SWOT analysis of ChatGPT for the healthcare industry can reveal information about its advantages, disadvantages, opportunities, and threats. Most of the past studies discussed the opportunities and challenges of this technology. Very few papers mentioned the strength and relevant threats. However, this paper is explaining all those factors in a systematic format. This can assist in formulating plans to maximize its utilization and enhance patient outcomes for healthcare. This study advances the field of conversational AI in healthcare. Using ChatGPT in healthcare settings helps guide the design and implementation of AI systems in healthcare by identifying its strengths and weaknesses. In addition to improving patient care and engagement, the study's findings could assist healthcare professionals in making better decisions. Also, it addresses challenges and ethical concerns relating to AI, ensures patient privacy, addresses biases, and fosters trust in AI-powered healthcare solutions.

2 | SWOT Analysis

2.1 | Strength of ChatGPT in Healthcare

The extensive knowledge base of ChatGPT is one of its key advantages. With the help of extensive training data, ChatGPT has developed a profound grasp of various subjects and can respond to user inquiries with precision. Also, because of its linguistic skills, consumers will find it more approachable and natural. Moreover, ChatGPT is versatile and can be adjusted to meet varied user demands since it can be adapted and integrated with various platforms.

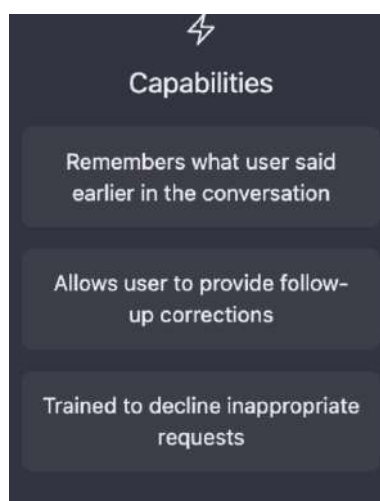


Fig. 2. ChatGPT's strength.

One of the main strengths of ChatGPT for healthcare is its NLP capabilities [7]. The vast amount of data available within a short amount of time is one of the biggest strengths of ChatGPT. Moreover, ChatGPT can provide consistent information and recommendations across different healthcare providers, reducing variability in care and improving patient outcomes.

ChatGPT has automated a storage system to remember what the user said earlier in the conversation. It allows the user to provide follow-up corrections and is trained to decline inappropriate requests.

2.2 | Weakness of ChatGPT in Healthcare

Although ChatGPT's NLP skills are one of its assets in the healthcare industry, they may occasionally be a liability. One possible drawback is that patients with inadequate reading or language abilities might not always be able to understand ChatGPT's replies. In such circumstances, a human healthcare expert may be more suited to explain medical facts to the patient in a manner that they may comprehend [16]. Another drawback of ChatGPT is that it cannot always be able to distinguish fine distinctions in language or communication, which is crucial in healthcare situations. For instance, ChatGPT might not be able to decipher crucial information about a patient's medical status from their tone of voice or other nonverbal indicators [17]. The significance of interpersonal communication and empathy in healthcare settings cannot be overstated, even though NLP is a potent tool for enhancing healthcare communication. Patients might choose to communicate with a live healthcare provider who can offer them both medical guidance and emotional support. ChatGPT's responses may be accurate but lack the emotional intelligence and empathy that a human healthcare professional can provide.

ChatGPT may not always be able to understand the context of a patient's situation or medical history, which can lead to inaccurate or inappropriate responses. Moreover, like any AI system, ChatGPT is susceptible to bias and errors that can impact the accuracy of its responses.

Because many medical reports, including radiology or imaging data, cannot be in text format, ChatGPT's inability to summarize a non-text report is a drawback for the healthcare usage of the model. ChatGPT may not be able to offer a thorough knowledge of a patient's health state or make precise treatment suggestions if it cannot summarize these findings. This could result in misdiagnoses or ineffective therapies, which might damage the patient.

For instance, ChatGPT might not be able to summarize the radiology report and determine the urgency of the problem if it shows worrisome growth. The patient can experience a worse prognosis as a result of a delayed or missing diagnosis. As a result, ChatGPT's inability to summarize non-text findings represents a substantial barrier to its adoption in the healthcare industry. Despite improvements being made, it is still difficult for AI to analyze non-text input, such as using picture recognition algorithms. To ensure that their patients receive the best care possible, healthcare practitioners must be aware of ChatGPT's limitations and utilize it in conjunction with other tools and examinations.

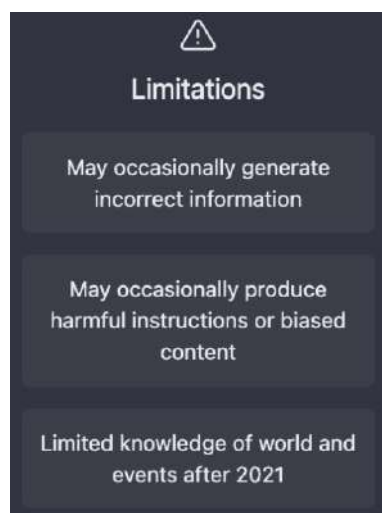


Fig. 3. ChatGPT's weaknesses in healthcare assistance – in the development stage.

Because healthcare is a profession that is continually growing and where new research and discoveries are frequently released, ChatGPT's inability to provide the most recent data is a limitation. ChatGPT may deliver obsolete or erroneous information if it does not have access to the most recent data, which might result in wrong treatment recommendations or missed diagnoses. For instance, ChatGPT may not be able to offer accurate information on the efficacy or potential adverse effects of a new treatment if it does not have access to the most recent clinical trial data. Patients may end up receiving unsuitable or inadequate therapies as a result, which might be harmful.

Moreover, the absence of the latest data may cause ChatGPT to overlook revised clinical standards, practices, or guidelines that are made in response to fresh scientific findings. This may affect its capacity to make suggestions that are accurate and up-to-date. Hence, ChatGPT's usage in healthcare is severely constrained by the lack of the most recent data. To provide the greatest service for patients, it is crucial to make sure ChatGPT gets access to the most recent and current information. To give ChatGPT the most recent information, healthcare practitioners must often update their knowledge base.

2.3 | Opportunities of ChatGPT in Healthcare

In this section, we aim to investigate the role of ChatGPT from the perspective of different participants of the healthcare system chain. The healthcare system generally comprises four major components: a healthcare provider (doctors and nurses), the health organization management, the patients, and the future ace of the system- the medical education taker and learner.

2.3.1 | Benefits for healthcare professionals

ChatGPT can act as an auxiliary for patients' diagnosis report summarization. ChatGPT is trained with NLP, which is a subfield of AI and computer science train machine to interpret human (natural) languages. NLP algorithms, Named Entity Recognition (NER), and sentiment analysis techniques extract key points from the report and can customize the summary of the report. The report provided by ChatGPT not only in a very short time but also delivers a succinct and lucid summary.

Additionally, ChatGPT has the ability to recommend diagnoses and treatments based on the data archive analysis. Not only can ChatGPT recommend diagnosis and treatment based on comparing the patient's reports and history with medical literature, but also it can predict the possible outcomes of the treatments. Thus, the system can aid doctors in providing customized treatment to patients and help to select the best option for fast recovery treatment.

Moreover, ChatGPT is a language model comprised of a vast corpus of text related to medical literature, including medical research studies, articles, and other publications. Indeed, among various methods and tools for medical literature analysis NLP and text analysis is the most efficient. Critical information on patients' demographics, treatment history, and outcome data can be extracted from the medical text by utilizing NLP techniques of ChatGPT, and the systems also assist the researchers in pinpointing the patterns and trends in the data, up-to-date and most beneficial treatment options or areas for further study. On the other hand, text analysis algorithms of ChatGPT can incorporate to identify the most important concepts and themes in the medical literature. One of the techniques is topic modeling, which the system utilizes for identifying the most common topics and themes in a set of documents. Overall, ChatGPT makes medical research a lot easier and more time efficient.

ChatGPT has vast medical information, so it can assist healthcare providers by delivering summaries of the latest research on a particular disease, treatment, or medication. To keep healthcare providers up to date, it can also give insights on recent trends and issues in healthcare, such as new treatment techniques, inventions of medicines, new therapies, diagnostic techniques, and technology, and prepare the healthcare providers by delivering background knowledge and training about disease outbreaks [10].

ChatGPT can perform a vital role by assisting healthcare professionals with telemedicine services. It accelerates the process by acting conducting patient triage, appointment scheduling, medication management, and follow-up care. By conducting the initial assessment of patients using NLP, it can refer patients to appropriate specialists. Moreover, the initial medication suggestion and information can be extracted from AI's database, including dosage level and side effects, which can be handy during medicine prescriptions. ChatGPT is an AI system that can be available 24/7 and is the best option for post-appointment updates and monitoring. Hence, ChatGPT makes after-appointment feedback tracking easy and available [5].

ChatGPT can remind patients of their upcoming appointments and medications, which is very useful in the case of chronic conditions. Moreover, by tracking patients' symptoms, this system can assist nurses and guide increasing patient involvement by spending less time maintaining a better patient outcome.

2.3.2 | Opportunities for healthcare management

AI can automate administrative processes of healthcare systems by performing tasks on behalf of administrative staff [4]. ChatGPT can facilitate patients in scheduling appointments with healthcare providers and remind them of upcoming appointments. ChatGPT can send automated messages to patients regarding appointment reminders, test results, and other important information. Adjoining AI, thus, not only can help reduce the workload of administrative staff but also can ensure that patients receive timely care. Therefore, chances of missed notification and human error can be reduced if not eliminated from the system.

Additionally, ChatGPT can help healthcare providers with billing and coding tasks by providing information on coding requirements. As an AI system, naturally, ChatGPT has the capability to identify potential billing errors and thus ensure that claims and transactions are accomplished correctly. Besides, ChatGPT can assist with health insurance management by providing information on insurance requirements, verifying patient eligibility, and submitting claims. This can help reduce errors and ensure that healthcare providers are reimbursed appropriately for their services.

ChatGPT can generate healthcare websites by performing tasks such as content creation, website design, and website maintenance if the necessary information is given. The AI system can guide to generate the website for a healthcare organization and incorporate it in answering patients' frequently asked questions, diverting patients to appropriate specialists in telemedicine management and system automation, enabling 24/7 service without human error and saving time for administrative staff to perform other priority tasks.

2.3.3 | Opportunities for patients

ChatGPT can assist patients in understanding medical terminology and jargon. It has a database from which it extracts information related to particular terminology and provides the querier with a description and meaning of the jargon. Thus, helps the patients to understand complex medical terms in a more straightforward language than that of as mentioned in their medical reports from either diagnoses or prescriptions from doctors, which helps to carry out the treatment plans better. As patients realize the terminologies, patients can explore all treatment options before making decisions. Also, ChatGPT provides the patients with information about the different treatment options available if only some particular key points are mentioned about the symptoms. However, more detailed queries can help ChatGPT provide a better and more accurate response. Moreover, by exploring the potential health risk of different drugs, health conditions, and treatments, ChatGPT guides patients in making more informed decisions.

According to the figure, ChatGPT provided treatment suggestions for fever, medicine, lifestyle, and home remedy. Moreover, it's suggested to make a doctor's appointment in case of a high fever and mention the temperature, which should be considered a high fever.

The database of ChatGPT can track related information about mediums, i.e., counseling services, emergency contact details, etc. For first aid and initial or emergency, thus, ChatGPT can be of great help. Lastly, ChatGPT helps to minimize the management procedural time and the lead time of waiting for treatment reduce, and patients are the ultimate benefited party from this time efficiency.

2.3.4 | Opportunities for medical education

Technology breakthroughs are advancing medical education, and AI like Chat GPT can serve many beneficial functions. ChatGPT has the potential to play a significant role in the field of medical education. It can be used to automate the grading process, generate exercises and scenarios, create personalized learning plans, provide research assistance, offer quick access to information, and even translate languages. With its ability to analyze sentence structure, vocabulary, grammar, and clarity of papers and essays, ChatGPT can be a valuable tool for educators who have to grade a large number of assignments. It can also generate exercises and quizzes, summaries, and translations, making complex learning materials easier for students to understand. Additionally, ChatGPT can create virtual tutors that can answer students' questions and provide feedback on their work. It can also assist in research by answering questions, generating bibliographies and outlines, and summarizing relevant articles [18].

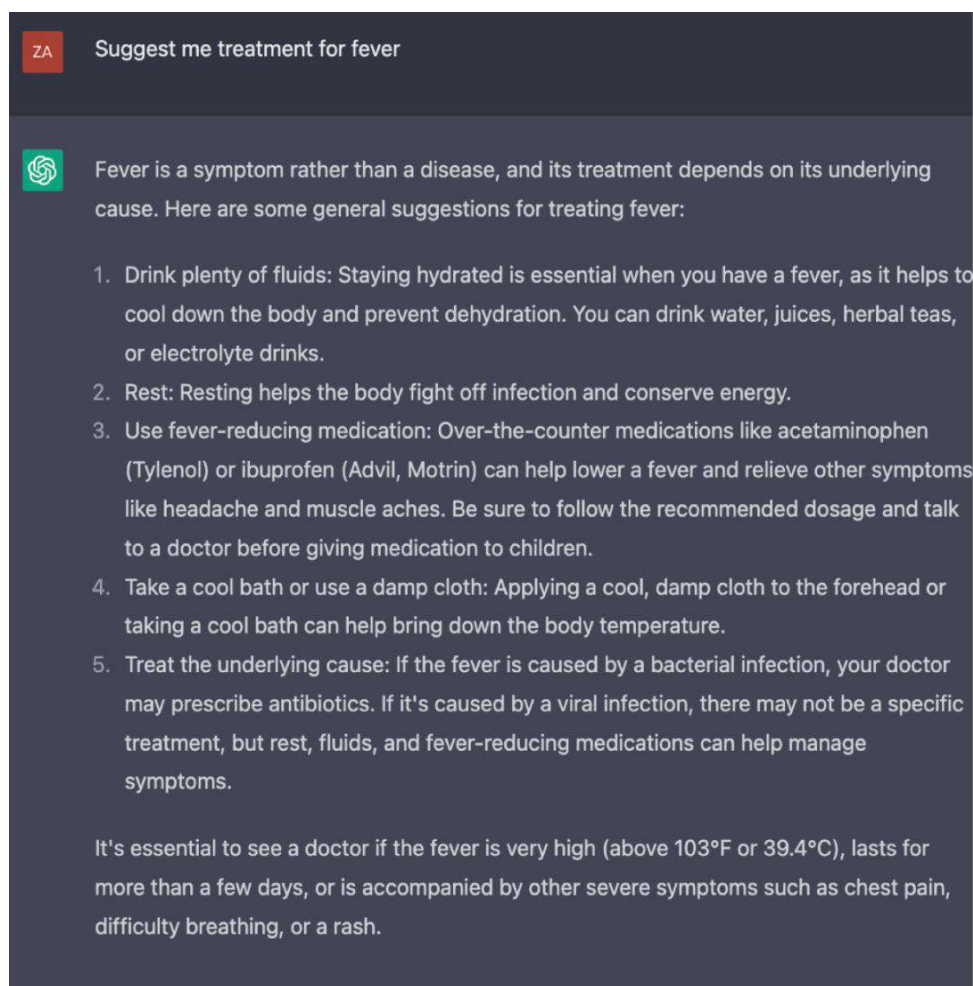


Fig. 4. ChatGPT's treatment suggestion for fever.

Furthermore, ChatGPT can generate case scenarios to help medical students practice and improve their diagnostic and treatment-planning abilities. It can also create relevant, engaging, and interactive materials such as summaries, quizzes, and flashcards to facilitate learning for students. Its language translation abilities can be used to communicate with patients from different linguistic backgrounds, providing the best medical care. ChatGPT's potential to revolutionize medical education is immense, and it can play a significant role in shaping the future of healthcare by creating a more skilled and knowledgeable workforce.

2.4 | Threats of ChatGPT in Healthcare

Because of its NLP capabilities, ChatGPT poses various possible risks to the healthcare industry. One possible risk is that ChatGPT's replies might be inaccurate or mistaken. Although while ChatGPT has been trained on a sizable quantity of data and has shown good accuracy in many situations, it is not perfect. Inaccurate or incorrect medical advice from ChatGPT might hurt patients or have unfavorable effects. The potential for bias in ChatGPT's replies represents a further danger. In healthcare situations, prejudice or discrimination may result if the data utilized to train ChatGPT is in any way skewed. Patients from marginalized populations who may already suffer discrepancies in healthcare may find this to be especially troubling.

Also, there may be security and privacy issues with the usage of ChatGPT in the medical field. If ChatGPT is not properly deployed or protected, it might result in data breaches or other security problems that endanger patient confidentiality and privacy. Lastly, the application of ChatGPT in healthcare may raise moral questions about the use of AI in clinical judgment. Some may contend that the application of AI language models in the medical field might diminish the value of human empathy and emotional support in patient care. Concerns about AI's capacity to completely replace human healthcare workers may also exist.

ChatGPT can potentially be a threat for healthcare due to a number of reasons. The use of ChatGPT in healthcare raises legal and ethical concerns around liability, accountability, and responsibility for medical advice given by an AI system [4].

Currently, there is a lack of clear regulation and standards for the use of AI in healthcare, which can make it difficult to ensure patient safety and quality of care [4], [5].

The widespread use of ChatGPT and other AI systems in healthcare may lead to job displacement for healthcare professionals, particularly those in lower-skilled roles [6].

Some patients and healthcare providers may be resistant to the use of AI in healthcare, preferring to rely on human expertise and interaction [19], [20].

Because inaccurate data can result in wrong treatment recommendations, missed diagnoses, and potential patient injury, it poses a serious danger to the implementation of ChatGPT in the healthcare industry [21]. Inaccurate data can seriously impair ChatGPT's capacity to give accurate and knowledgeable replies to healthcare practitioners and patients. For instance, ChatGPT may provide erroneous treatment suggestions or omit crucial information that might have an influence on a patient's care if it gets inaccurate data regarding a patient's medical history or present symptoms.

Moreover, biases in the data that ChatGPT is trained on may contribute to erroneous results [22]. These prejudices may cause ChatGPT to make incorrect or biased, especially in the direction of underprivileged groups. Further discrepancies in healthcare results and patient experiences may result from this. As a result, healthcare practitioners must make sure ChatGPT is trained using reliable, impartial data and constantly evaluate its performance to spot and fix any errors. In order to assure its correctness and relevance to the patient's particular circumstance, it is also crucial to check and confirm any information that ChatGPT delivers. Patients may suffer injury if this is not done, which might lower the standard of treatment.

The inclination of patients to self-treat poses a risk to the use of ChatGPT in healthcare since it may result in improper and perhaps hazardous self-treatment techniques. ChatGPT is a tool designed to help medical staff and give people information, but it shouldn't take the place of advice from a licensed healthcare expert.

Patients could be tempted to diagnose and treat their diseases entirely based on the information supplied by ChatGPT without consulting a doctor [23]. This may result in self-medicating with the wrong drugs, delaying getting the right help, or failing to realize how bad their illness is. For instance, a patient may utilize ChatGPT to self-diagnose their symptoms before buying and taking over-the-counter drugs without consulting a doctor. This could exacerbate their disease, conceal the intensity of their symptoms, or lead to unfavorable drug interactions.

Moreover, patients could lack the medical expertise required to correctly evaluate and implement the data offered by ChatGPT. This increases the risk of injury by increasing the likelihood of misconceptions or incorrect interpretations of the information. As a result, healthcare professionals need to inform individuals on how to utilize ChatGPT properly and stress the value of consulting a doctor before self-treating any ailment. Patients should be made aware that ChatGPT is an adjunct to medical therapy, not a substitute for it. To ensure that patients are informed about ChatGPT's limits and possible hazards, it is crucial to create precise guidelines for its usage. Patients may suffer injury and the standard of treatment may be compromised if this is not done.

The learning process of medical students may be endangered by the usage of ChatGPT in healthcare teaching [24]. Students may avoid learning from real-world experiences, which are essential for enhancing clinical decision-making abilities, as a result of their reliance on ChatGPT. Moreover, the likelihood of plagiarism when utilizing ChatGPT can be detrimental to the standard of medical education. To hone their clinical abilities, medical students must learn how to assess and analyze medical information in the moment, such as during patient interactions. The development of these abilities may be hampered by relying simply on ChatGPT for information since it does not take into account the subtleties and complexity of real-time medical decision-making.

The quality of medical education may suffer as a result of the inclination toward plagiarism when utilizing ChatGPT. Without a thorough comprehension of the underlying medical ideas, medical students may be tempted to copy and paste material from ChatGPT, which might result in subpar patient care and even cause injury to patients.

It is crucial to use ChatGPT in conjunction with medical education, not as a substitute for it. In order to help their learning process, medical students must obtain sufficient instruction on how to utilize ChatGPT appropriately and successfully. This includes highlighting how critical it is for them to practice making clinical decisions in real-world settings and offering advice on how to utilize ChatGPT responsibly and without plagiarism. Failing to do so might degrade medical education standards and have a severe effect on patient care.

5 | Conclusion

This paper presents a thorough SWOT analysis of ChatGPT in healthcare, providing an overview of its strengths, weaknesses, opportunities, and threats. The analysis revealed several potential benefits of using ChatGPT in healthcare, such as improved patient engagement, instant access to medical information, and support for medical education. However, there are also limitations to its use, such as the risk of inaccurate data and an inability to summarize non-text reports.

Furthermore, the analysis identified potential opportunities for ChatGPT, including supporting remote patient monitoring and enabling personalized healthcare delivery. Nevertheless, its use also poses potential threats, such as the possibility of self-treatment among patients and the risk of an AI-driven infodemic.

Table 1. SWOT analysis of ChatGPT for healthcare highlight.

Strengths	Extensive knowledge base Linguistic skills Versatility NLP capabilities is a main strength for healthcare. ChatGPT can provide consistent information, recommendations across healthcare providers. Automated storage system to remember user input and decline inappropriate requests
Weaknesses	Limited patient comprehension due to language and reading Lack of emotional intelligence and empathy Inability to understand context or medical history Susceptibility to bias and errors Inability to summarize non-text data format Lack of access to the most recent data
Opportunities	Benefits for healthcare professionals: – Summarise patient reports quickly and accurately. – Recommends diagnoses and predicts possible outcomes. – Extracts critical information from medical text. – Delivers summaries of latest research on diseases, treatments and medications. – Assists with telemedicine services, patient triage, appointments scheduling and medication management. – Reminds patients of upcoming appointments and medications. Opportunities for healthcare management: – Automates administrative processes and reduces workload. – Helps with billing and coding tasks and insurance management. – Generates healthcare websites and provides 24/7 service. Opportunities for patients: – Assists patients in understanding medical terminology and jargon. – Provides information about different treatment options available. – Enables patients to ask more detailed queries for better guidance. – Provides reminders of upcoming appointments and medications.
Threats	Inaccurate or mistaken replies from ChatGPT Potential bias in ChatGPT's replies Security and privacy issues Ethical concerns around the use of AI in clinical judgment Lack of clear regulations and standards for the use of AI in healthcare Job displacement for healthcare professionals Patient and healthcare provider resistance to AI in healthcare Inaccurate data could result in wrong treatment recommendations missed diagnoses, and potential patient injury. Patients' inclination to self-treat leading to improper and potentially hazardous self-treatment techniques Endangerment of the learning process of medical Students who rely too heavily on ChatGPT and may be prone to plagiarism.

It is clear that ChatGPT can dramatically improve patient care and medical education. Yet, because of the inherent hazards, its use in healthcare necessitates a careful evaluation of moral and practical considerations. Hence, while using ChatGPT in healthcare, professionals and policymakers should exercise caution and make sure that it is done so in accordance with ethical standards and safety precautions.

Overall, this study adds to the continuing discussion about ChatGPT's application in healthcare and its possible effects on patient care and general health. This paper's SWOT analysis approach offers useful direction for the study and development of ChatGPT and other big language models in healthcare.

- [1] Kim, S. G. (2023). Using ChatGPT for language editing in scientific articles. *Maxillofacial plastic and reconstructive surgery*, 45(1), 13. <https://link.springer.com/article/10.1186/s40902-023-00381-x>
- [2] Krishnan, C., Gupta, A., Gupta, A., & Singh, G. (2022). Impact of artificial intelligence-based chatbots on customer engagement and business growth. In *Deep learning for social media data analytics* (pp. 195–210). Springer.
- [3] Abedin, Y., Ahmad, O. F., & Bajwa, J. (2023). AI in primary care, preventative medicine, and triage. In *AI in clinical medicine: a practical guide for healthcare professionals* (pp. 81–93). Wiley Online Library. <https://doi.org/10.1002/9781119790686.ch9>
- [4] Jadczyk, T., Wojakowski, W., Tendera, M., Henry, T. D., Egnaczyk, G., & Shreenivas, S. (2021). Artificial intelligence can improve patient management at the time of a pandemic: the role of voice technology. *Journal of medical internet research*, 23(5), e22959. <https://www.jmir.org/2021/5/e22959/>
- [5] Hoffmann, C. H., & Hahn, B. (2020). Decentered ethics in the machine era and guidance for AI regulation. *AI & society*, 35, 635–644.
- [6] Roisenzvit, A. B. (2023). *From euclidean distance to spatial classification: unraveling the technology behind GPT models*. <https://ucema.edu.ar/sites/default/files/2023-04/853.pdf>
- [7] Panda, S., & Kaur, N. (2023). Exploring the viability of ChatGPT as an alternative to traditional chatbot systems in library and information centers. *Library hi tech news*, 40(3), 22–25.
- [8] Tustumi, F., Andreollo, N. A., & Aguilar-Nascimento, J. E. de. (2023). Future of the language models in healthcare: the role of chatGPT. *ABCD. arquivos brasileiros de cirurgia digestiva (são paulo)*, 36, e1727. <https://www.scielo.br/j/abcd/a/6CLbpwhNDWx9WpKZd56hYtm/>
- [9] Chen, S., Kann, B. H., Foote, M. B., Aerts, H. J. W. L., Savova, G. K., Mak, R. H., & Bitterman, D. S. (2023). The utility of ChatGPT for cancer treatment information. *MedRxiv*, 2003–2023. <https://doi.org/10.1101/2023.03.16.23287316>
- [10] Arslan, S. (2023). Exploring the potential of Chat GPT in personalized obesity treatment. *Annals of biomedical engineering*, 51, 1887–1888.
- [11] Sinha, R. K., Roy, A. D., Kumar, N., Mondal, H., & Sinha, R. (2023). Applicability of ChatGPT in assisting to solve higher order problems in pathology. *Cureus*, 15(2), e35237. <https://www.cureus.com/articles/140097-applicability-of-chatgpt-in-assisting-to-solve-higher-order-problems-in-pathology.pdf>
- [12] Jeblick, K., Schachtner, B., Dextl, J., Mittermeier, A., Stüber, A. T., Topalis, J. (2023). ChatGPT makes medicine easy to swallow: an exploratory case study on simplified radiology reports. *European radiology*, 1–9. <https://link.springer.com/article/10.1007/s00330-023-10213-1>
- [13] Bhattacharya, K., Bhattacharya, A. S., Bhattacharya, N., Yagnik, V. D., Garg, P., & Kumar, S. (2023). ChatGPT in surgical practice—a New Kid on the Block. *Indian journal of surgery*, 1–4. <https://link.springer.com/article/10.1007/s12262-023-03727-x>
- [14] Sallam, M. (2023). ChatGPT utility in healthcare education, research, and practice: systematic review on the promising perspectives and valid concerns. *Healthcare*, 11(6), 887. <https://doi.org/10.3390/healthcare11060887>
- [15] Leigh, D. (2009). SWOT analysis. *Handbook of improving performance in the workplace: volumes 1-3*, 115–140.
- [16] Hu, X., Tian, Y., Nagato, K., Nakao, M., & Liu, A. (2023). *Opportunities and challenges of ChatGPT for design knowledge management*. <https://arxiv.org/abs/2304.02796>
- [17] George, A. S., George, A. S. H., Baskar, T., & Martin, A. S. G. (2023). Human Insight AI: An Innovative Technology Bridging The Gap Between Humans And Machines For a Safe, Sustainable Future. *Partners universal international research journal*, 2(1), 1–15.
- [18] Khan, R. A., Jawaid, M., Khan, A. R., & Sajjad, M. (2023). ChatGPT-Reshaping medical education and clinical management. *Pakistan journal of medical sciences*, 39(2), 605. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10025693/>
- [19] Longoni, C., Bonezzi, A., & Morewedge, C. K. (2019). Resistance to medical artificial intelligence. *Journal of consumer research*, 46(4), 629–650.

- [20] Asan, O., Bayrak, A. E., & Choudhury, A. (2020). Artificial intelligence and human trust in healthcare: focus on clinicians. *Journal of medical internet research*, 22(6), e15154. <https://www.jmir.org/2020/6/e15154/>
- [21] Oviedo-Trespacios, O., Peden, A. E., Cole-Hunter, T., Costantini, A., Haghani, M., Kelly, S., & Reniers, G. (2023). The risks of using ChatGPT to obtain common safety-related information and advice. *Safety science*, 167, 106244. <https://doi.org/10.1016/j.ssci.2023.106244>
- [22] Hosseini, M., & Horbach, S. P. J. M. (2023). Fighting reviewer fatigue or amplifying bias? Considerations and recommendations for use of ChatGPT and other Large Language Models in scholarly peer review. *Research integrity and peer review*, 8(1), 4. <https://link.springer.com/article/10.1186/s41073-023-00133-5>
- [23] Morley, J., & Floridi, L. (2023). *Foundation Models are exciting, but they should not disrupt the foundations of caring*. <https://dx.doi.org/10.2139/ssrn.4424821>
- [24] Abdulai, A. F., & Hung, L. (2023). Will ChatGPT undermine ethical values in nursing education, research, and practice. *Nurs. inq.* e12556--e12556. https://www.researchgate.net/profile/Abdul-Fatawu-Abdulai/publication/370323174_Will_ChatGPT_undermine_ethical_values_in_nursing_education_research_and_practice/links/644c24084af788735245a8f7/Will-ChatGPT-undermine-ethical-values-in-nursing-education-research-and-practice.pdf



Paper Type: Research Paper



Hybrid Metaheuristic Artificial Neural Networks for Stock Price Prediction Considering Efficient Market Hypothesis

Milad Shahvaroughi Farahani^{1,*} , Hamed Farrokhi-Asl², Saeed Rahimian¹

¹ Department of Finance, Khatam University, Tehran, Iran; m.shahvaroughi@khatam.ac.ir; s.rahimian@khatam.ac.ir.

² Sheldon B. Lubar College of Business, University of Wisconsin-Milwaukee, Milwaukee, WI, USA; farrokh5@uwm.edu.

Citation:



Shahvaroughi Farahani, M., Farrokhi-Asl, H., & Rahimian, S. (2023). Hybrid metaheuristic artificial neural networks for stock price prediction considering efficient market hypothesis. *International journal of research in industrial engineering*, 12(3), 234-272.

Received: 08/09/2022

Reviewed: 12/10/2022

Revised: 19/11/2022

Accepted: 01/12/2022

Abstract

Investigating stock price trends and determining future stock prices have become focal points for researchers within the finance sector. However, predicting stock price trends is a complex task due to the multitude of influencing factors. Consequently, there has been a growing interest in developing more precise and heuristic models and methods for stock price prediction in recent years. This study aims to assess the effectiveness of technical indicators for stock price prediction, including closing price, lowest price, highest price, and the exponential moving average method. To thoroughly analyze the relationship between these technical indicators and stock prices over predefined time intervals, we employ an Artificial Neural Network (ANN). This ANN is optimized using a combination of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Harmony Search (HS) algorithms as meta-heuristic techniques for enhancing stock price prediction. The GA is employed for selecting the most suitable optimization indicators. In addition to indicator selection, PSO and HS are utilized to fine-tune the Neural Network (NN), minimizing network errors and optimizing weights and the number of hidden layers simultaneously. We employ eight estimation criteria for error assessment to evaluate the proposed model's performance and select the best model based on error criteria. An innovative aspect of this research involves testing market efficiency and identifying the most significant companies in Iran as the statistical population. The experimental results clearly indicate that a hybrid ANN-HS algorithm outperforms other algorithms regarding stock price prediction accuracy. Finally, we conduct run tests, a non-parametric test, to evaluate the Efficient Market Hypothesis (EMH) in its weak form.

Keywords: Technical indicators, Artificial neural network, Genetic algorithm, Harmony search, Particle swarm optimization algorithm, Efficient market hypothesis.

1 | Introduction

Various methods for predicting stock prices include technical analysis, mathematical and statistical approaches, and econometric models. The primary motivation behind the stock market prediction is rooted in the Efficient Market Hypothesis (EMH) and the pursuit of financial gains. EMH is of particular significance because it serves as a foundational concept underpinning the effectiveness of prediction. An efficient market implies that all available information is reflected in stock prices. Conversely, an inefficient market suggests the presence of individuals and entities with privileged access to additional market information. It underscores the idea that information can significantly impact the decisions made by investors, consequently leading to changes in stock prices [1].



Licensee

International Journal of Research in Industrial Engineering. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).



Corresponding Author: m.shahvaroughi@khatam.ac.ir



<https://doi.org/10.22105/riej.2023.361216.1336>

EMH rests on two fundamental assumptions: 1) all investors have equal access to identical information, and 2) there are no superior or premier strategies or systems that can consistently outperform the market [2].

In the realm of Machine Learning (ML), the concept of Artificial Neural Networks (ANNs) stands out as a powerful tool known for its remarkable capabilities, such as identifying intricate patterns (e.g., pattern recognition), making predictions, conducting clustering, and more [3]. Institutional investors have embraced artificial intelligence-based methods, including ML and Deep Learning (DL), to enhance their profit maximization strategies [4]. Financial data exhibit two prominent characteristics: nonlinearity and irregularity [5]. While econometric and time series models can be effective under certain assumptions, such as data stationarity [6], using NNs can help tackle these challenges effectively.

NNs are a widely adopted tool for predicting stock prices due to their proficiency in recognizing both linear and nonlinear relationships between inputs and outputs [7]. The financial world, including the stock market, is known for its inherent complexity and chaos [8]. By harnessing the ability of NNs to identify nonlinear relationships, we can enhance traditional analytical methods and other computational techniques for stock market prediction [9]. Beyond stock market forecasting, NNs find utility in various financial applications. Experimental and trading systems leverage them to track commodity and futures markets, conduct Forex trading, assist with financial planning, and predict corporate stability and bankruptcy probabilities [10]. Banks employ NNs to evaluate loan applicants and estimate bankruptcy risk. Financial managers utilize them to optimize portfolio planning for profitable investments. With increased interest in tools and methods for maximizing profitability and minimizing risk as investment levels rise, various prediction models, such as statistical methods, technical analysis, fundamental analysis, and linear regression, have been employed. None of these methods, however, have consistently proven their ability to predict the market precisely. They exhibit varying performances across different criteria, including predictability, accuracy, and computational complexity.

Due to the multifaceted nature of factors influencing stock prices, achieving precise predictions is challenging. Consequently, this paper proposes a hybrid approach. It involves using the Genetic Algorithm (GA) for feature selection, focusing on identifying the most relevant input variables. Furthermore, two meta-heuristic algorithms, Harmony Search (HS) and Particle Swarm Optimization (PSO), are employed to enhance the predictive capabilities of the ANN. These algorithms work together to minimize network errors, optimize weights, and determine the optimal number of hidden layers. Eight estimation criteria have been introduced to evaluate and compare the model's performance based on error metrics. The experimental results demonstrate that the hybrid ANN-HS algorithm exhibits the best performance.

The primary objective of this study is to predict stock prices using AI-based and econometric models. Additionally, it aims to explore the implications of the EMH on market efficiency and the applicability of various techniques and models, such as technical and fundamental analysis. Furthermore, the study evaluates the effectiveness of GA for feature selection. The comparison of methods and models is conducted based on error metrics and fitness functions, with the hypothesis that a combination of AI-based and econometric models, along with financial input data, can enhance model robustness and accuracy.

Notably, the study distinguishes itself in two key ways. Firstly, it conducts tests to assess the EMH, a crucial aspect often overlooked in previous research that frequently proceeds without considering this assumption. Secondly, the study encompasses a broader scope by selecting significant companies in Iran across various industries as the statistical population, in contrast to previous articles that have typically focused on predicting the index or share price of a limited number of companies.

This paper combines financial data as input variables, AI-based and econometric models, and statistical techniques to create a robust predictive model. The subsequent sections of this paper are structured as follows: Section 2 provides a literature review. Section 3 outlines the proposed algorithm and examines EMH. Section 4 delves into the experimental process and presents the results, and finally, Section 5 offers concluding remarks.

2 | Literature Review

The stock market is influenced by a multitude of factors, including economic conditions, psychological emotions and expectations, and political events. These factors collectively contribute to the stock market's inherent volatility, nonlinearity, and discontinuity [11]. Furthermore, technological advancements and communication systems have amplified the speed of stock market processes, intensifying stock price fluctuations. Consequently, parties and sectors such as banks, financial institutions, major investors, and brokers must prioritize rapid trading [12]. Investors primarily aim for profit maximization, which has prompted researchers to seek methods or models to achieve this objective [13].

The literature presents two main perspectives on market efficiency. The first perspective asserts the efficiency of the market and its resistance to the prediction of market returns [14]. The second perspective argues for the weak efficiency of the market, emphasizing a low degree of serial correlation and transaction costs, particularly in emerging markets [15]. Proponents of the EMH in the second group contend that future price changes cannot be predicted using historical data. In contrast, those who challenge the EMH assert the presence of anomalies that undermine the theory of efficient markets, as exemplified in various empirical studies [1]. These anomalies represent deviations from theoretical expectations [16].

The advancement of computer technology over the past decades has facilitated the development of optimization methods, resulting in the compilation of numerous techniques during this period. Mathematical optimization models encompass various types, including linear, nonlinear, integer, binary, probabilistic, and complex models [17]. Broadly speaking, methods for solving optimization problems can be categorized into two primary groups: exact and meta-heuristic. Accurate methods comprise algorithms such as simplex, linear, and dynamic programming, including integer programming and its derivatives. In contrast, unlike exact methods, meta-heuristic methods offer viable solutions within acceptable timeframes for large-scale problems. The expansion and diversification of applications of these methods in recent decades have garnered interest among researchers across various scientific disciplines and fields, including design engineering, aerodynamics, robotics, telecommunications, chemical process simulation, control, transportation, logistics, and supply chain management. The widespread utilization of these algorithms highlights their practical suitability and effectiveness. Noteworthy advantages of meta-heuristic methods include accelerated computational speeds, user-friendliness, and other benefits previously mentioned.

The structural framework of various optimization algorithms can be outlined in *Fig. 1*. As previously discussed, meta-heuristic algorithms find applications in diverse fields. In the context of this paper, these meta-heuristic algorithms play a pivotal role in training the ANN and serving as an optimization method. To represent the history of ML in *Fig. 2*, along with corresponding expert phrases, you can follow these guidelines provided in reference [18]. In *Fig. 2*, the methods, NNs, and tools can be categorized into green, red, and blue colors. It is evident that with each successive phase, ML has evolved and become more sophisticated, enabling it to perform a wide range of tasks, including graphical tasks, reasoning-based tasks, and decision-making, among others. In its early stages, ML experiments focused on the concept of computers recognizing patterns in data and learning from them. Over time, these foundational experiments have paved the way for developing increasingly complex ML techniques. Although ML algorithms have existed for quite some time, the rapid and effective application of intricate algorithms for handling big data is a more recent advancement.

ML has progressed from automating manual data entry to tackling more intricate tasks like fraud detection and insurance risk assessment. It is in these areas that ML truly shines. A significant advantage of ML lies in its ability to discern what the human eye might overlook. ML models are adept at identifying complex patterns that could easily elude human analysis.

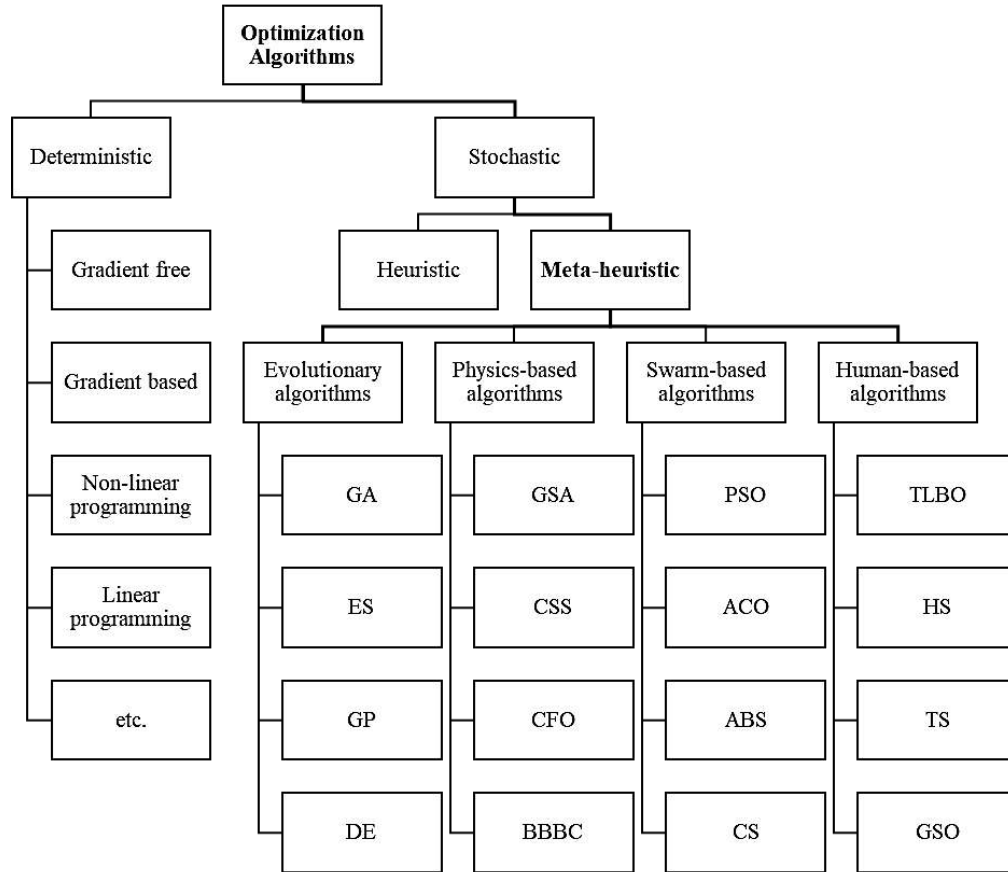


Fig. 1. Optimization algorithms.

Fig. 1. represents the position of meta-heuristic algorithms among other optimization algorithms.

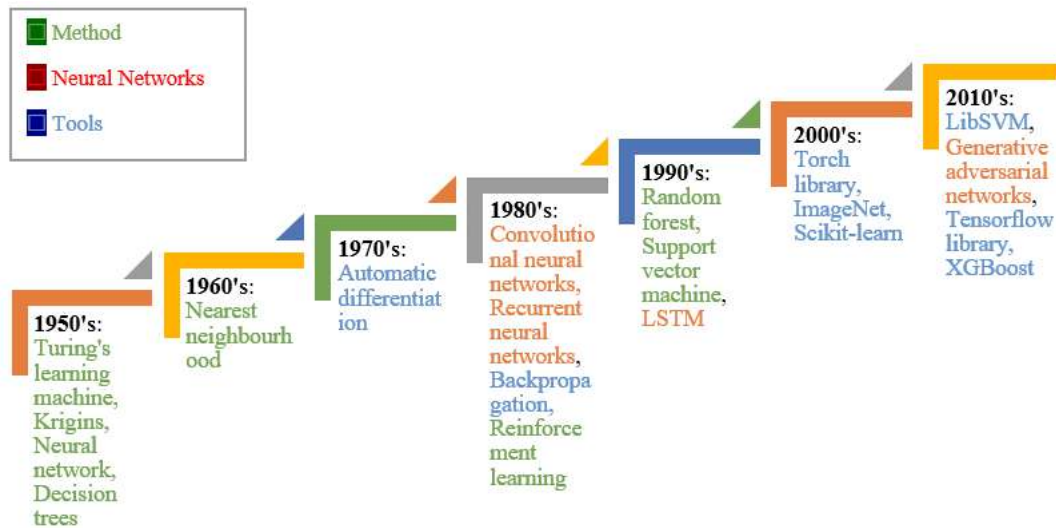
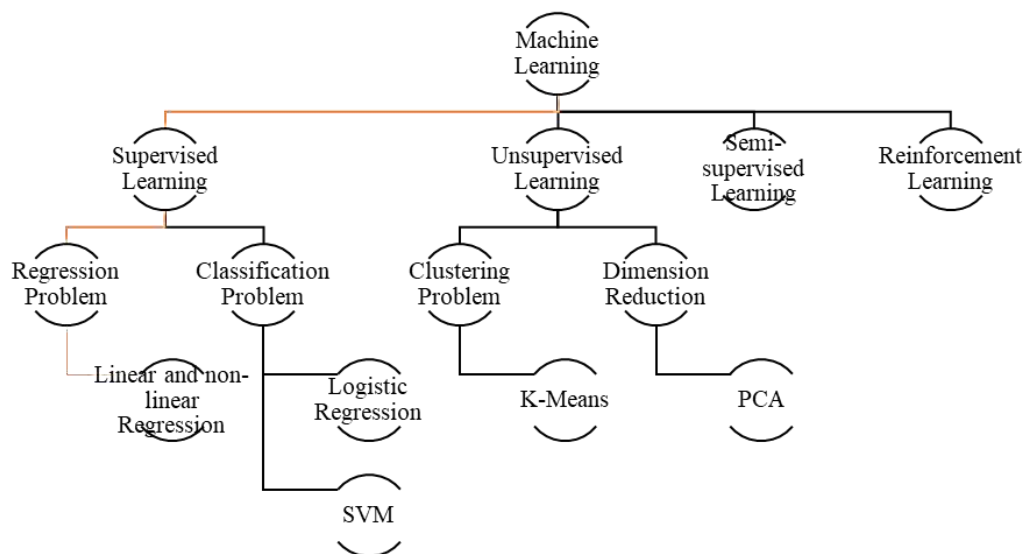


Fig. 2. ML history.

ML can automate nearly any task that relies on data-defined patterns or a set of rules. Table 1 provides a concise overview of various ML techniques. To better understand the relationship between categories and AI components, Fig. 3 is depicted [19].

Table 1. ML components and techniques.

Name	Definition
Regression	Regression methods help to predict or explain a particular numerical value based on a set of prior data.
Classification	Classification methods predict or explain a class value.
Clustering	Group or cluster observations that have similar characteristics.
Dimensionality reduction	Remove the least important information (sometimes redundant columns) from a data set.
Ensemble methods	Combining several predictive models (supervised ML) to get higher quality predictions than each of the models could provide on its own.
NN and DL	NNs aim to capture nonlinear patterns in data by adding layers of parameters to the model.
Transfer learning	It refers to re-using part of a previously trained neural net and adapting it to a new but similar task.
Supervised learning	Allows you to collect data or produce a data output from a previous ML deployment.
Unsupervised learning	Helps you find all kinds of unknown patterns in data.
Reinforcement learning	Taking suitable action to maximize reward in a particular situation.
Natural language processing	A widely used technique to prepare text for ML.


Fig. 3. ML subsets.

The experimental findings and research studies consistently demonstrate the robustness of ANNs in forecasting stock prices [20]. Researchers continually seek models to enhance prediction accuracy, reduce errors, and expedite calculations. In this regard, meta-heuristic algorithms are highly effective, offering optimization and model selection capabilities. ANNs serve as a powerful tool for various forecasting tasks, including stock prices, stock returns, exchange rates, and inflation. Notably, they outperform traditional statistical models [21].

Göçken et al. [22] employed a hybrid ANN based on GA and HS to predict the Turkish price index, incorporating technical indicators as input variables. The results underscored the robustness of the hybrid ANN-HS approach. Hassanin et al. [23] explored the use of Grey Wolf Optimization (GWO) for providing initial solutions to ANNs, highlighting the superiority of the hybrid GWO-ANN method. Faris et al. [24] utilized a Multi-Verse Optimizer (MVO) to optimize weights and biases for multilayer perceptron networks, comparing their performance with several other algorithms. Rather et al. [25] emphasized the burgeoning interest in hybrid forecasting approaches, concluding that hybrid ANNs contribute to model robustness.

Yang et al. [26] predicted Chinese stock prices using an ensemble of multilayer feedforward networks, incorporating the Backpropagation Neural Network (BPNN) for training and a bagging approach for

ensemble formation [27]. Their results indicated the somewhat predictable nature of the Chinese market using this approach with satisfactory accuracy, precision, and recall. Zhang et al. [9] proposed a system that predicts stock price movement and growth/decline rate intervals within predefined durations. They employed a random forest model to classify stocks into four primary classes and achieved superior results in terms of market volatility prediction. Ahmed et al. [28] utilized Ant Colony Optimization (ACO) for stock price prediction from the Nigerian stock exchange, demonstrating the robustness of ACO when compared to other criteria. Ghanbari and Arian [29] employed Support Vector Regression (SVR) and Butterfly Optimization Algorithm (BOA) for stock market prediction, achieving significant improvements in parameter optimization and model performance. Chandana [30] introduced a hybrid prediction method for stock prices based on LSSVR and ML, simplifying calculations while enhancing accuracy. Rajesh et al. [31] explored ensemble learning techniques to predict S&P500 trends, favoring Random Forest, SVM, and K-nearest neighbors' classifiers as the most powerful predictive models. Lv et al. [32] compared traditional ML algorithms with advanced deep NN models to predict index component stocks, highlighting the conventional ML algorithms' superiority under no transaction cost and DNN models' better performance when considering transaction costs.

Zaman [33] identified a weak form of market efficiency in the largest stock market of Bangladesh, using parametric and non-parametric tests to test EMH. Shahvaroughi Farahani and Razavi Hajiagha [34] applied ANN to predict indices such as S&P500, DAX, FTSE100, NASDAQ, and DJI. They utilized meta-heuristic algorithms like Social Spider Optimization (SSO) and Bat Algorithm (BA) for network training. GAs were used for feature selection, and various loss functions were employed for error evaluation. Time series models like ARMA and ARIMA were also incorporated into their analysis.

Ranjbarzadeh et al. [35] reviewed AI methods for diagnosing brain tumors using MRI images, employing supervised, unsupervised, and DL techniques alongside image segmentation methods. Farahani et al. [36] examined the impact of Covid-19 vaccines on economic conditions and sustainable development goals, utilizing ANN and the Beetle Antennae Search (BAS) algorithm for prediction. The study revealed that both AI and econometric models yielded similar results, with AI optimization models enhancing robustness.

In the context of supply chain design, Tirkolaee et al. [37] addressed critical issues such as supplier selection, order size identification, and order allocation across three supply chain levels. Their objectives encompassed cost minimization, product value maximization, and supply chain reliability maximization. Sensitivity analyses were conducted on key model parameters to assess supply chain reliability. For further insights into the applications of ANN and algorithms, please refer to Abiodun et al. [38] and Tkáč and Verner [39].

Table 2 overviews previous research on forecasting stock prices using NNs and the methods considered.

Table 2. Some current research on forecasting stock price using ANN and other methods.

Author(s)	Title	Methodology	Results
Pierdzioch and Risse [40]	A machine-learning analysis of the rationality of aggregate stock market forecasts	Testing rationality of aggregate stock market forecasts based on an ML algorithm called Boosted Regression Trees (BRT)	Rational The Expectations Hypothesis (REH) did not reject short-term forecasts, but for a longer term, there was evidence against the REH
Zhong and Enke [41]	Predicting the daily return direction of the stock market using hybrid ML algorithms	Prediction of future stock market index returns using DNN and ANN	The results showed the superiority of DNNs using two PCAs over other hybrid ML algorithms based on classification accuracy

Table 2. Continued.

Author(s)	Title	Methodology	Results
Aytac et al. [42]	Digital currency forecasting with chaotic meta-heuristic bio-inspired signal processing techniques	Proposing a novel hybrid model based on Long Short-Term Memory (LSTM), NN and Empirical Wavelet Transform (EWT) along with Cuckoo Search (CS) algorithm to the prediction of crypto currency time series.	Their proposed model succeeded in capturing the nonlinear features of the crypto currency time series.
Jiang et al. [43]	The two-stage ML ensemble models for stock price prediction by combining mode decomposition, Extreme Learning Machine (ELM) and Improved Harmony Search (IHS) algorithm	Introducing a new model by combining three models means Empirical Mode Decomposition (EMD) (or Variational Mode Decomposition (VMD)), ELM and HIS algorithm for stock price prediction	The results showed the superiority of their model based on accuracy and stability compared to the other models.
Behravan and Razavi [44]	Stock price prediction using ML and swarm intelligence	Phase I. uses an automatic clustering algorithm for clustering data. Phase II. using a hybrid regression model based on PSO and SVR for training each cluster, parameter tuning and feature selection.	On average, the proposed method has shown 82.6% accuracy in predicting stock price in 1-day.
Kumar Chandar [45]	Grey Wolf optimization-Elman NN model for stock price prediction	Optimize parameters of ENN using ENN and GWO	The results showed the high predictability of the proposed model and outperformed the benchmark models taken for comparison.
Wei and Cheng [46]	A novel graph convolutional feature-based convolutional NN for stock trend prediction	Proposing a novel method for stock trend prediction using Graph Convolutional feature Convolutional Neural Network (GC-CNN) model, in which both stock market information and individual stock information are considered	The experimental analysis and results presented the superiority of the proposed GC-CNN-based method over several stock trend prediction methods and stock trading strategies.
Kumar Chandar [47]	Hybrid models for intraday stock price forecasting based on ANNs and metaheuristic algorithms	Offering nine new integrated models for forecasting intraday stock price based on the potential of three ANNs.	The results proved that the PSO-BPNN model outperformed other considered models.
Shahvaroughi Farahani and Razavi Hajiagha [34]	Prediction of international stock indices using hybrid models	Training ANN using SSO and BA algorithms.	Better performance of Hybrid model
Shahvaroughi Farahani et al. [48]	Hybrid meta-heuristic ANNs for stock price prediction considering EMH	Testing market efficiency, training ANN using HS and PSO algorithms, technical indicators as input variables, and GA as feature selection.	The best results were obtained in the HS and almost in PSO algorithms with the lowest loss functions.

Researchers have been actively exploring the hybridization of methods to improve results. It is evident that simple algorithms (those without hybridization) exhibit the following characteristics:

- I. Increased computation time.
- II. Greater model complexity.
- III. Vulnerability to local minima or maxima trapping.
- IV. Rapid convergence.

First and foremost, we believe that assessing market efficiency should precede any attempts at predicting stock prices using models or methods. This assessment serves as a litmus test for the effectiveness of the considered models or methods inefficiently predicting market trends and volatilities and their potential impacts on the market. Secondly, it's worth noting that not all technical indicators need to be considered as input variables. Hence, a method such as GA becomes essential for feature selection. Thirdly, optimizing and fine-tuning the ANN is crucial. Therefore, HS and PSO are employed as optimization methods. Finally, comparing the results with previous studies helps demonstrate the robustness of the model.

This paper aims to address the following key questions:

- I. Does utilizing a GA for feature selection impact the speed and quality of results?
- II. Can an ANN effectively predict the target stock price?
- III. Can meta-heuristic algorithms optimize the performance of an ANN?

For a more comprehensive understanding of the limitations of early models, interested readers can refer to *Table B1*.

3 | Hybrid Meta-Heuristic Artificial Neural Networks for Stock Price Prediction

3.1 | Technical Indicators

This section outlines the methodology employed for selecting input variables. In each case, a set of 42 technical indicators is considered as input variables. Technical indicators play a pivotal role in the analysis of stock prices, as they are derived from specific formulas designed for assessing stock prices or market indices through graphical tools. The literature encompasses a wide array of technical indicators, making selecting the most crucial ones a key determinant for profitability among stock market investors [38]. To address this challenge, we employ GA to identify the most relevant input variables. GA serves as the mechanism to pinpoint the indicators that exert the most significant influence on forecasting performance. *Table 3* provides an exhaustive list of all the technical indicators under consideration [34].

Table 3. Important and most common technical indicators as input variables.

Technical Indicators and their Formulas	
$\text{Diff} = \text{Close}_{\text{Today}} - \text{Close}_{\text{Yesterday}}$	$M_{\text{Open}} = \text{Open}_{\text{Today}} - \text{Open}_{\text{Yesterday}}$
Close	$M_{\text{High}} = \text{High}_{\text{Today}} - \text{High}_{\text{Yesterday}}$
High	$M_{\text{Low}} = \text{Low}_{\text{Today}} - \text{Low}_{\text{Yesterday}}$
Low	$M_{\text{Close}} = \text{Close}_{\text{Today}} - \text{Close}_{\text{Yesterday}}$
Open	$\text{Acc}_{\text{Open}} = M_{\text{Open}_{\text{Today}}} - M_{\text{Open}_{\text{Yesterday}}}$
$\text{SMA}(5) = \frac{(\text{Close}_1 + \text{Close}_2 + \dots + \text{Close}_5)}{5}$	$\text{Acc}_{\text{Close}} = M_{\text{Close}_{\text{Today}}} - M_{\text{Close}_{\text{Yesterday}}}$
$\text{SMA}(6) = \frac{(\text{Close}_1 + \text{Close}_2 + \dots + \text{Close}_6)}{6}$	$\text{Acc}_{\text{High}} = M_{\text{High}_{\text{Today}}} - M_{\text{High}_{\text{Yesterday}}}$
$\text{SMA}(10) = \frac{(\text{Close}_1 + \text{Close}_2 + \dots + \text{Close}_{10})}{10}$	$\text{Acc}_{\text{Low}} = M_{\text{Low}_{\text{Today}}} - M_{\text{Low}_{\text{Yesterday}}}$
$\text{SMA}(20) = \frac{(\text{Close}_1 + \text{Close}_2 + \dots + \text{Close}_{20})}{20}$	$\%K = \left[\frac{(\text{Close} - \text{Low})}{(\text{High} - \text{Low})} \right] * 100$

Table 3. Continued.

Technical Indicators and their Formulas	
$\text{EMA}(5)\text{Today} = \frac{\text{Close Today} * k + \text{EMA}(5)\text{Yesterday} * (1 - k)}{5}$ $K = \frac{2}{5 + 1} \cdot \text{EMA}(5)0 = \text{SMA}(5)$	%D = 3 – day SMA of %K
$\text{EMA}(6)\text{Today} = \frac{\text{Close Today} * k + \text{EMA}(6)\text{Yesterday} * (1 - k)}{6}$ $K = \frac{2}{6 + 1} \cdot \text{EMA}(5)0 = \text{SMA}(6)$	Slow%K == Fast%D
$\text{EMA}(10)\text{Today} = \frac{\text{Close Today} * k + \text{EMA}(10)\text{Yesterday} * (1 - k)}{10}$ $K = \frac{2}{10 + 1} \cdot \text{EMA}(10)0 = \text{SMA}(10)$	Slow%D = 3 – day SMA of %D
$\text{EMA}(20)\text{Today} = \frac{\text{Close Today} * k + \text{EMA}(20)\text{Yesterday} * (1 - k)}{20}$ $K = \frac{2}{20 + 1} \cdot \text{EMA}(20)0 = \text{SMA}(20)$	William's %R $= \frac{(\text{Highest high} - \text{Close})}{(\text{Highest high} - \text{Lowset low})}$
$\text{TMA}(5) = \frac{(\text{SMA}(1) + \text{SMA}(2) + \dots + \text{SMA}(5))}{5}$	RSI = $100 - \frac{100}{1 + \text{RS}}$, RS = $\frac{\text{Average Gain}}{\text{Average Loss}}$
$\text{TMA}(6) = \frac{(\text{SMA}(1) + \text{SMA}(2) + \dots + \text{SMA}(6))}{6}$	Middle Band = SMA(20)
$\text{TMA}(10) = \frac{(\text{SMA}(1) + \text{SMA}(2) + \dots + \text{SMA}(10))}{10}$	Upper Band = MA(TP.n) + m * σ[TP.n]
$\text{TMA}(20) = \frac{(\text{SMA}(1) + \text{SMA}(2) + \dots + \text{SMA}(20))}{20}$	Lower Band = MA(TP.n) – m * σ[TP.n]
$\text{AccDist} = \text{Acc Dist}_{\text{Yesterday}} + \text{Volume} * \text{CLV}$ $\text{CLV} = \frac{[(\text{Close} - \text{Low}) - (\text{High} - \text{Close})]}{\text{High} - \text{Low}}$	MP = $\frac{(\text{High} + \text{Low})}{2}$
$\text{MACD} = \text{EMA}(12) - \text{EMA}(26)$	ROC $= \frac{(\text{Close today} - \text{Close N previous day})}{\text{Close N previous day}}$
$\text{Signal MACD} = \text{EMA}(\text{MACD}.9)$ $= \text{MACD Today} * 0.2$ $+ (\text{Signal MACD Yesterday} * (0.8))$	Typical Price $= \frac{(\text{High} + \text{Low} + \text{Close} + \text{Open})}{4}$
$\text{Weighted Close} = \frac{((\text{Close} * 2) + \text{High} + \text{Low})}{4}$	

Table 3 shows stochastic indicators (%K and %D) have two types: fast and slow. Also, low and high are the minimum and maximum prices of the n periods ago. About the RSI indicator, average gain and average loss are calculated as follows:

Average Gain = [(previous Average Gain) x 13 + current Gain] / 14.

Average Loss = [(previous Average Loss) x 13 + current Loss] / 14.

According to the Bollinger Band indicator, MA stands for moving average, TP is typical price, n is equal to the number of periods, which is usually 20 and m is standard deviation and often equals 20. The last one, σ[TP.n], is equal to the standard deviation during the n period of TP.

3.2 | Artificial Neural Network

The study initially employs a simple ANN without any additional algorithms. Subsequently, a hybrid ANN approach is employed to select input variables and determine the number of input and hidden

layers. Similar to the methodology employed by Göçken et al. [22], a Multilayer Perceptron (MLP) is utilized in this research, comprising three layers (two layers for input and output variables and one layer for the hidden layer). The input layer incorporates 42 input variables, effectively consisting of 42 neurons. Since the output layer pertains to a single variable, it contains one neuron. The inclusion of hidden layers enhances the model's capacity to detect complexity.

A trial-and-error approach is adopted to determine the number of hidden layer neurons in the standard NN model. A range of 1 to 32 neurons in the hidden layer is explored, and the optimal number of neurons that yields the highest accuracy is selected. Additionally, error-back propagation is employed as the network's training method. The Levenberg-Marquardt optimization algorithm is utilized to minimize errors [49]. The training process involves 1000 epochs, with the initial training rate set at 0.01 and gradually decreasing to 0.001 to achieve greater precision. To enhance ANN recognition and predictive capabilities, two threshold functions are incorporated. The first recognizes linear qualifications, while the second identifies nonlinear qualifications within the model. The output function of the hidden layer is the sigmoid function, while a linear function represents the output layer's threshold function. Fig. 4 illustrates the architectural design of the proposed NN [22].

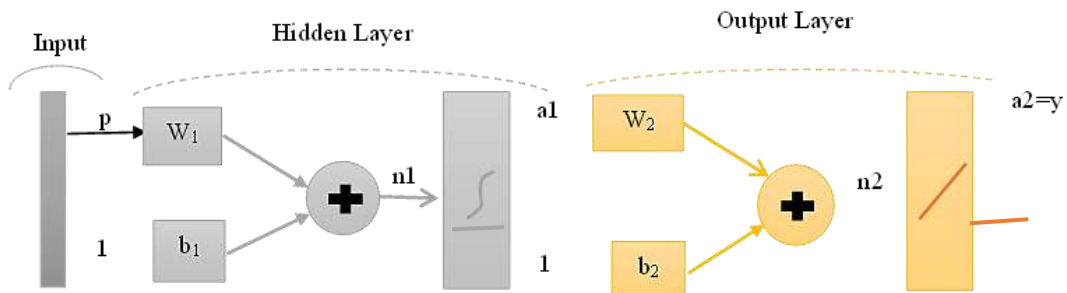


Fig. 4. Architecture of the proposed NN.

The notations used in Fig. 4 are summarized as follows:

P : The input patterns.

b_1 : The vector of bias weights on the hidden neurons.

W_1 : The weight matrix between the 0th (i.e., input) and 1th (i.e., hidden) layers.

a_1 : The vector containing the outputs from the hidden neurons.

n_1 : The vector containing net-inputs going into the hidden neurons.

a_2 : The column-vector coming from the second output layer.

n_2 : The column-vector containing the net inputs going into the output layer.

W_2 : The synaptic weight matrix between the 1st (i.e., hidden) layer and the 2nd (i.e., output) layer.

b_2 : The column-vector containing the bias inputs of the output neurons.

In each layer of the NN, weights and biases play a crucial role [1]. These weights and biases are summed, passing the result through a nonlinear activation function [50]. These activation functions are control parameters, limiting the output values [51]. Moreover, recognizing nonlinear characteristics within the hidden layer is important, necessitating carefully selecting an appropriate nonlinear activation function [52].

The proposed hybrid approach in this study unfolds in two main steps. Firstly, technical indicators are calculated, and the optimal indicators are selected using GA. Subsequently, different hybrid ANN models are employed to predict the closing price, and their prediction errors are compared. To facilitate this analysis, the stock price data from 2013 to 2018 are divided into two subsets: one for training, consisting of 70% of the observations, and the other for testing and validation, comprising the remaining 30%. The performance of the models is assessed using eight different evaluation criteria. In this research, 42 technical indicators are utilized as input variables. These variables are normalized within the range of 0 to 1 using *Eq. (1)*, rendering them suitable for input into the models. In *Eq. (1)*, the numerator i represents the data point. Moreover, *Fig. 5* represents the research methodology.

$$\widetilde{S}_i = \frac{(S_i - S_{\min})}{S_{\max} - S_{\min}} . i = 1 \dots N. \quad (1)$$

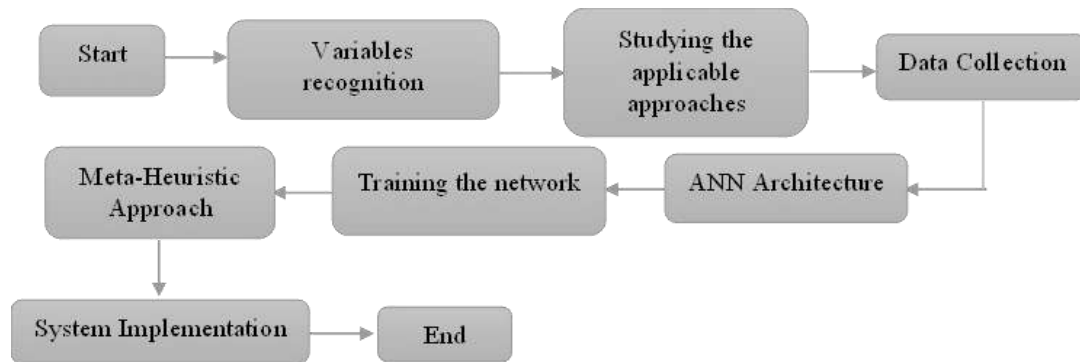


Fig. 5. Research methodology [53].

Algorithm parameter tuning is a critical aspect of AI-based algorithms. Some parameters, like crossover and mutation, are set based on existing literature, while others are chosen according to the default settings of the corresponding software. The hyper-parameters subject to tuning encompass the number of neurons, activation function, optimizer, learning rate, batch size, and epochs.

To determine the optimal number of neurons, a trial-and-error approach is employed. Neuron counts ranging from one to 32 are tested, and the architecture that yields the best number of neurons and fitness value is selected based on the loss function [54]. For the activation function, two categories are considered: nonlinear and linear. MATLAB software is used to identify the most suitable activation function, exploring options like sigmoid, tanh, and exponential. Leveraging the LM optimization algorithm, the best activation function type, learning rate, batch size, and epochs are determined.

Additional details regarding parameter tuning are summarized in *Table 4*. The batch size signifies the number of samples passed through the network in a single iteration.

Table 4. Tuning the parameters and layers of ANN.

No	Parameters	Values
1	Neurons	1, 32
2	Activation	0, 5
3	Learning rate	0.01, 1
4	Batch size	100, 1000
5	Epochs	1, 1000
6	Layer 1	1, 3
7	Layer 2	1, 3

3.3 | Genetic Algorithm-Artificial Neural Network Model

In this study, a binary solution representation is employed to encode solutions. Each chromosome consists of 47 bits, each representing the presence or absence of an input variable (technical indicator).

Specifically, "1" denotes the existence of the corresponding variable, while "0" signifies its non-existence. An additional five bits are allocated to express a number within the range of 1-32 ($2^5=32$), indicating the number of neurons in the hidden layer.

The GA operates with a population size of 20 [55]. The initial population is generated randomly. The loss function is the Mean Square Error (MSE), with the input variables comprising technical indicators. The number of neurons in the hidden layer is estimated based on minimizing the MSE rate. The smallest MSE is considered the optimal choice for the subsequent forecasting period. The initial number of epochs is set to 100 to accelerate the algorithm's training process and progressively increase it to achieve improved results. Initially, the training (learning) rate is set at 0.01 to facilitate extensive exploration, expanding the search space. Subsequently, it is systematically reduced during training to obtain more precise outcomes. The number of epochs can be increased to 1000 to enhance result accuracy. The parameters considered for the GA are summarized in *Table 5*. *Fig. 6* also represents the related flowchart of the Genetic Algorithm-Artificial Neural Network (GA-ANN) [22].

Table 5. GA parameters.

Output Error	Output Activation Function	Input Activation Function	Mutation Rate	Crossover Rate	Number of Generation	Population Size
SSE	Logistic	Logistic	0.1	0.9	50	20

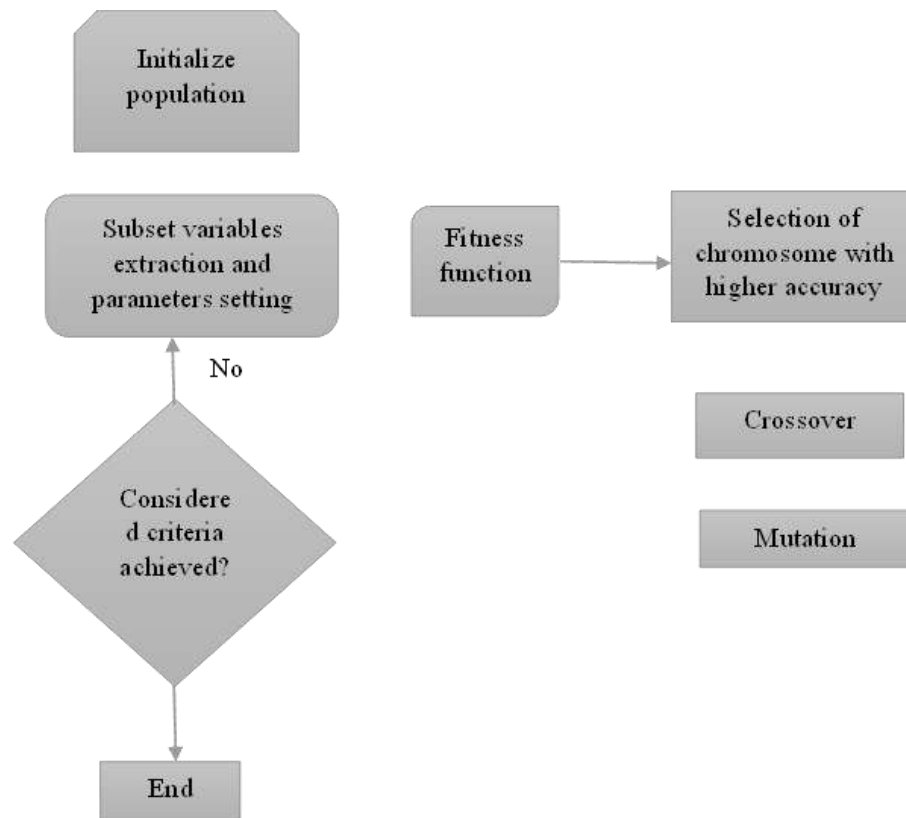


Fig. 6. Considered GA flowchart for training ANN.

Within the GA framework, parent selection is performed using the roulette wheel method, with a crossover rate set at 0.8. A one-point crossover technique is applied for crossover operations. The mutation is incorporated with a rate of 0.2, utilizing a binary mutation approach. Among the 20 parents and 20 children generated, the 20 best individuals are selected to form the new generation. This process continues until a

termination condition is met. One of the termination conditions entails repeating the best-found solution for up to 100 iterations. If this condition is not met, the maximum iteration count is checked, with the maximum allowable iterations set at 2000. The mutation and crossover operators are visually depicted in Fig. 7.

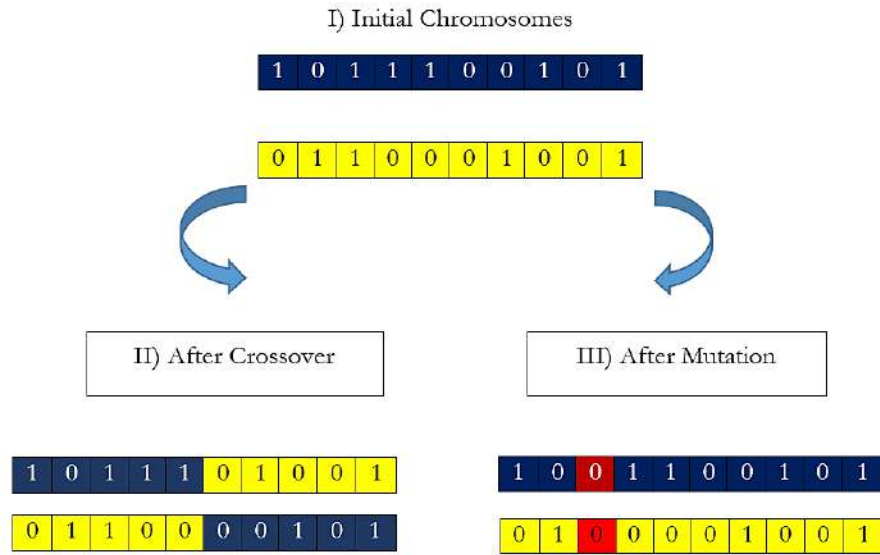


Fig. 7. Crossover and mutation operator.

Offspring, representing newly generated solutions resulting from the crossover of two-parent strings, are primarily produced with a relatively high probability, typically within the range of 0.8 to 0.95. Conversely, mutation involves the alteration of certain digits within a string, resulting in the creation of novel solutions. The pseudocode for the GA used in hyperparameter tuning is outlined as Algorithm 1.

Algorithm 1. GA-ANN pseudocode.

Function GENETIC-ALGORITHM (*population*, *FITNESS-FN*) **returns** an individual

Inputs: *population*, a set of individuals

FITNESS-FN, a function that measures the fitness of an individual

Repeat

new_population $\leftarrow$ empty set

For $i = 1$ **to** SIZE (*population*) **do**

$x \leftarrow$ RANDOM-SELECTION (*population*, *FITNESS-FN*)

$y \leftarrow$ RANDOM-SELECTION (*population*, *FITNESS-FN*)

Child $\leftarrow$ REPRODUCE (x, y)

If (*small random probability*) **then** *child* $\leftarrow$ MUTATE (*child*)

Add *child* to *new_population*

Population $\leftarrow$ *new_population*

Until some individual is fit enough, or enough time has elapsed

Return the best individual in the *population*, according to *FITNESS-FN*

3.4 | Optimization Algorithm (PSO-ANN & HS-ANN)

PSO algorithm begins with the initial population of solutions and moves toward optimal solutions in sequential iterations. In each iteration, two solutions are updated (X_j^{Gbest} and $X_j^{i.pbest}$), representing the best solution found by all particles and the best solution found by a particle j , respectively. The foundation of PSO is that each moment, each particle sets its location in searching space with the best location currently existing and the best location in its neighborhood [56]. Accordingly, speed movement and the next particle location are obtained as:

$$V_{j+1}^i = W_j V_j^i + c_1 r_1 (X_j^{i, \text{pbest}} - X_j^i) + c_2 r_2 (X_j^{\text{Gbest}} - X_j^i), \quad (2)$$

$$X_{j+1}^i = X_j^i + V_{j+1}^i, \quad (3)$$

where

c_1 : Importance of personal best.

c_2 : Importance of best neighborhood.

Usually, $c_1 + c_2 = 4$ [57]. Accelerate constant c_1 and c_2 represent the particle stochastic acceleration weight toward the personal best (pbest) and the global best (gbest). The c_1 and c_2 need to be chosen in such a way that the search speed decreases over time. r_1 and r_2 are random numbers between 0.1. V_j^i and X_j^i are speed and location of the j th particle in i th iteration. Table 4 illustrates the parameters of PSO. Fig. 8 represents the process of training ANN with PSO [58]. The pseudocode of Particle Swarm Optimization-Artificial Neural Network (PSO-ANN) is also shown is Algorithm 2.

Table 6. PSO parameters.

Parameters	Size
Upper bound	1.5
Lower bound	-1.5
C_1	1.5
C_2	2.5
Max iteration	2000

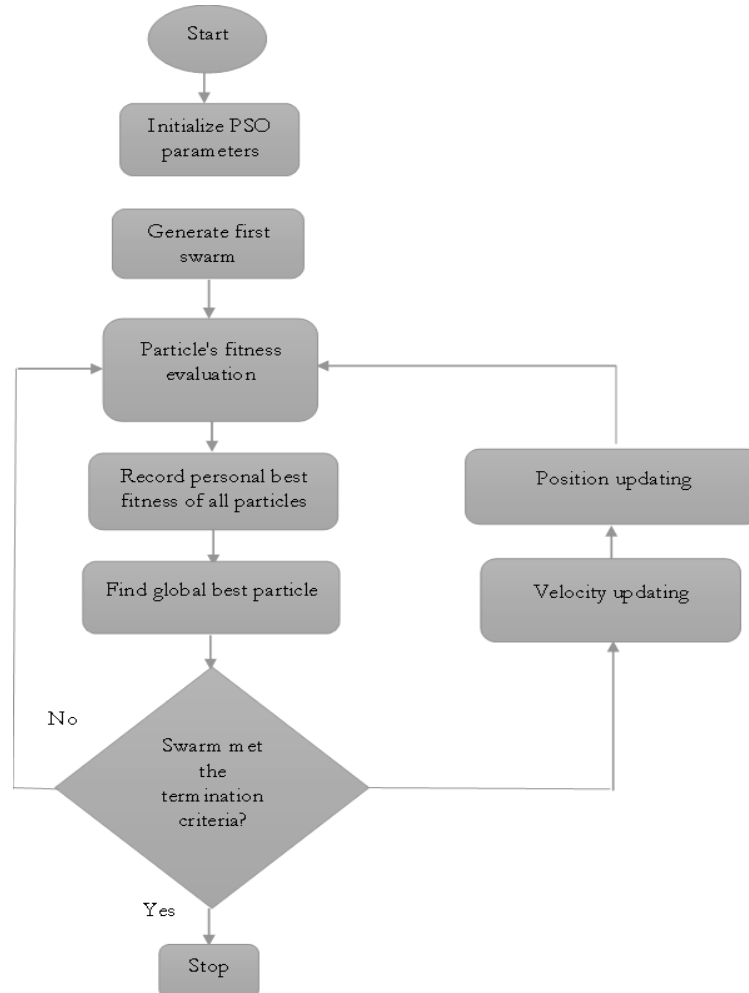


Fig. 8. Considered PSO flow chart for training ANN.

```

For each particle
Initialize particle
END
Do
For each particle
Calculate fitness value
If the fitness value is better than the best fitness value (pBest) in history
set current value as the new pBest
End
Choose the particle with the best fitness value of all the particles as the gBest
For each particle
Calculate particle velocity according to equation (2)
Update particle position according to equation (3)
End

```

To fine-tune the parameters of the PSO algorithm, two distinct methods are employed: offline and online approaches. In the offline method, meta-optimization is utilized to adjust the parameters of PSO using an external optimizer. In contrast, the online method encompasses two techniques:

- I. Self-adaptation: this approach involves including some or all of the optimizer's behavioral parameters in the search space, allowing them to be optimized alongside the primary problem.
- II. Meta-adaptation: in this technique, an external optimizer dynamically adjusts the parameters of another optimizer during the optimization process.

In our study, we work with training and theoretical datasets. Instead of relying on random values for particle initialization, we use the training data. For this purpose, we reference Fei Ye's article on tuning PSO hyperparameter estimation [59]. In this study, we use the HS algorithm to train ANN and find the fittest number of input and hidden layers. The HS consists of three basic phases: initialization, improvisation of a harmony vector and updating the HM, described below respectively [60]. In addition, other parameters of HS should be determined. These parameters are Harmony Memory Size (HMS), which is equal to 100; Harmony Memory Considering Rate (HMCR), which is equal to 0.95 and Pitch Adjusting Rate (PAR), which is 0.3; and Bandwidth (BW), which is 0.2. We can show the HM with $HMS \times (N+1)$, which in this study N is 42. Running HS algorithm including multiple steps (the HS parameters are determined in Table 7):

Step 1. Parameter initialization.

Step 2. Harmony memory initialization.

Step 3. Update harmony memory.

Step 4. Checking the stopping criterion.

Table 7. HS parameters.

Parameters	Size
Lower bound	-11
Upper bound	11
HMS	11
NHMS	100
Max iteration	1000
HMCR	0.75
PAR	0.05
Fret Width (FW)	0.1
FW-damp	0.95

Table 5 is equivalently employed as the BW, one factor affecting the algorithm's time complexity and performance. The BW value is a random number between 0 and 1, intended to possess both exploratory and exploitative characteristics. The underlying concept involves initiating the search with a broad exploration of the entire domain and dynamically adjusting it as we approach the optimal solution. FW-Damp, on the other hand, refers to an influence exerted on an oscillatory system that serves to reduce, restrict, or dampen its oscillations. Fig. 9 illustrates the ANN training process with HS [61].

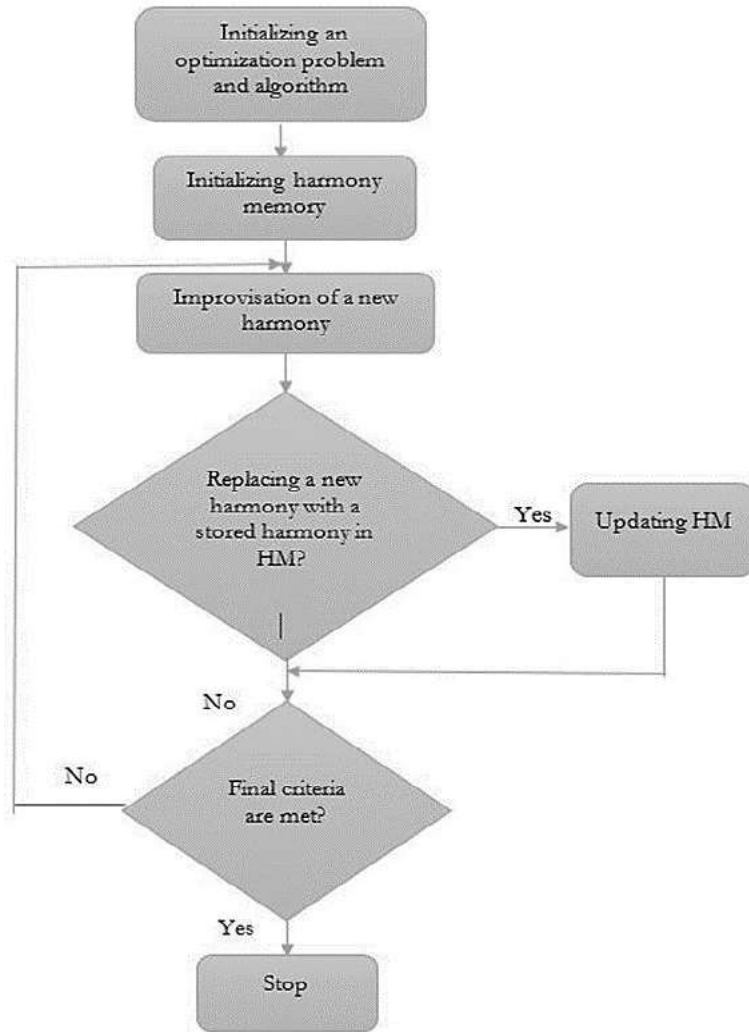


Fig. 9. Considered HS flow chart for training ANN.

The pseudocode for Harmony Search-Artificial Neural Network (HS-ANN) is shown in Algorithm 3. Like other algorithms, the HS algorithm needs parameter tuning. As a result, Kang et al. [62] is used as a reference for this purpose [48].

Algorithm 3. HS-ANN Pseudo-Code.

```

for (j=1 to n) do
  if (r1 < HMCR) then
    Xnew(j) = Xa(j) where a ∈ (1, 2, ..., HMS)
  if (r2 < PAR) then
    Xnew(j) = Xnew(j) ± r3 × BW where r1, r2, r3 ∈ (0,1)
  endif
else
    Xnew(j) = LBj + r × (UBj - LBj), where r ∈ (0,1)
  endif
endfor
  
```

3.5 | Loss Functions

This study employs a range of pre-existing loss functions available in MATLAB to identify the optimal model performance, aiming for the highest accuracy and lowest error. These loss functions are summarized in *Table 8*, which are readily accessible within MATLAB. Ultimately, the accuracy of the various methods is compared based on the values of the loss function.

Table 8. Most common loss functions.

Error Criterion Formula	Error Criterion
$MAE = \frac{1}{n} \sum_{i=1}^n e_i $	Mean absolute error
$MSE = \frac{1}{n} \sum_{i=1}^n e_i^2$	MSE
$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	Root MSE
$MARE = \frac{1}{n} \sum_{i=1}^n \left \frac{e_i}{a_i} \right $	Mean absolute relative error
$MSRE = \frac{1}{n} \sum_{i=1}^n \left \frac{e_i}{a_i} \right ^2$	Mean squared root error
$RMSRE = \sqrt{\frac{1}{n} \sum_{i=1}^n \left \frac{e_i}{a_i} \right ^2}$	Root mean squared relative error
$MAPE = \frac{100}{n} \sum_{i=1}^n \left \frac{e_i}{a_i} \right $	Mean absolute percentage error
$MSPE = \frac{100}{n} \sum_{i=1}^n \left \frac{e_i}{a_i} \right ^2$	Mean squared prediction error

3.6 | Testing Efficient Market Hypothesis

One of the pivotal considerations for investors before making stock market investment decisions is the assessment of market efficiency. Consequently, measuring stock market efficiency is paramount and can exert a profound impact. In modern economies, market efficiency bears significant implications because it facilitates accurate stock price determination and optimizes capital allocation [62]. Market efficiency, when realized, signifies a state of information transparency among market participants, the absence of mispricing in the stock market, and the inability to earn abnormal returns. Under such circumstances, technical analysis becomes less applicable.

Various methods exist for evaluating the EMH. Given that financial data typically exhibit abnormal characteristics with skewness and kurtosis, we have employed a non-parametric test, namely the run test. The run test is a statistical procedure that assesses whether a data sequence follows a random distribution pattern. It examines the occurrence of similar events separated by dissimilar events.

In investing, a run test holds significance for investors to discern whether the dataset they are utilizing is generated randomly or influenced by an underlying variable. In inefficient markets, pertinent information affecting asset prices is not readily accessible, rendering it challenging to ascertain or predict accurate asset prices. It, in turn, obscures the true value of financial holdings, resulting in a weakened market. The selected test for evaluating the randomness of the data is the run test.

Table 9. Run test notification.

Term	Description
Observed	The number of runs in the sample
Expected	$1 + \frac{2 \times A \times B}{N}$
Variance	$\frac{2 \times A \times B \times (2 \times A \times B - N)}{N^2(N-1)}$
A	The number of observations above K
B	The number of observations below or equal to K
N	The number of observations

Since the article's main focus is on ANN, a brief and complementary explanation is provided about EMH. It could be possible to use the Kolmogorov-Smirnov goodness of fit test to check if a sample comes from a population with a specific distribution [63]. The randomness of data is also evaluated using a run test [64].

Table 10. Kolmogorov-Smirnov (K-S) hypothesis.

H_0 :	There is a specific distribution in the data structure.
H_1 :	There is no specific distribution in the data structure.
Test statistic:	The Kolmogorov-Smirnov test statistic is defined as.

4 | Results and Discussion

4.1 | Data Statistics and Results

A set of 42 technical indicators is employed for stock price prediction, encompassing 41 input variables and 1 output variable, which serves as the target variable representing the closing price for the following day. The analysis spans a time frame from the commencement of 2013 to the conclusion of 2018, approximately 5 years, with data recorded daily. The stocks under consideration belong to different sectors, namely Fakhouz, Zagros, Khodro, Fameli, and Kechad, operating in the steel, petrochemical, automotive, copper production, and mining industries. The Risk Laboratory at Khatam university serves as the data source for this study. It is worth noting that some data may be missing in certain intervals. To address this issue, various approaches are available, with the current research opting for a direct write-off method, a common and default approach in many software applications.

The selection of the most relevant indicators is facilitated through a GA. *Table 11* provides a comprehensive overview of the companies, time frame, and data volume incorporated into the study. These five companies were selected due to 1) availability and easy access to data, and 2) they are important and well-known companies in their industry.

Table 11. Statistical description of data.

Target Indicator	Number of Output Layer	Number of Input Variables	Number of Data (After Normalizing)	Number of Data (Before Normalizing)	Time Interval	Symbol
Closing price	1	42	923	1176	2013-2018	Fakhouz
Closing price	1	42	963	1230	2013-2018	Zagros
Closing price	1	42	1086	1213	2013-2018	Khodro
Closing price	1	42	997	1231	2013-2018	Fameli
Closing price	1	42	974	1211	2013-2018	Kechad

4.2 | Artificial Neural Network

To begin with, stock prices for each company are predicted using an ANN without applying any additional algorithms. *Fig. 10* visually illustrates the architecture of the ANN, comprising an input layer, a hidden layer, and an output layer. In this depiction, the input layer consists of 42 nodes, the hidden layer consists of 10 nodes and the output layer consists of 1 node. The activation function employed in the hidden layer is the tangent sigmoid, while the output layer employs a simple linear activation function.

The network is trained using 70% of the available data, with the remaining 30% allocated for validation and testing purposes. The training algorithm utilized for the network is the Levenberg-Marquardt algorithm. One of the primary loss functions employed is the MSE. The training iterations are initially set to 1000, representing the software's default setting. The subsequent figure illustrates the optimal

performance, considering three segments: training, validation, and testing. Regression analysis and corresponding figures are presented below, accompanied by an estimation criterion.

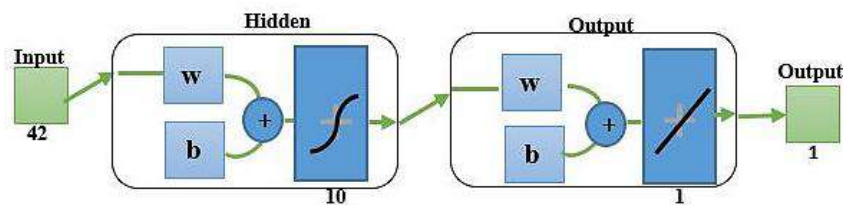
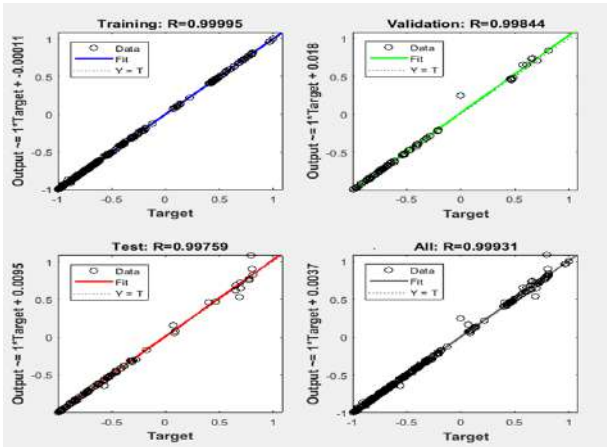
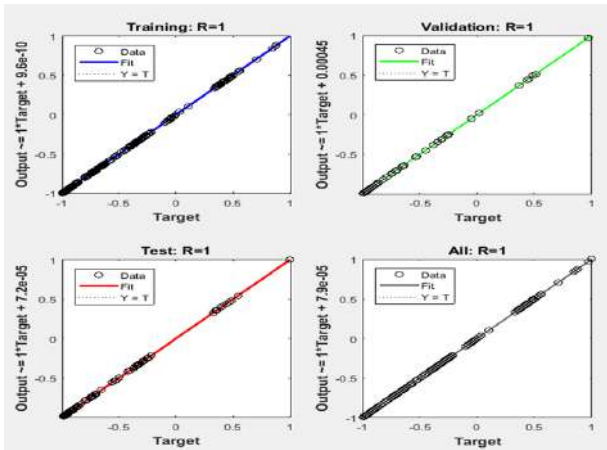


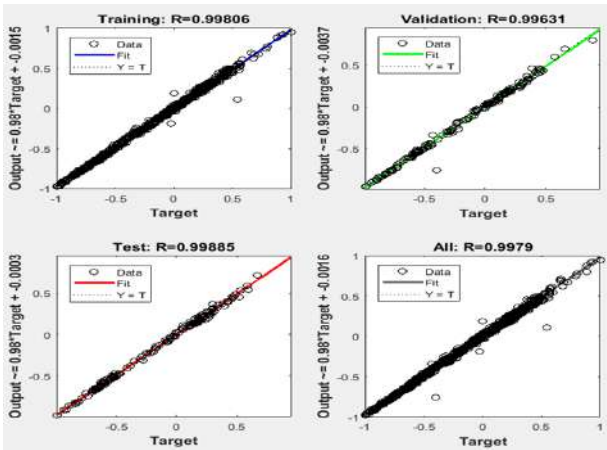
Fig. 10. The structure of ANN.



a.



b.



c.

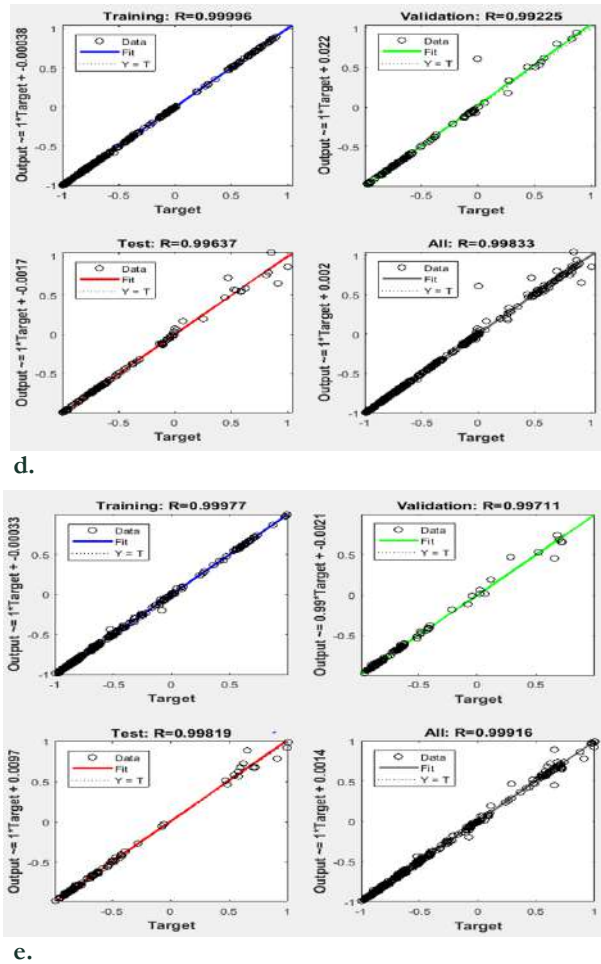


Fig. 11. ANN regression for five companies: a. ANN regression (Fakhouz); b. ANN regression (Zagros); c. ANN regression (Khodro); d. ANN regression (Fameli); e. ANN regression (Kechad).

To effectively train and test our model, it is essential to partition our dataset into three distinct subsets.

Training set: this set comprises data used to train the model and enable it to learn the underlying patterns and features in the dataset. The same training data is repeatedly fed into the NN architecture during each training epoch, allowing the model to grasp the dataset's intricacies progressively. It is crucial for the training set to encompass a diverse range of inputs to ensure that the model is trained comprehensively, enabling it to make accurate predictions on unseen data in the future.

Validation set: the validation set consists of data separate from the training set and is employed to assess the model's performance during training. This validation process provides valuable insights that aid in fine-tuning the model's hyperparameters and configurations. Essentially, it acts as a critic, indicating whether the training is progressing in the right direction. While the model is being trained on the training set, its performance is simultaneously evaluated on the validation set after each training epoch. The primary purpose of this separation is to prevent overfitting, ensuring that the model generalizes well to unseen data rather than merely memorizing the training set.

Test set: the test set is an independent dataset employed to evaluate the model's performance once the training is completed. It provides an unbiased assessment of the final model's accuracy, precision, and performance metrics. It answers the fundamental question of how well the model performs on new, unseen data.

As evident from the results, all five regression models fit the data exceptionally well, as indicated by the R-squared values exceeding 99% for all five companies. Further results details are presented in Table 12, where error rates are provided for each dataset. The MSE varies across the datasets, with the lowest and

highest values belonging to Zagros and Khodro. SSE and SAE represent the Sum Squared Error and Sum of Absolute Errors, respectively, which are additional metrics used to assess the model's performance.

Table 12. Training, validation and testing error (before using GA).

Symbol	Training Error	Validation Error	Testing Error	MSE	MAE	SSE	SAE	R ²
Fakhrouz	0.003	0.02	0.0452	0.0117	0.52	0.1087	4.837	0.9993
Zagros	4.02e-08	6.01e-04	7.01e-04	9.7e-05	0.003	0.0092	2.6	0.9999
Khodro	0.076	0.14	0.046	0.080	0.0174	0.8780	18.86	0.9979
Fameli	0.0014	0.028	0.15	0.052	0.55	0.65	5.44	0.9983
Kechad	0.008	0.076	0.0795	0.028	0.73	0.281	7.12	0.9916

4.3 | Hybrid GA-ANN

Now, we apply the GA to select the most suitable input and hidden layers for the ANN. To achieve this, we must determine key parameters such as the population size, the number of generations, the mutation rate, and the crossover rate.

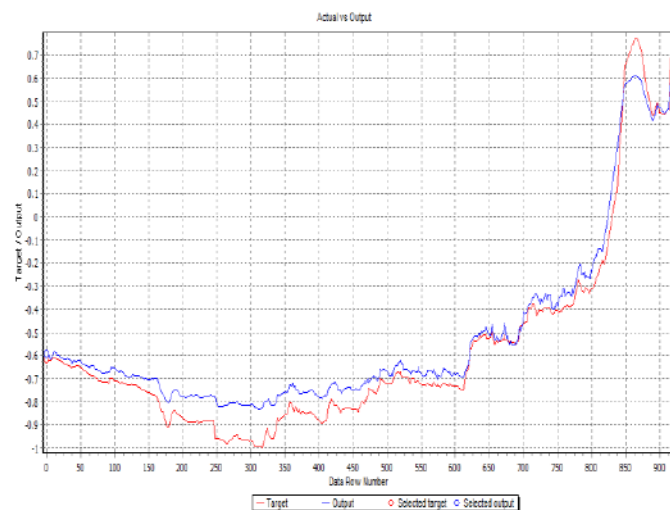
Similar to the previous sections, we employ the GA separately for each company. A summary of the results is presented in *Table 13*. Notably, the error rates for several companies, including Fakhrouz, Fameli, and Kechad, have decreased. For the remaining two companies, the error rates are closely aligned. It suggests that the use of the GA has positively impacted model performance. Please refer to *Tables (B2) and (B3)* in the appendix for more detailed information.

Table 13. Training, validation and testing error (after using GA).

Symbol	Training Error	Validation Error	Testing Error	MSE	MAE	SSE	SAE	R ²
Fakhrouz	3.01e-04	1.33e-04	2.95e-04	2.75e-04	0.0084	0.2297	6.99	0.9996
Zagros	2.02e-04	1.45e-04	1.66e-04	1.88e-04	0.0064	0.1798	6.112	0.9989
Khodro	0.0013	0.0032	0.0015	0.0016	0.0263	1.7331	28.46	0.9959
Fameli	0.0015	7.57e-04	4.75e-04	0.0012	0.0153	1.2240	15.22	0.9985
Kechad	2.46e-04	1.83e-04	0.0022	5.25e-04	0.0088	0.5108	8.5220	0.9999

Indeed, after the implementation of GA, we observed a decrease in the error rate and a simultaneous increase in the R-Squared rate. This outcome shows the efficiency of GA as a feature selection method.

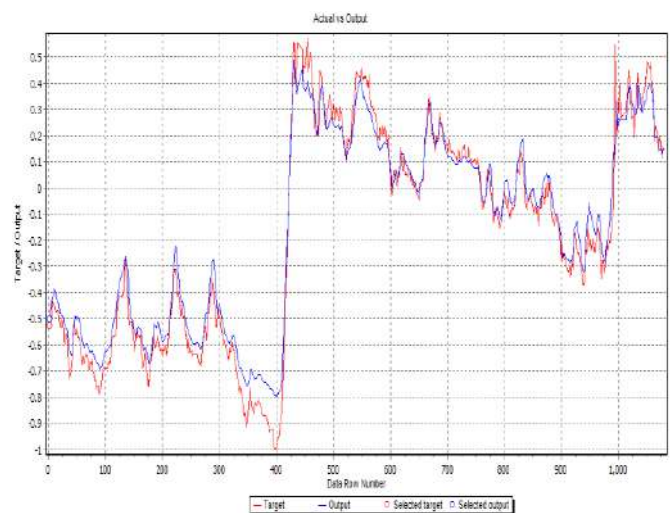
Figs. 12(a) to 12(e) pertain to the testing phase of the network. In these figures, the horizontal line represents the closing price, while the vertical line denotes the output range, which has been normalized to fall within the range of [1, -1]. The blue line represents the output results generated by the NN, in line with the red line, which represents the input variables. For a more comprehensive overview, please consult *Tables B4 and B5* in the appendix, which detail the results and the selected most relevant technical indicators.



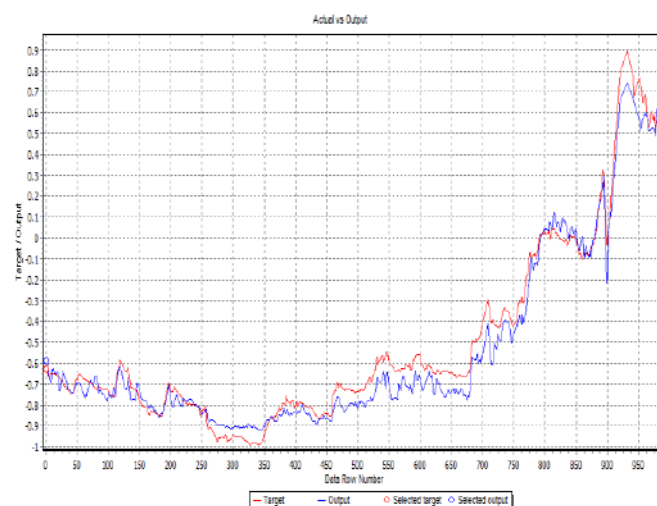
a.



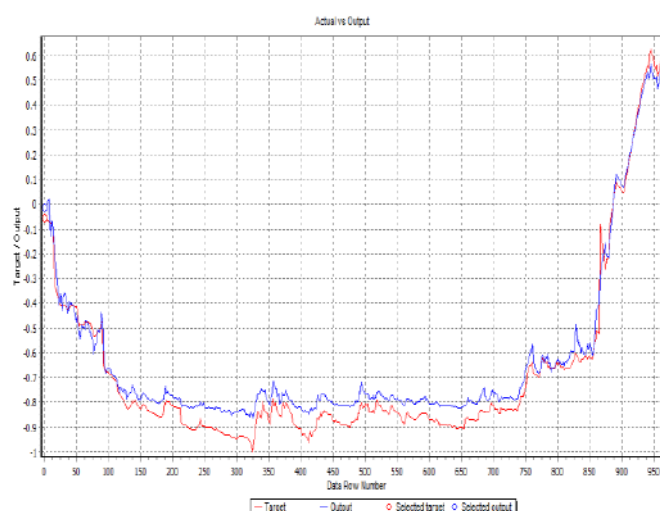
b.



c.



d.



e.

Fig. 12. Target vs. Output trend for five symbols: a. Target versus output trend (Fakhouz); b. Target versus output trend (Zagros); c. Target versus output trend (Khodro); d. Target versus output trend (Fameli); e. Target versus output trend (Kechad).

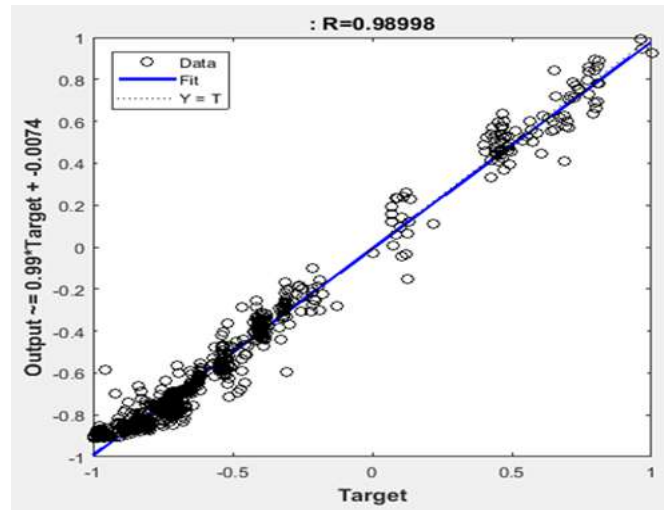
The blue and red lines are aligned and coincidentally but are not fully matched, and it can be better to apply different methods mentioned at the end.

4.4 | Hybrid PSO-ANN

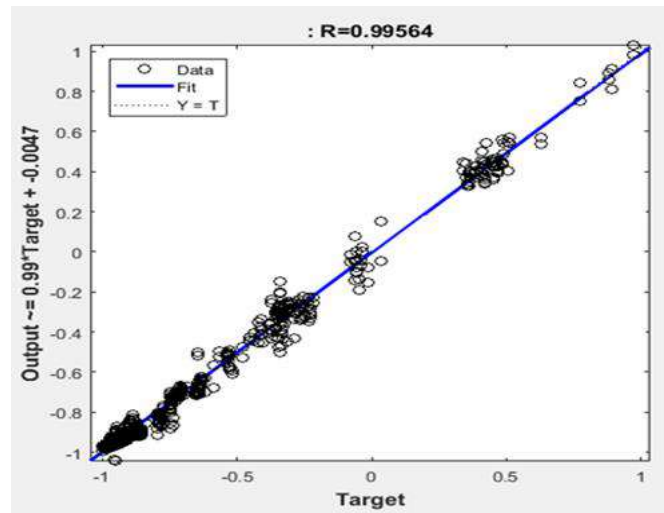
To train the NN using the PSO algorithm, we follow seven key steps as outlined below:

- I. Data collection.
- II. Network creation.
- III. Network estimation.
- IV. Weights and biases initialization.
- V. Network training using PSO.
- VI. Network validation.
- VII. Network utilization.

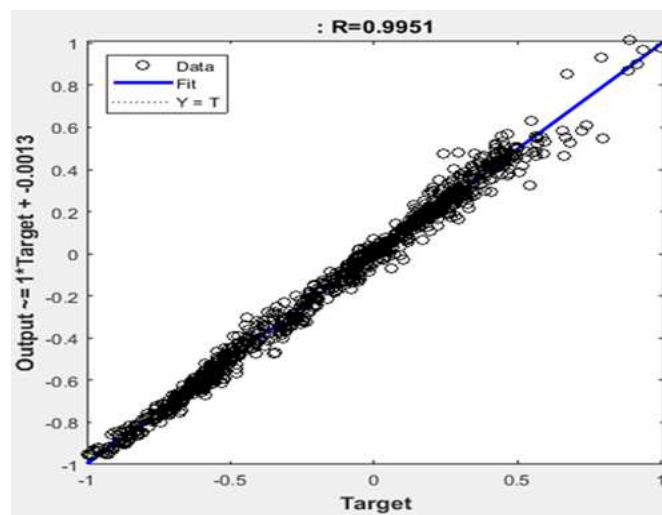
We require a fitness function to predict the stock price, specifically the closing price. The algorithm is initialized, including population and speed, with initial personal best (pbest) and global best (gbest) values. The values for C_1 and C_2 are set for a given number of iterations, which in this case is 1000. It's important to note that the network is a feedforward NN. The regression results are visualized in Figs. 13(a) to 13(e).



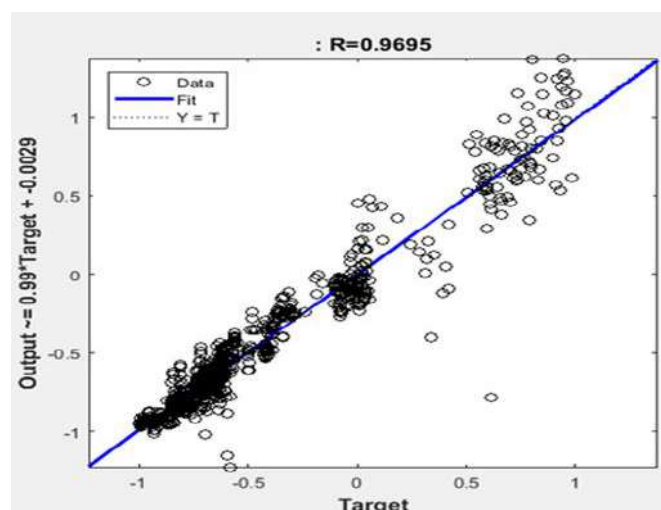
a.



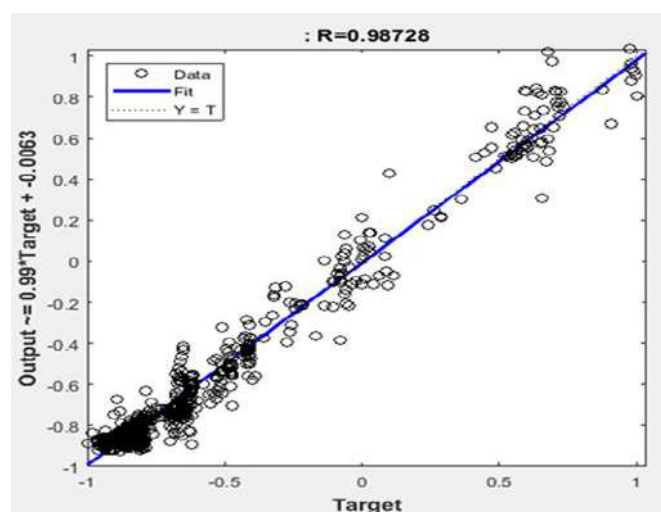
b.



c.



d.



e.

Fig. 13. ANN-PSO regression for five symbols: a. ANN-PSO regression (Fakhouz); b. ANN-PSO regression (Zagros); c. ANN-PSO regression (Khodro); d. ANN-PSO regression (Fameli); e. ANN-PSO regression (Kechad).

From the figures, it's evident that this algorithm exhibits strong predictive capabilities and a good fit. However, there is still room for improvement. Figs. 13(a) to 13(c) exhibit the highest R-squared values, while the remaining figures do not perform as strongly.

Figs 13(d) and 13(e) notably contain more data points that deviate further from the trend line, indicating some prediction variance.

Table 14 provides additional insights into the hybrid ANN-PSO model's training, validation, and testing. Table 9 presents eight error measurements along with R-squared values and the identification of the best particle for each of the five companies. Specifically, the best particles are numbered 8, 8, 1, 9, and 10 for Fakhouz, Zagros, Khodro, Fameli, and Kechad, respectively.

Table 14. Hybrid ANN-PSO.

Symbol	MSE	RMSE	MAE	MAPE	MSRE	MARE	RMSRE	RMSPE	R ²	Best Particle
Fakhouz	3.06e-05	0.0005	0.005	0.0003	0.0018	3.17e-06	1.4e-05	0.001	0.989	8
Zagros	1.5e-05	0.0003	0.0002	0.0003	0.0038	3.05e-06	2.0e-05	0.02	0.995	8
Khodro	1.0e-05	0.0004	0.0004	-0.0001	0.0002	1.97e-06	4.0e-05	0.0042	0.995	1
Fameli	1.4e-05	0.0011	0.004	0.0007-	0.004	7.98e-06	2.0e-05	0.0002	0.969	9
Kechad	4.0e-05	0.0006	0.014	0.0019-	0.0351	2.0e-05	6.0e-06	0.006	0.987	10

4.5 | Hybrid HS-ANN

Like other algorithms, e.g., GA and PSO, several steps are followed for training the network and solving the problem. The network structure is Feed Forward ANN (FFANN). First, the number of iterations is 1000, and to achieve better results, it is increased to 5000. Finally, the result after 5,000 iterations is illustrated in *Table 15*.

Table 15. Hybrid ANN-HS.

Symbol	MSE	RMSE	MAE	MAPE	MSRE	MARE	RMSRE	RMSPE	R ²
Fakhrouz	5.51e-07	0.0002	5.49e-15	6.88e-11	8.98e-07	6.86e-12	0.00002	0.002	0.9992
Zagros	2.56e-07	0.00005	5.10e-15	2.30e-11	4.08e-08	2.08e-13	0.000005	0.0005	0.9996
Khodro	3.09e-08	0.00001	4.70e-15	4.23e-11	6.19e-09	4.23e-13	0.000001	0.0001	0.9996
Fameli	1.37e-07	0.00003	5.55e-15	3.88e-11	1.22e-07	3.88e-13	0.000003	0.0003	0.9993
Kechad	3.05e-07	0.00005	5.99e-15	4.36e-11	1.4e-07	4.36e-13	0.000005	0.0005	0.9995

The results of *Table 15* show that HSA is a powerful algorithm in prediction because all of the R-squareds are high and close to 1. The rate of MSE and most of the other error measurements are better than PSO algorithms.

4.6 | Comparing Results

In this section, this study's obtained results are compared with similar studies. The comparison results are summarized in *Table 16*.

Table 16. Comparative study.

Author(s)	Proposed Approaches	Data Type	MSE	MAE	R2
Ghasemiyeh et al. [65]	GA-ANN	Train	0.0074	0.0584	0.9866
		Test	0.0079	0.0585	
	PSO-ANN	Train	0.0013	0.0253	0.9895
		Test	0.0014	0.0260	
	ICS-ANN	Train	0.0076	0.0720	0.9972
		Test	0.0068	0.0694	
Sedighi et al. [66]	ARIMA-SVM	Final outcome	1.0042	0.0142	0.9969
	SVM-RF	Final outcome	0.000295	0.0245	0.9966
Safa and Panahian [67]	ANFIS-SVM	Final outcome	3.5849	0.0117	0.9995
	FA-MSVR	Final outcome	0.0014	0.0130	0.9986
		Final outcome	0.02776	0.05177	0.9641
Emamverdi et al. [68]	HS-ANN	Final outcome	0.00030	0.0174	0.9893
		Final outcome	0.00042	0.0162	0.9795
Zheng et al. [69]	Wavelet Neural Networks (WNNs)	Final outcome	0.00510	6.742e-04	0.9877
Dong et al. [70]	One-step ahead and multi-step ahead predictions	Final outcome	0.0043	0.1043	0.9012
Wang et al. [71]	Delayed Neural Network (DNN)	Final outcome	1.60e-03	1.00e-07	0.9955
Sin and wang [72]	Ensembles of NN	Final outcome	2.05e-05	2.045e-09	0.9963
Current research	ANN	Train	0.01768	0.036408	0.9973
		Test	0.06578	0.00621	
	GA-ANN	Train	0.00070	0.0130	0.9984
		Test	0.00045	0.000532	
	PSO-ANN	Train	0.000042	0.00392	0.9993
		Test	0.00431	0.000216	
	HS-ANN	Train	3.0258E-07	5.366E-15	0.9995
		Test	0.000061402	0.00042	

As per *Table 11*, the HS and, to a similar extent, the PSO algorithms yield the best results with the lowest loss functions. These results are based on each algorithm's average R-squared values, indicating their effectiveness in predictive performance.

For further insights and detailed information regarding the number of layers in each input and hidden layer, activation functions, and other related details, you can refer to *Table B6* in the appendix.

4.7 | EMH Testing

First, the series should be checked to determine whether they follow a normal distribution. Since the sample is more than 100, the Kolmogorov-Smirnov normality test is used separately for each symbol.

Table 17. Test of normality.

Fakhouz						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Adj.Closing Price;	.209	923	.000	.752	923	.000
Zagros						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Adj.Closing Price;	.234	963	.000	.711	963	.000
Khodro						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Adj.Closing Price;	.097	1086	.000	.963	1086	.000
Fameli						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Adj.Closing Price;	.242	997	.000	.793	997	.000
Kechad						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Adj.Cl osing Price;	.266	973	.000	.650	973	.000

a. Lilliefors significance correction

As it is clear, the significance of all symbols is less than 5%, which means the series is not normal. So, the non-parametric test is used for checking EMH.

Table 18. Run test.

Fakhouz	
	Adj.Closing Price;
Test value ^a	-.57223850
Cases < test value	620
Cases >= test value	303
Total cases	923
Number of runs	2
Z	-30.327
Asymp. Sig. (2-tailed)	.000

Table 18. Continued.

Zagros	
	Adj.Closing Price;
Test value ^a	-.71050612
Cases < test value	680
Cases >= test value	283
Total cases	963
Number of runs	12
Z	-30.200
Asymp. Sig. (2-tailed)	.000
Khodro	
	Adj.Closing Price;
Test value ^a	-.16692865
Cases < test value	504
Cases >= test value	582
Total cases	1086
Number of runs	12
Z	-32.299
Asymp. Sig. (2-tailed)	.000
Fameli	
	Adj.Closing Price;
Test value ^a	-.52997966090
Cases < test value	698
Cases >= test value	299
Total cases	997
Number of runs	2
Z	-31.522
Asymp. Sig. (2-tailed)	.000
Kechad	
	Adj.Closing Price;
Test value ^a	-.64985740
Cases < test value	716
Cases >= test value	257
Total cases	973
Number of runs	9
Z	-30.558
Asymp. Sig. (2-tailed)	.000
a. Mean	

In all the tables, the sigma value is consistently less than 0.05, indicating that the data is not random. It implies that the market is not efficient. In inefficient markets, crucial information that impacts asset prices is not readily available. Consequently, it becomes challenging to determine or predict asset prices accurately. This situation can result in financial holdings not reflecting their true value, contributing to a weak market.

5 | Conclusion

This paper employs a neural network-based approach to predict stock prices for five symbols representing various industries: Fakhouz, Zagros, Khodro, Fameli, and Kechad. The process involves selecting essential technical indicators, such as SMA, EMA, TMA, etc., as input variables using GAs. Subsequently, the NN is trained using two meta-heuristic algorithms, HS and PSO. Different loss functions are computed for each algorithm after optimizing the indicators and weights through GA. *Table (B7)* in the appendix presents each algorithm's comprehensive loss function values. HS exhibits the lowest training and testing errors, while ANN demonstrates the highest forecasting error. Evaluating model performance with new data, referred to as testing performance, proves to be a reliable indicator of predictive performance.

The primary advantages of HS and PSO include speeding up calculations, reducing model complexity, increasing network accuracy, and facilitating model utilization. Ultimately, HS, PSO, and ANN yield the lowest error rates. Given the market's inefficiency, past information significantly influences future stock prices, allowing for accurate stock price forecasting.

In summary, the most significant finding is the high predictability of ANN. The results underscore the effectiveness of GA as a feature selection method, improving model robustness. Moreover, employing meta-heuristic algorithms like PSO and HS for optimization enhances R-squared values or reduces error estimates.

Key considerations for future research include investigating different parameters, such as the number of hidden layers, activation functions, and alternative HS models like HIS. Additionally, fine-tuning GA parameters, such as crossover and mutation rates, holds potential interest. Lastly, future studies should explore other novel meta-heuristic algorithms like Aquila Optimization Algorithm (AO) and Bald Eagle Search (BES) optimization algorithms.

Acknowledgments

We would like to express our special gratitude to our parents and the God we trust.

Funding

Any organization does not fund this paper.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

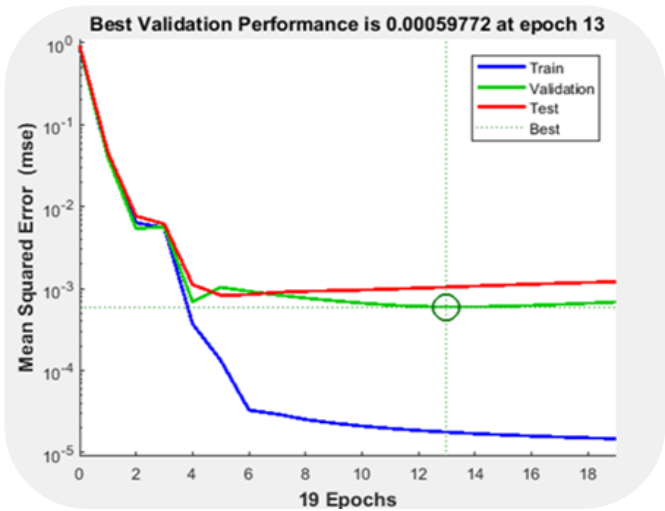
References

- [1] Mehwish, N., & Yasir, B. T. (2015). The efficient market hypothesis: a critical review of the literature. *The IUP journal of financial risk management*, 12(4), 48–63.
- [2] Guerrien, B., & Gun, O. (2011). Efficient market hypothesis : what are we talking about ? *Analysis*, (56), 19–30. <http://paecon.net/PAERreview/issue56/GuerrienGun56.pdf>
- [3] Bhowmik, P. (2019). Research study on basic understanding of artificial neural networks. *Global journal of computer science and technology*, 19(4), 5–7.
- [4] Krauss, C., Do, X. A., & Huck, N. (2017). Deep neural networks, gradient-boosted trees, random forests: statistical arbitrage on the S&P 500. *European journal of operational research*, 259(2), 689–702.
- [5] Caginalp, G., & Desantis, M. (2011). Nonlinearity in the dynamics of financial markets. *Nonlinear analysis: real world applications*, 12(2), 1140–1151. DOI:10.1016/j.nonrwa.2010.09.008
- [6] Khashei, M., & Bijari, M. (2011). A novel hybridization of artificial neural networks and ARIMA models for time series forecasting. *Applied soft computing journal*, 11(2), 2664–2675.
- [7] De Oliveira, F. A., Nobre, C. N., & Zárte, L. E. (2013). Applying artificial neural networks to prediction of stock price and improvement of the directional prediction index - case study of PETR4, Petrobras, Brazil. *Expert systems with applications*, 40(18), 7596–7606. DOI:10.1016/j.eswa.2013.06.071
- [8] Abolfazli, N., Eshghali, M., & Fatemi Ghomi, S. M. T. F. (2022). Pricing and coordination strategy for green supply chain under two production modes. *IEEE 2022 systems and information engineering design symposium, sieds 2022* (pp. 13–18). IEEE. DOI: 10.1109/SIEDS55548.2022.9799373
- [9] Zhang, J., Cui, S., Xu, Y., Li, Q., & Li, T. (2018). A novel data-driven stock price trend prediction system. *Expert systems with applications*, 97, 60–69. DOI:10.1016/j.eswa.2017.12.026
- [10] Jóhannsson, Ó. S. (2020). *Forecasting the icelandic stock market using a neural network* (Master Thesis, Reykjavík). https://skemman.is/bitstream/1946/36421/1/MSO_OMAR_2020.pdf
- [11] Hadavandi, E., Ghanbari, A., & Abbasian-Naghneh, S. (2010). *Developing an evolutionary neural network model for stock index forecasting. dvanced intelligent computing theories and applications. ICIC 2010. communications in computer and information science.* (Vol. 93 CCIS, pp. 407–415). Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-14831-6_54

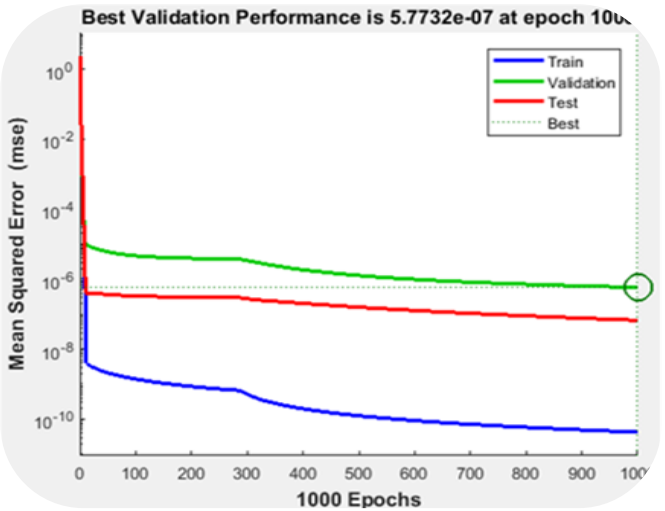
- [12] Hull, J. C. (2012). *Risk management and financial institutions*, + Web Site (Vol. 733). John Wiley & Sons. <https://www.google.com/books/edition/>
- [13] Prasanna, S. (2013). An analysis on stock market prediction using data mining techniques. *International journal of computer science & engineering technology (IJCSET)*, 4(02), 49–51.
- [14] Fama, E. F. (1998). Market efficiency, long-term returns, and behavioral finance. *Journal of financial economics*, 49(3), 283–306.
- [15] Gimba, V. K. (2012). Testing the weak-form efficiency market hypothesis: evidence from nigerian stock market. *CBN journal of applied statistics*, 3(1), 117–136.
- [16] Fama, E. F. (1965). The behavior of stock-market prices. *The journal of business*, 38(1), 34–105.
- [17] Dixit, A., Mishra, A., & Shukla, A. (2019). Vehicle routing problem with time windows using meta-heuristic algorithms: A survey. In *Advances in intelligent systems and computing* (Vol. 741, pp. 539–546). Springer. DOI: 10.1007/978-981-13-0761-4_52
- [18] Dramsch, J. S. (2020). 70 Years of Machine learning in geoscience in review. *Advances in geophysics*, 61, 1–55. DOI:10.1016/bs.agph.2020.08.002
- [19] Sindayigaya, L., & Dey, A. (2022). Machine learning algorithms: a review. *International journal of science and research (IJSR)*, 11(8), 1127–1133.
- [20] Iuhasz, G., Tirea, M., & Negru, V. (2012). Neural network predictions of stock price fluctuations. *Proceedings - 14th international symposium on symbolic and numeric algorithms for scientific computing, synasc 2012* (pp. 505–512). IEEE. DOI: 10.1109/SYNASC.2012.7
- [21] Huang, W., Lai, K. K., Nakamori, Y., Wang, S., & Yu, L. (2007). Neural networks in finance and economics forecasting. *International journal of information technology & decision making*, 6(01), 113–140.
- [22] Göçken, M., Özcalici, M., Boru, A., & Dosdoğru, A. T. (2016). Integrating metaheuristics and artificial neural networks for improved stock price prediction. *Expert systems with applications*, 44, 320–331.
- [23] Hassanin, M. F., Shueb, A. M., & Hassanien, A. E. (2016). *Grey wolf optimizer-based back-propagation neural network algorithm*. 2016 12th international computer engineering conference (ICENCO) (pp. 213–218). IEEE. <https://ieeexplore.ieee.org/abstract/document/7856471>
- [24] Faris, H., Aljarah, I., & Mirjalili, S. (2016). Training feedforward neural networks using multi-verse optimizer for binary classification problems. *Applied intelligence*, 45(2), 322–332. DOI:10.1007/s10489-016-0767-1
- [25] Rather, A. M., Sastry, V. N., & Agarwal, A. (2017). Stock market prediction and Portfolio selection models: a survey. *Opsearch*, 54(3), 558–579. DOI:10.1007/s12597-016-0289-y
- [26] Yang, B., Gong, Z. J., & Yang, W. (2017). *Stock market index prediction using deep neural network ensemble*. 2017 36th chinese control conference (CCC) (pp. 3882–3887). IEEE. DOI: 10.23919/ChiCC.2017.8027964
- [27] Galar, M., Fernandez, A., Barrenechea, E., Bustince, H., & Herrera, F. (2012). A review on ensembles for the class imbalance problem: bagging, boosting, and hybrid-based approaches. *IEEE transactions on systems, man and cybernetics part C: applications and reviews*, 42(4), 463–484. DOI:10.1109/TSMCC.2011.2161285
- [28] Kabir Ahmed, M., Maksha Wajiga, G., Vachaku Blamah, N., & Modi, B. (2019). Stock market forecasting using ant colony optimization based algorithm. *American journal of mathematical and computer modelling*, 4(3), 52. DOI:10.11648/j.ajmcm.20190403.11
- [29] Ghanbari, M., & Arian, H. (2019). *Forecasting stock market with support vector regression and butterfly optimization algorithm*. <https://doi.org/10.48550/arXiv.1905.11462>
- [30] Chandana, P. H. (2019). A survey on soft computing techniques and applications. *International research journal of engineering and technology (IRJET)* 6(4), 1258–1266.
- [31] Rajesh, P., Srinivas, N., Vamshikrishna Reddy, K., Vamsipriya, G., Vakula Dwija, M., & Himaja, D. (2019). Stock trend prediction using ensemble learning techniques in python. *International journal of innovative technology and exploring engineering*, 8(5), 150–154.
- [32] Lv, D., Yuan, S., Li, M., & Xiang, Y. (2019). An empirical study of machine learning algorithms for stock daily trading strategy. *Mathematical problems in engineering*, 2019. DOI:10.1155/2019/7816154
- [33] Zaman, S. (2019). Weak form market efficiency test of Bangladesh stock exchange: an empirical evidence from dhaka stock exchange and chittagong stock exchange. *Journal of economics, business and accountancy ventura*, 21(3), 285. DOI:10.14414/jebav.v21i3.1615
- [34] Shahvaroughi Farahani, M., & Razavi Hajiagha, S. H. (2021). Forecasting stock price using integrated artificial neural network and metaheuristic algorithms compared to time series models. *Soft computing*, 25(13), 8483–8513. DOI:10.1007/s00500-021-05775-5

- [35] Ranjbarzadeh, R., Caputo, A., Tirkolaee, E. B., Jafarzadeh Ghouschi, S., & Bendechache, M. (2023). Brain tumor segmentation of MRI images: a comprehensive review on the application of artificial intelligence tools. *Computers in biology and medicine*, 152, 106405. DOI:10.1016/j.compbiomed.2022.106405
- [36] Farahani, M. S., Esfahani, A., & Alipoor, F. (2022). The application of machine learning in the corona era, with an emphasis on economic concepts and sustainable development goals. *International journal of mathematical, engineering, biological and applied computing*, 1(2), 95–149. DOI:10.31586/ijmebac.2022.519
- [37] Tirkolaee, E. B., Mardani, A., Dashtian, Z., Soltani, M., & Weber, G. W. (2020). A novel hybrid method using fuzzy decision making and multi-objective programming for sustainable-reliable supplier selection in two-echelon supply chain design. *Journal of cleaner production*, 250, 119517. DOI:10.1016/j.jclepro.2019.119517
- [38] Abiodun, O. I., Jantan, A., Omolara, A. E., Dada, K. V., Mohamed, N. A. E., & Arshad, H. (2018). State-of-the-art in artificial neural network applications: a survey. *Heliyon*, 4(11). DOI:10.1016/j.heliyon.2018.e00938
- [39] Tkáč, M., & Verner, R. (2016). Artificial neural networks in business: two decades of research. *Applied soft computing journal*, 38, 788–804. DOI:10.1016/j.asoc.2015.09.040
- [40] Pierdzioch, C., & Risse, M. (2018). A machine-learning analysis of the rationality of aggregate stock market forecasts. *International journal of finance and economics*, 23(4), 642–654. DOI:10.1002/ijfe.1641
- [41] Zhong, X., & Enke, D. (2019). Predicting the daily return direction of the stock market using hybrid machine learning algorithms. *Financial innovation*, 5(1), 1–20. DOI:10.1186/s40854-019-0138-0
- [42] Altan, A., Karasu, S., & Bekiros, S. (2019). Digital currency forecasting with chaotic meta-heuristic bio-inspired signal processing techniques. *Chaos, solitons and fractals*, 126, 325–336. DOI:10.1016/j.chaos.2019.07.011
- [43] Jiang, M., Jia, L., Chen, Z., & Chen, W. (2022). The two-stage machine learning ensemble models for stock price prediction by combining mode decomposition, extreme learning machine and improved harmony search algorithm. *Annals of operations research*, 309(2), 553–585. DOI:10.1007/s10479-020-03690-w
- [44] Behravan, I., & Razavi, S. M. (2020). Stock price prediction using machine learning and swarm intelligence. *Journal of electrical and computer engineering innovations (JECEI)*, 8(1), 31–40.
- [45] Kumar Chandar, S. (2021). Grey Wolf optimization-elman neural network model for stock price prediction. *Soft computing*, 25(1), 649–658. DOI:10.1007/s00500-020-05174-2
- [46] Wei, L. Y., & Cheng, C. H. (2012). A hybrid recurrent neural networks model based on synthesis features to forecast the Taiwan stock market. *International journal of innovative computing, information and control*, 8(8), 5559–5571.
- [47] Chandar, S. Kumar. (2021). Hybrid models for intraday stock price forecasting based on artificial neural networks and metaheuristic algorithms. *Pattern recognition letters*, 147, 124–133. DOI:10.1016/j.patrec.2021.03.030
- [48] Accounting, M., Farahani, M. S., Nejad, M., Moghaddam, F., & Ramezani, A. (2023). Forecasting Tehran price index (TEPIX) using novel meta-heuristic algorithms keywords. *International journal of finance & managerial accounting*, 8(28), 185–216.
- [49] Monfared, J. H., Alinejad, M. A., & Metghalchi, S. (2012). A comparative study of neural network models with box Jenkins methodologies in prediction of Tehran price index (TEPIX). *Financial engineering and securities management (portfolio management)*, 3(11), 1-16. <https://sid.ir/paper/197900/en>
- [50] Ahmed, J., Jafri, M. N., Ahmad, J., & Khan, M. I. (2007). Design and implementation of a neural network for real-time object tracking. *International journal of computer and information engineering*, 1(6), 1816–1819.
- [51] Haider, A., & Hanif, M. N. (2009). Inflation forecasting in pakistan using artificial neural networks. *Pakistan economic and social review*, 47(2), 123–138. <https://www.jstor.org/stable/25825345>
- [52] Chopra, S., Yadav, D., & Chopra, A. N. (2019). Artificial neural networks based indian stock market price prediction : before and after demonetization. *International journal of swarm intelligence and evolutionary computation*, 8(1), 1–7.
- [53] Ravichandran, K. S., Thirunavukarasu, P., Nallaswamy, R., & Babu, R. (2005). Estimation of return on investment in. *Journal of theoretical and applied information technology*, 3, 44–54.
- [54] Hawaldar, I. T., Rohit, B., & Pinto, P. (2017). Testing of weak form of efficient market hypothesis: evidence from the Bahrain bourse. *Investment management and financial innovations*, 14(2), 376–385. DOI:10.21511/imfi.14(2-2).2017.09

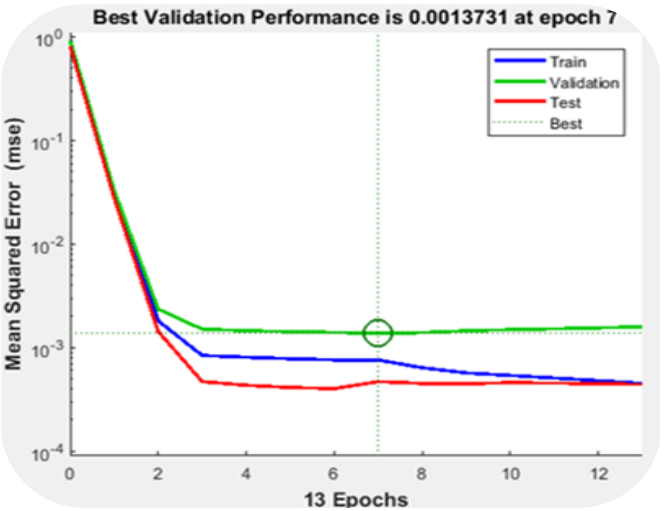
- [55] Ghasemiyeh, R., Moghdani, R., & Sana, S. S. (2017). A hybrid artificial neural network with metaheuristic algorithms for predicting stock price. *Cybernetics and systems*, 48(4), 365–392. DOI:10.1080/01969722.2017.1285162
- [56] Davallou, M., & Azizi, N. (2017). The investigation of information risk pricing; evidence from adjusted probability of informed trading measure. *Financial research journal*, 19(3), 415–438.
- [57] Eberhart, R., & Kennedy, J. (1995). *New optimizer using particle swarm theory*. IEEE Proceedings of the international symposium on micro machine and human science (pp. 39–43). IEEE. DOI: 10.1109/mhs.1995.494215
- [58] Yang, X. S. (2020). Nature-inspired optimization algorithms: challenges and open problems. *Journal of computational science*, 46, 101104. <https://doi.org/10.1016/j.jocs.2020.101104>
- [59] Al Masud, M. A., Paul, S. K., & Azeem, A. (2014). Optimisation of a production inventory model with reliability considerations. *International journal of logistics systems and management*, 17(1), 22–45.
- [60] Ye, F. (2017). Particle swarm optimization-based automatic parameter selection for deep neural networks and its applications in large-scale and high-dimensional data. *PLoS one*, 12(12), 1–36.
- [61] Geem, Z. W., Kim, J. H., & Loganathan, G. V. (2001). A new heuristic optimization algorithm: harmony search. *Simulation*, 76(2), 60–68. DOI:10.1177/003754970107600201
- [62] Kang, J., Kwon, S., Ryu, D., & Baik, J. (2021). HASPO: harmony search-based parameter optimization for just-in-time software defect prediction in maritime software. *Applied sciences*, 11(5), 2002. DOI:10.3390/app11052002
- [63] Leković, M. (2018). Evidence for and against the validity of efficient market hypothesis. *Economic themes*, 56(3), 369–387. DOI:10.2478/ethemes-2018-0022
- [64] Pervez, M., Harun Ur Rashid, M., Asad Iqbal Chowdhury, M., & Rahaman, M. (2018). International journal of economics and financial issues predicting the stock market efficiency in weak form: a study on dhaka stock exchange. *International journal of economics and financial issues*, 8(5), 88–95.
- [65] Ghasemiyeh, R., Moghdani, R., & Sana, S. S. (2017). A hybrid artificial neural network with metaheuristic algorithms for predicting stock price. *Cybernetics and systems*, 48(4), 365–392.
- [66] Sedighi, M., Jahangirnia, H., Gharakhani, M., & Fard, S. F. (2019). A novel hybrid model for stock price forecasting based on metaheuristics and support vector machine. *Data*, 4(2), 75. <https://doi.org/10.3390/data4020075>
- [67] Safa, M., & Panahian, H. (2019). Ranking P/E predictor factors in Tehran stock exchange with using the harmony search meta heuristic algorithm. *Journal of investment knowledge*, 8(29), 67–82.
- [68] Emamverdi, G., Karimi, M. S., Khakie, S., & Karimi, M. (2016). Forecasting the total index of tehran stock exchange. *Financial studies*, 20(1), 55–68.
- [69] Zheng, T., Fataliyev, K., & Wang, L. (2013). *Wavelet neural networks for stock trading* [presentation]. Independent component analyses, compressive sampling, wavelets, neural net, biosystems, and nanoengineering xi (Vol. 8750, pp. 83–92).
- [70] Dong, Guanqun., Kamaladdin, F., & Wang, L. (2013). One-step and multi-step ahead stock prediction using backpropagation neural networks. *ICICS 2013 - conference guide of the 9th international conference on information, communications and signal processing* (pp. 1–5). IEEE. DOI: 10.1109/ICICS.2013.6782784
- [71] Wang, L., Chan, F. F., Wang, Y., & Chang, Q. (2016). *Predicting public housing prices using delayed neural networks* (pp. 3589–3592). IEEE.
- [72] Sin, E., & Wang, L. (2017). Bitcoin price prediction using ensembles of neural networks. *2017 13th international conference on natural computation, fuzzy systems and knowledge discovery (ICNC-FSKD)* (pp. 666–671). IEEE.



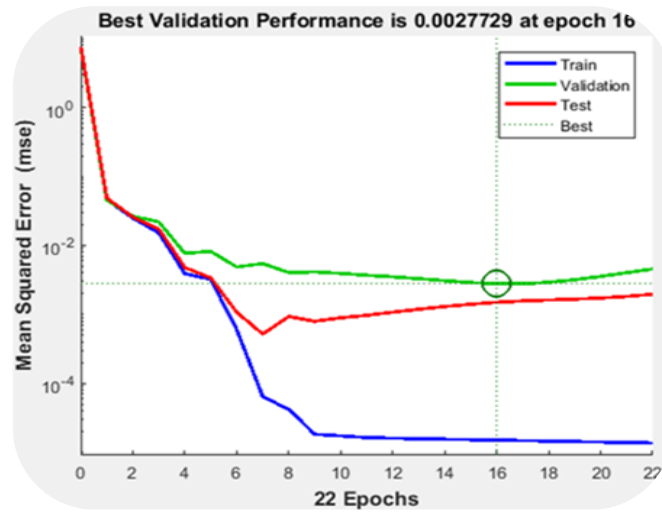
a.



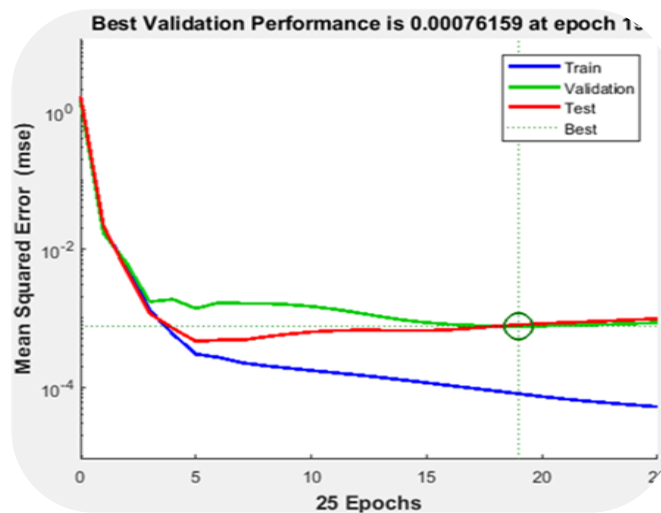
b.



c.



d.



e.

Fig. A1. a. the best validation performance(Fakhouz); b. the best validation performance(Zagros); c. the best validation performance(Khodro); d. the best validation performance(Fameli); e. the best validation performance(Kechad).

Table B1. Limitations of the previous methods.

No	Methods	Purpose	Limitations
1	ARIMA ¹	Forecasting and clustering	-Incompatible with nonlinear time series -Working with a large data set and more data - Decreasing speed with a larger data - Susceptive to noise
2	BPNN ²	Forecasting	- Actual performance depends on initial values - Slow convergent speed - High possibility of local minima/maxima trap
3	CART ³	Classification and forecasting	- The stability of the network will be affected by a little change in training data
4	GP ⁴	Classification and forecasting	-Generates" black box" models which are difficult to interpret. -This type of calculation can be expensive
5	GRNN ⁵	Classification and forecasting	- This method needs more memory space to store the model - This type of calculation can be expensive because of its huge size

¹ Autoregressive Integrated Moving Average (ARIMA) model

² Back Propagation Neural Network (BPNN)

³ Classification and Regression Trees (CART)

⁴ Gaussian Process (GP)

⁵ Generalized Regression Neural Network (GRNN)

Table B1. Continued.

No	Methods	Purpose	Limitations
6	Hierarchical clustering	Clustering	-The length of each time series is the same because of the euclidean distance - Compatible with small datasets because of its quadratic computational complexity
7	HMM ¹	Clustering, classification and clustering	- Very sensitive due to personal tuning - Sensitive to a larger dataset. So, the processing may take a longer time. - Needs to determine the number of clusters in advance - Sensitive to noise
8	K-Mean	clustering	- Limitations and shortage in clustering - Due to poor scalability, incompatible and unable to handle long-time series - Needs to determine the number of nearest neighbors at first
9	KNN ²	Classification and forecasting	- This type of calculation can be expensive - Memory constraint/restriction - Network performance depends on the local structure of the data
10	Logistic Regression (LR)	Classification and forecasting	- Sensitive to outliers - Determinative assumptions
11	LSTM ³	Classification and forecasting	- The high possibility of overfitting - Sensitive to initial random weights - Needs more memory to train -Almost slow convergence
12	MLP ⁴	Classification and forecasting	- be sensitive to local minima while it can affect the performance. - Hard to scale
13	PSO ⁵	Forecasting	- The possibility of local optimum increases in high dimensional space - Low convergence rate
14	RBF ⁶	Classification and forecasting	-Slower classification process of this method proportional to MLP
15	RF ⁷	Classification and forecasting	- Complicated calculations due to the creation of trees - Decision trees require less time via RF.
16	RNN ⁸	Classification and forecasting	-Hardness of training
17	SOM ⁹	Clustering and classification	- Lack of performance power against time series of unequal length because of the difficulty involved in determining the scale of weight vectors - Sensitive to outliers
18	SVM ¹	Classification and forecasting	-Sensitive to outliers
19	SVR ¹	Forecasting	- Sensitive to tuning - Sensitive to personal tuning and setting free parameters
20	ANN ¹	Classification and forecasting	- Overfitting - Local minima/maxima trap - Training and the network performance depend on parameter setting and tuning - Limited exploration and exploitation, which leads to the use of the optimization algorithm - Sensitive to data structure

¹ Hidden Markov Model (HMM)² K Nearest Neighbor (KNN)³ Long Short-Term Memory (LSTM)⁴ Multi-Layer Perceptron (MLP)⁵ Particle Swarm Optimization (PSO)⁶ Radial Basis Function (RBF)⁷ Random Forest (RF)⁸ Recurrent Neural Network (RNN)⁹ Self-Optimizing Maps (SOM)¹⁰ Support Vector Machine (SVM)¹¹ Support Vector Regression (SVR)¹² Artificial Neural Network (ANN)

Table B2. Loss function for ANN before and after using GA.

Error Before Using GA				Error After Using GA		
Fakhouz	Training	Selection	Testing	Training	Selection	Testing
SSE	1246.79	409.51	403.57	103.5	37.39	41.56
MSE	2.2464	2.2256	2.1933	0.186	0.203	0.22
RMSE	1.4988	1.4918	1.4809	0.431	0.4508	0.4752
NSE	12.59	11.6286	12.7699	1.07	1.04	1.23
ME	989.909	325.64	322.606	135.33	47.35	51.24
Zagros	Training	Selection	Testing	Training	Selection	Testing
SSE	263.69	88.36	82.2	91.26	31.83	41.67
MSE	0.4602	0.465	0.432	0.152	0.167	0.219
RMSE	0.6783	0.6819	0.657	0.399	0.409	0.468
NSE	2.7339	2.9913	2.46	1.03	1.04	1.02
ME	296.79	99.3	94.43	120.3	40.97	49.27
Khodro	Training	Selection	Testing	Training	Selection	Testing
SSE	721.35	244.33	244.14	220.23	71.52	61.01
MSE	1.109	1.13	1.13	0.338	0.33	0.28
RMSE	1.05	1.06	1.06	0.582	0.575	0.53
NSE	6.29	6.14	6.27	1.85	1.78	1.76
ME	690.2	232.66	232.2	253.9	82.3	72.11
Fameli	Training	Selection	Testing	Training	Selection	Testing
SSE	230.63	82.51	52.61	221.22	71.89	57.8
MSE	0.38	0.416	0.265	0.37	0.36	0.29
RMSE	0.621	0.645	0.5154	0.608	0.6	0.54
NSE	1.62	1.68	1.67	1.52	1.6	1.74
ME	224.09	79.94	56.39	238.5	77.94	66.19
Kechad	Training	Selection	Testing	Training	Selection	Testing
SSE	300.7	99.11	99.25	1594.5	522.9	511.08
MSE	0.51	0.51	0.51	2.72	2.69	2.63
RMSE	0.717	0.714	0.71	1.65	1.64	1.62
NSE	2.91	3.64	2.75	17.27	15.68	12.51
ME	345.05	114.37	114.1	12.14	397.48	389.4

Table B3. ANN-GA structure for determining weight.

Symbol	Structure	Weight	Tra... Error	Val... Error	Tes... Error	AIC	Correlation	R ²	Tra... Error (AE)	Val... Error (AE)	Itr	Tra... Algo
Fakhouz	19-50-1	1101	0.045	0.04	0.044	-2987	0.997	0.96	0.066	0.064	7	LM
Zagros	16-40-1	721	0.063	0.06	0.061	-3724	0.996	0.96	0.067	0.066	7	LM
Khodro	11-17-1	222	0.057	0.06	0.060	-6022	0.99	0.97	0.055	0.059	6	LM
Fameli	15-19-1	343	0.054	0.05	0.052	-4976	0.99	0.97	0.059	0.06	12	LM
Kechad	16-25-1	451	0.06	0.06	0.06	-4430	0.99	0.94	0.06	0.06	8	LM

Table B4. Selection of most important technical indicators using GA.

Symbol	Technical Indicators	Selected Using GA	Selected (Deleted)
Fakhouz	Open, High, Low, WC, EMA (5), EMA (6), EMA (10), EMA (20), MACD, RS, Lowest Low, %K, SMA (5), SMA (6), SMA (10), SMA (20), TMA (5), TMA (6), TMA (10), TMA (20), Diff, MOpen, MHigh, MLow, MClose, AccOpen, AccHigh, AccLow, AccClose, AccDist, Fast %K, Fast %D, Slow %K, Slow %D, %R, RSI, Middle Band, Upper Band, Lower Band, MP, ROC, TP	Open, High, Low, WC, EMA (6), MACD, RS, Lowest Low, %K, Upper Band, SMA(5), SMA(10), SMA(20), TMA(20), MLow, AccClose, %R	(25)-17

Table B4. Continued.

Symbol	Technical Indicators	Selected Using GA	Selected (Deleted)
Zagros		Low, MP, MOpen SMA (5), EMA (5), EMA (10), EMA (20), EMA (6), MACD, TP, Highest High, ROC, SMA (3), %R	(26)-16
Khodro		High, ROC, %R, EMA (20), EMA (6), EMA (10), Lowest Low, SMA (20), TMA (5), TMA (6), TMA (20)	(31)-11
Fameli		Low, EMA (3), EMA (5), EMA (20), RS, RSI, Highest High, Lowest Low, %D, ROC, SMA (5), SMA (6), SMA (10), TMA (5)	(27)-15
Kechad		Open, Upper Band, Lower Band, %D, %R, Highest High, Lowest Low, RS, SMA (5), SMA (6), TMA (5), TMA (6), TMA (10), Mhigh, Mclose, AccClose	(26)-16

Table B5. The most important selected technical indicators.

LOW	EMA (6)	EMA (20)	SMA (5)	SMA (6)	SMA (20)	TMA (20)
ROC	RSI	R%	MACD	Highest high	Lowest low	TMA (5)

Table B6. Parameters of the models.

Symbol	Network Element	Algorithm			
Fakhrouz	Parameters	ANN	GA-ANN	PSO-ANN	HS-ANN
	Input layers	42	19	19	19
	Hidden layers	10	50	20	6
	The activation function in the hidden layer	Tan-Sigmoid	Logistic	Tan-Sigmoid	Tan-Sigmoid
	Activation function in the output layer	Simple Linear	Simple Linear	Simple Linear	Simple Linear
	Training function	LM	LM	LM	LM
Zagros	Parameters	ANN	GA-ANN	PSO-ANN	HS-ANN
	Input layers	42	16	16	16
	Hidden layers	10	40	15	15
	The activation function in the hidden layer	Tan-Sigmoid	Logistic	Tan-Sigmoid	Tan-Sigmoid
	Activation function in the output layer	Simple Linear	Simple Linear	Simple Linear	Simple Linear
	Training Function	LM	LM	LM	LM
Khodro	Parameters	ANN	GA-ANN	PSO-ANN	HS-ANN
	Input layers	42	11	11	11
	Hidden layers	10	17	12	14
	The activation function in the hidden layer	Tan-Sigmoid	Logistic	Tan-Sigmoid	Tan-Sigmoid
	Activation function in the output layer	Simple Linear	Simple Linear	Simple Linear	Simple linear
	Training function	LM	LM	LM	LM

Table B6. Continued.

Fameli	Parameters	ANN	GA-ANN	PSO-ANN	HS-ANN
	Input layers	42	15	15	15
	Hidden layers	10	19	15	4
	The activation function in the hidden layer	Tan-Sigmoid	Logistic	Tan-Sigmoid	Tan-Sigmoid
	Activation function in the output layer	Simple Linear	Simple Linear	Simple Linear	Simple Linear
	Training function	LM	LM	LM	LM
Kechad	Parameters	ANN	GA-ANN	PSO-ANN	HS-ANN
	Input layers	42	16	16	16
	Hidden layers	10	25	16	15
	The activation function in the hidden layer	Tan-Sigmoid	Logistic	Tan-Sigmoid	Tan-Sigmoid
	Activation function in the output layer	Simple Linear	Simple Linear	Simple Linear	Simple Linear
	Training function	LM	LM	LM	LM

Table B7. Evaluation criteria error for ANN, GA-ANN, PSO-ANN and HS-ANN.

SAE	SSE	RMSPE	RMSRE	MARE	MSRE	MAPE	MAE	RMSE	MSE	Fakhouz
4.837	0.1087						0.52		0.003	Tr error ANN
6.99	0.2297						0.0084		0.000301	Tr error GA-ANN
		0.0014	0.000014	3.18E-06	-0.0018	0.000318	0.005	0.00059	0.000036	Tr error PSO-ANN
		0.0021	0.00002	-6.9E-10	8.98E-05	-6.7E-08	-5.5E-15	0.0002	5.51E-07	Tr error HS-ANN
		0.02138	0.000213	0.00117	0.00329	-0.00023	0.0057	0.0096	0.04527	Tes error ANN
		0.0036	0.000036	3.61E-06	7.98E-07	0.000761	-7.1E-06	8.42E-05	0.000295	Tes error GA-ANN
		0.096	0.00096	0.01	0.00049	0.111	-0.00068	0.0096	0.0093	Tes error PSO-ANN
		0.013	0.00011	-0.0013	0.00006	-0.1305	0.0008	0.0011	0.00012	Tes error HS-ANN
SAE	SSE	RMSPE	RMSRE	MARE	MSRE	MAPE	MAE	RMSE	MSE	Zagros
4.837	0.1087						0.003		4.02E-08	Tr error ANN
6.112	0.1798						0.0064		0.000202	Tr error GA-ANN
		0.02	0.00002	3.05E-06	-0.0038	0.0003	0.00024	0.00038	0.000015	Tr error PSO-ANN
		0.0005	5.10E-06	-2.08E-11	4.08E-08	-2.07E-09	-5.10E-15	0.00005	2.56E-07	Tr error HS-ANN
		5.80E-03	5.81E-05	-2.38E-06	1.96E-07	1.30E-03	6.33E-03	4.31E-02	7.01E-04	Tes error ANN
		2.00E-02	2.00E-04	-1.39E-03	1.70E-04	4.40E-02	-2.56E-03	7.12E-05	5.08E-09	Tes error GA-ANN
		0.51	0.00051	0.00043	0.0065	-0.04	0.00036	0.0051	0.0026	Tes error PSO-ANN
		0.0113	0.00011	-0.0013	0.00006	-0.1305	0.0008	0.0012	0.00014	Tes error HS-ANN
SAE	SSE	RMSPE	RMSRE	MARE	MSRE	MAPE	MAE	RMSE	MSE	Khodro
18.86	0.878						0.0174		0.076	Tr error ANN
28.46	1.7331						0.0263		0.0013	Tr error GA-ANN
		4.20E-03	4.00E-05	-1.97E-04	-0.0002	-0.00019	0.0004	0.0004	1.00E-05	Tr error PSO-ANN
		0.0001	1.00E-06	-4.23E-13	6.19E-09	-4.23E-11	-4.70E-15	0.00001	3.09E-08	Tr error HS-ANN
		4.20E-02	4.20E-03	-3.37E-03	5.10E-03	-3.10E-02	1.65E-03	7.40E-03	4.69E-02	Tes error ANN
		3.00E-01	3.00E-03	-8.19E-05	6.00E-03	1.20E-02	-6.42E-05	2.80E-04	1.50E-03	Tes error GA-ANN
		0.068	0.00068	0.0008	0.0003	0.087	-0.00038	0.0068	0.0046	Tes error PSO-ANN
		0.002	0.000026	0.0004	0.00007	0.0421	-0.0001	0.00026	7.01E-06	Tes error HS-ANN
SAE	SSE	RMSPE	RMSRE	MARE	MSRE	MAPE	MAE	RMSE	MSE	Fameli
5.45	0.6505						0.55		0.0014	Tr error ANN
15.22	1.224						0.0153		0.0015	Tr error GA-ANN
		2.00E-04	2.00E-05	-7.98E-06	-0.004	-0.0007	0.004	0.0011	1.40E-04	Tr error PSO-ANN
		0.0003	3.00E-06	-3.88E-13	1.22E-07	-3.88E-11	-5.55E-15	0.00003	3.70E-07	Tr error HS-ANN
		1.00E-02	1.00E-04	1.42E+00	1.80E-05	-9.00E-02	-1.23E-03	4.32E-03	1.57E-01	Tes error ANN
		1.00E-02	1.00E-04	-3.16E-03	1.00E-03	7.50E-03	-1.91E-05			Tes error GA-ANN
	1.00E-03	4.75E-04								Tes error PSO-ANN
		0.029	0.00029	0.0003	0.0039	-0.03	-0.00068	0.0029	0.00086	Tes error HS-ANN
		0.00615	0.00006	-0.00065	0.00017	-0.0653	0.0004	0.000615	0.00003	Kechad
SAE	SSE	RMSPE	RMSRE	MARE	MSRE	MAPE	MAE	RMSE	MSE	Tr error ANN
7.123	0.2817						0.73		0.008	Tr error GA-ANN
8.522	0.5108						0.0088		0.000246	Tr error PSO-ANN
		6.00E-03	6.00E-05	-2.00E-05	-0.0351	-0.0019	0.01	0.0006	4.00E-05	Tr error HS-ANN
		0.0005	5.00E-06	-4.36E-13	1.40E-07	-4.36E-11	-5.99E-15	0.00005	3.05E-07	Tes error ANN
		3.20E-01	3.20E-03	2.40E-04	1.86E-01	-2.20E-03				Tes error GA-ANN
	1.86E-02	3.60E-03	7.95E-02							Tes error PSO-ANN
		5.40E-02	5.40E-03							Tes error HS-ANN



Paper Type: Research Paper



Designing an Innovative Closed-Loop Supply Chain Network Considering Economic and Environmental Aspects

Maryam Rahmaty* 

Department of Management, Chalous Branch, Islamic Azad University, Chalous, Iran; rahmaty.maryam61@gmail.com.

Citation:



Rahmaty, M. (2023). Designing an innovative closed-loop supply chain network considering economic and environmental aspects. *International journal of research in industrial engineering*, 12(3), 273–286.

Received: 03/01/2023

Reviewed: 06/02/2023

Revised: 19/03/2023

Accepted: 24/05/2023

Abstract

In this paper, the modeling of a closed-loop supply chain problem is discussed concerning economic and environmental aspects. The considered supply chain simultaneously makes strategic and tactical decisions, such as locating potential facilities, optimal allocation of product flow, and determining the optimal level of discount. Since the presented model is an NP-Hard model, MOPSO and SPEA II algorithms have been used to solve the problem. For this purpose, a priority-based encoding is presented, and the Pareto front resulting from solving different problems is compared. The results show that the MOPSO algorithm has obtained the most significant number of Pareto solutions in the large size. In contrast, the SPEA algorithm has included more Pareto solutions in the small and medium sizes. This is despite the fact that in different sizes, the MOPSO algorithm has the lowest calculation time among all algorithms. Also, according to the results obtained from the TOPSIS method, it was observed that the MOPSO algorithm in small and medium sizes and the SPEA2 algorithm in larger sizes have better performance than other proposed algorithms.

Keywords: Network design, Closed-loop supply chain, Economic and environmental aspects, Meta-heuristic algorithms.

1 | Introduction

Some of these organizations seek to achieve a competitive advantage by improving environmental performance by complying with environmental laws and standards, increasing customer knowledge, and reducing negative environmental effects. With the development of technology and the emergence of new technologies, companies need systematic integration in all production processes, from raw material to the final consumer. Supply chain management, as an integrated approach for the proper management of material and goods flow, information and money flow, can respond to these conditions and includes the coordination of production activities, inventory, positioning, and transportation among supply chain actors to achieve efficiency. More and meeting customer expectations [1], [2].

Due to the reduction of natural resources and reserves of raw materials, along with the increase in the cost of production of products and the problems caused by the landfilling of industrial waste and consumer goods, the cycle of products from the point of production to their final recovery has been taken into consideration, which has led to the emergence of new concepts such as the chain Closed-

 Licensee
International Journal of Research in Industrial Engineering. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0>).



Corresponding Author: rahmaty.maryam61@gmail.com

<https://doi.org/10.22105/riej.2023.391773.1374>

loop provision has been made over the past decade [3]. Due to the economic, social, and environmental challenges that threatened organizations in the last decade, the customer-oriented approach and focusing on its demands and designing the organization's strategy based on this have lost its ability to create a competitive advantage. This attitude caused environmental pollution and the production of products and processes incompatible with the environment [4]. In this regard, organizations have survived in taking responsibility in three economic, social, and environmental fields. Greening the supply chain is the process of considering environmental criteria or considerations throughout the supply chain. Green supply chain management integrates supply chain management with environmental requirements at all stages of product design, raw material selection and procurement, manufacturing, distribution and transportation processes, delivery to the customer, and management of recycling and reuse in order to maximize the efficiency of energy and resource consumption along with improving the performance of the entire supply chain [5], [6]. In recent years, a few articles have focused on designing an integrated forward and reverse supply chain network, which can prevent suboptimality, increase efficiency and reactivity of the entire network, and coordinate between direct and reverse processes. For this reason, the closed-loop innovative supply chain network is presented in this paper, considering economic and environmental aspects.

The structure of this article is as follows; in the second part, the literature review is presented. In the third part, the problem definition and modeling are presented. The solution method is explained in the fourth part, and finally, the conclusion is presented in the last part.

2 | Literature Review

In recent years, several articles have been published in this field due to the increasing importance of closed and reverse supply chain design issues. Pishvae et al. [7] designed a four-level model of a closed-loop supply chain network, considering the levels of reproduction, recycling, collection, and final customers of the first-hand and second-hand markets. In this model, reducing the costs of the entire chain is considered the main goal, and facility location and optimal flow allocation are considered secondary goals. Since demand parameters and transmission costs are non-deterministic, a stable optimization method controls the parameters. The results show an increase in system costs against an increase in the uncertainty rate. Khatami et al. [8] designed an integrated forward and reverse supply chain problem under demand uncertainty and product return rate in different scenarios. In this article, they considered two important strategic decisions, including facility location and tactical decisions, including the optimal amount of production, distribution, storage, shortage, and transportation. To simultaneously achieve the above objective function, they used the objective function of total cost minimization. The results obtained from Bandarz's analysis show that the number of problem scenarios can be reduced by using the K-means clustering algorithm. Saeedi et al. [9] modeled a robust closed-loop supply chain network under uncertainty by considering an M/M/1 queuing system. This model considers two objective functions of maximizing the profit of the entire supply chain network and minimizing the productivity costs of recycling centers. The Denovo method is used to form the Pareto front, and the stable method is used to control the non-deterministic demand parameter. The results show the high efficiency of the model in determining the facility capacity levels.

Mohammed et al. [10] used a robust method to control uncertainty conditions in the closed-loop supply chain network considering carbon policies. The main goal of this article is to reduce the fixed costs of construction, shortage, maintenance, operation, and transportation. In order to achieve the above objective function, location and allocation decisions must be taken. They also designed another model considering carbon emission policies and compared the results with the original one. Polo et al. [11] modeled an integrated forward and reverse supply chain network under uncertain environmental conditions. The model presented by them is a mixed integer non-linear programming model that pays attention to economic and risk aspects. Due to the indeterminacy of the problem's parameters, the stable optimization method has been used. The objective function of the problem is to maximize the total profit of the supply chain network design, which is obtained by subtracting the assumed value from the

total costs of the network design (fixed, transportation, operational, maintenance, and shortage). They implemented their model in an electronic component manufacturing industry and obtained favorable results. Kim et al. [12] designed and developed a closed-loop supply chain network under conditions of demand uncertainty and product return rate. In this model, the stable method is used to increase the profit of the supply chain in conditions of uncertainty. The model results show a decrease in the profit of the supply chain network due to the increase in the uncertainty rate. Darestani and Hemmati [13] designed a closed-loop supply chain network under conditions of uncertainty of demand and transportation costs. In this model, a queue distribution system is used to distribute products. Since the problem's parameters are non-deterministic, the robust optimization method has been used. The objective functions of the problem are the simultaneous minimization of the total system costs and the minimization of greenhouse gas emissions. The solution of the two-objective model has been done by using three methods of comprehensive criteria, utility function, and TH, and the results show the high efficiency of the TH method in solving the two-objective model.

Ghahremani-Nahr et al. [14] designed a two-objective and 11-level closed-loop supply chain network under demand uncertainty and transportation costs. In this model, considering the discussion of discount, they measured the impact of this concept on the objective functions of minimizing network design costs and the amount of greenhouse gas emissions. They used the robust method to control their uncertain parameters. The results show an increase in model stability costs against an increase in uncertain demand. Gholizadeh et al. [15] designed a closed-loop supply chain model to apply it to the destruction of products, where the goal was to increase the return rate of returned products for recycling and destruction. The problem's objective function is the maximization of profit from product return and recycling and reproduction of products. In this model, location-allocation and routing decisions are taken together. In this research, they used a stable method to control non-deterministic parameters and used a priority-based genetic algorithm to solve the problem. The results show the high efficiency of the genetic algorithm in solving large-size problems. Vahdani and Mohammadi [16] presented a fuzzy/probabilistic hybrid optimization method to control the non-deterministic model of a multi-objective closed-loop supply chain network. This model considers four levels of production and reproduction centers, distribution and collection centers, final customers, and destruction centers. The objectives presented in this model are the simultaneous maximization of three objective functions of net present value, maximization of service level, and minimization of delivery time and collection of final products. Due to the indeterminacy of the demand parameter, the new fuzzy/probabilistic hybrid method is used to control the parameter, and the TH method is used to solve the three-objective model. The model results show the TH method's high efficiency in solving the problem. Fathollahi-Fard et al. [17] presented an integrated sustainable closed-loop supply chain network model for water supply and wastewater collection systems under uncertainty. They applied a case study in Iran to a new multi-objective stochastic optimization model. Kalantari Khalil Abad and Pasandideh [18] presented a model for designing a green closed-loop supply chain network with stochastic demand. To solve the model, they applied a new accelerated Benders decomposition algorithm together with the Pareto optimal cut method.

Pishvae and Razmi [19] designed a multi-objective environmental supply chain model using fuzzy mathematical programming under uncertainty, which is able to consider and balance multiple environmental impacts along with cost minimization. An interactive fuzzy approach was developed to solve the problem. A real industrial case example was investigated to show the importance and application of the proposed model. Hamidieh et al. [20] modeled a bi-objective model of a closed-loop supply chain network by considering the minimization of total network design costs and the minimization of delivery time. They used a robust probabilistic programming method to control uncertain demand parameters and transmission costs.

Ghahremani-Nahr et al. [21] developed a single-objective closed-loop chain network model under the uncertainty of demand parameters, operational costs, and transportation costs. To control the model, they used the robust fuzzy programming method and concluded that the cost of the whole system increases with the increase of the uncertainty rate. They also used Wall's optimization algorithm to solve the problem

by designing a priority-based chromosome. Liu et al. [22] modeled a green closed-loop supply chain network under demand uncertainty and used a fuzzy robust optimization method. They considered two objective functions of minimizing network design costs and minimizing greenhouse gas emissions and implemented their model in the Coca-Cola company. The results indicate the management of system costs under uncertainty. Boronoos et al. [23] modeled a closed-loop green supply chain multi-objective model under uncertain conditions. At the same time, in this model, they minimized the total costs of the Zanijare supply network and the amount of greenhouse gas emissions in the forward and reverse supply chain. Since transportation and operating costs are considered non-deterministic and triangular fuzzy numbers in this demand model, the fuzzy stable combination method controls these parameters. The results of the TH method in solving the two-objective model show that with the increase in system costs, greenhouse gas emissions increase under uncertainty. Sadrnia et al. [24] presented a multi-objective optimization model in an automotive supply chain network. The objective function presented in their model included the simultaneous minimization of the costs of the entire supply chain network and the amount of greenhouse gas emissions. They used the MOGSA algorithm to solve the problem.

According to the literature review, each article has built or expanded a supply chain network model by considering some limiting assumptions. So that in these articles, a comprehensive model that includes assumptions closer to the real world is less visible. Therefore, this article, which is a new model in the continuation of solving some of the limitations and assumptions of other articles, refers to a mixed integer non-linear programming model for the design of a multi-objective green supply chain network that seeks to locate potential facilities and optimize the amount of flow between the facility can be compensated by considering the discount factor and shortage, which has not been reviewed in other articles. Multi-objective meta-heuristic algorithms with a modified priority-based encoding have been used to solve the developed model.

3 | Problem Definition and Modeling

In this article, a multi-level green supply chain network is considered. The forward network includes levels of raw material suppliers, production centers, warehouses, product distribution centers, and final customers. The reverse network also includes levels of collection centers, repair centers, recycling centers, and destruction centers. According to Fig. 1, in the forward flow path, the supplier of raw materials sends the raw materials needed to produce products to the production centers. Raw materials are sent to the product warehouse after assembly in production centers and stored. After receiving the products from the warehouse, product distribution centers send them to the final customers. On the way back, a percentage of returned products is collected, and after product inspection, items that can be repaired are sent to repair centers and the rest to recycling centers. The repaired products in the repair center are finally sent to the distribution centers or potential warehouses. Recyclable products, if they are usable, are sent to production centers for reuse after disassembly in recycling centers. Otherwise, they are sent to destruction centers for disposal.

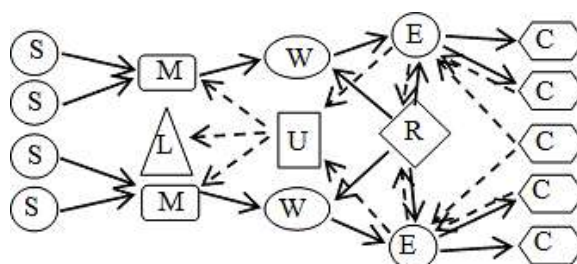


Fig. 1. Proposed green supply chain network.

To specify the study area, the following assumptions have been considered for the proposed model:

- I. Production centers provide the raw materials needed for the production of products with a discount from the suppliers of the products.
- II. Production centers store part of the purchased raw materials in their warehouse.
- III. The capacity of all centers is limited and specific.
- IV. The location of all centers is potential and uncertain.
- V. Customers' demands are fulfilled until the last period of time, taking into account the compensable deficiency.
- VI. Distribution and collection centers are considered dual center.

For index modeling, the parameter and variables of the problem are defined as follows:

Sets

S	The set of potential points of raw material supply centers.
M	Set of potential points of manufacturing plants.
W	A set of potential storage points.
E	The set of potential points of distribution and collection centers.
C	Set of customer fixed points.
R	Set of potential points of repair centers.
U	Set of potential points of recycling centers.
L	Set of potential points of destruction centers.
I	Set of raw materials.
P	Set of final products.
H	Set of discount levels.
N	Cargo vehicle set.
T	Set of time periods.

Assuming $\mathcal{V}^f = (G^1, A', A'')$ and $\mathcal{V}^r = (G^2, A''', A''')$ where G is the nodes of the graph and A are the arcs of the graph according to the following definitions:

$$\begin{aligned}
 G^1 &= \{S \cup M \cup W \cup E \cup C\}. \\
 A' &= \{(j, j') \mid i \in M, j \in W\} \cup \{i \in W, j \in E\} \cup \{i \in E, j \in C\}. \\
 A'' &= \{(j, j') \mid (i \in S, j \in M)\}. \\
 G^2 &= \{C \cup E \cup R \cup U \cup L\}. \\
 A''' &= \left\{ (j, j') \mid \begin{array}{l} i \in C, j \in E \cup i \in E, j \in R \cup i \in E, j \in U \\ \cup i \in R, j \in E \cup (i \in R, j \in W) \end{array} \right\}. \\
 A'''' &= \{(j, j') \mid (i \in U, j \in L) \cup (i \in U, j \in M)\}. \\
 G &= \{G^1 \cup G^2\} - C. \\
 A_1 &= \{A'' \cup A''''\}. \\
 A_2 &= \{A' \cup A'''\}.
 \end{aligned}$$

Parameters

fi_{jt}	Annual fixed cost of facility j in time period t .
op_{jt}	Establishment cost of facility j in time period t .
cl_{jt}	Closing cost of facility j in time period t .
$TC_{jj'in}$	The cost of transporting a unit of raw material i between facilities $(j, j') \in A_1$ by freight forwarder n .
$TC_{jj'pn}$	The cost of transporting a unit of product p between facilities $(j, j') \in A_2$ by freight forwarder n .
$Co_{2jj'in}$	The amount of Co_2 gas emission per unit of raw material i between facilities $(j, j') \in A_1$ by cargo carrier n .
$Co_{2jj'pn}$	The amount of Co_2 gas emission per unit of product p between facilities $(j, j') \in A_2$ by cargo carrier n .
h_{mit}	The cost of keeping a unit of raw material i in the storage center m at period t 's end.
h'_{wpt}	The cost of keeping a unit of product p in warehouse center w at the end of period t .

Pr_{shit}	The purchase price of a unit of raw material i at discount level h from supplier s in period t .
VA_{shit}	The lower limit of the discount range for raw material i at discount level h from supplier s in period t .
C_{1mpt}	The cost of producing a unit of product p in factory m in period t .
C_{2ept}	The cost of distributing a unit of product p by distribution center e in period t .
C_{3ept}	The cost of collecting a unit of returned product p by collection center e in period t .
C_{4rpt}	The cost of repairing a unit of product p at repair center r in period t .
C_{5upt}	The cost of recycling a unit of product p at the recycling center u in period t .
C_{6lit}	Cost of destroying one unit of raw material i in destruction center l in period t .
π_{cpt}	Penalty cost of facing a shortage of one unit of product p from customer c in period t .
δ_{ip}	The number of raw material i needed to make a product p .
De_{cpt}	Customer c 's demand for product p in period t .
α_{cpt}	Percentage of product p returned from customer c in period t .
β_{pt}	Percentage of product p that can be repaired in period t .
γ_{pt}	Percentage of product p transferred to the distribution center in period t .
θ_{it}	Percentage of usable raw materials i in period t .
cap_{si}	The supply capacity of raw material i from supplier s .
cap_{mi}	The storage capacity of raw material i in the raw material warehouse of the factory m .
cap_{mp}	Production capacity of product p in factory m .
cap_{wp}	The storage capacity of the final product p in the warehouse w .
cap_{ep}	Distribution capacity of product p in distribution center e .
cap'_{ep}	Return product capacity p in the collection center e .
cap_{rp}	Repair capacity of repairable product p in repair center r .
cap_{up}	The recycling capacity of the recyclable product p in the recycling center u .
cap_{li}	The destruction capacity of substance i in the center of destruction l .
M	A very large non-negative number.

Decision variables

$X_{jj'itn}$	The amount of raw material i that is transported by freight vehicle n between facilities $(j, j') \in A_1$ in period t .
$X_{jj'ptn}$	The amount of product p that is transported by freight vehicle n between facilities $(j, j') \in A_2$ in period t .
VQ_{mit}	The amount of inventory of raw material i in the raw material warehouse of factory m at the end of period t .
IQ_{wpt}	Inventory amount of product p in warehouse w at period t 's end.
Q_{sit}	The total purchase amount of raw material i from supplier s in period t .
sh_{cpt}	The amount of shortage of product p from customer c in period t .
Y_{jt}	If the facilitation center $j \in G$ is established in period t , it takes the value 1 and otherwise 0.
A_{jhit}	If the discount level h is selected for the raw material i in the facilitation center $j \in S$ in the period t , the value is 1, and otherwise, it is 0.

$$\begin{aligned}
\min z1 = & \sum_{j \in G} \sum_{t \in T} \left(fi_{jt} Y_{jt} + op_{jt} Y_{jt} (1 - Y_{j,t-1}) \right. \\
& \left. + cl_{jt} Y_{jt} (1 - Y_{j,t+1}) \right) \\
& + \sum_{(j,j') \in A_1} \sum_{i \in I} \sum_{t \in T} \sum_{n \in N} tc_{jj'in} X_{jj'itn} + \sum_{j \in m} \sum_{i \in I} \sum_{t \in T} h_{jit} VQ_{jit} \\
& + \sum_{(j,j') \in A_2} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} tc_{jj'pn} X_{jj'ptn} + \sum_{j \in W} \sum_{p \in P} \sum_{t \in T} h'_{jit} IQ_{jpt} \\
& + \sum_{j \in S} \sum_{j' \in M} \sum_{i \in I} \sum_{t \in T} \sum_{n \in N} \sum_{h \in H} pr_{jhita} A_{jhita} X_{jj'itn} \\
& + \sum_{j \in M} \sum_{j' \in W} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} C_{1jpt} X_{jj'ptn} \\
& + \sum_{j \in E} \sum_{j' \in C} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} (C_{2jpt} X_{jj'ptn} + C_{3jpt} X_{j'jptn}) \\
& + \sum_{j \in E} \sum_{j' \in R} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} C_{4j'pt} X_{jj'ptn} \\
& + \sum_{j \in E} \sum_{j' \in U} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} C_{5j'pt} X_{jj'ptn} \\
& + \sum_{j \in U} \sum_{j' \in L} \sum_{i \in I} \sum_{t \in T} \sum_{n \in N} C_{6j'it} X_{jj'itn} + \sum_{j \in C} \sum_{p \in P} \sum_{t \in T} \pi_{ipt} sh_{jpt}. \\
\min z2 = & \sum_{(j,j') \in A_1} \sum_{i \in I} \sum_{t \in T} \sum_{n \in N} co2_{jj'in} X_{jj'itn} + \sum_{(j,j') \in A_2} \sum_{p \in P} \sum_{t \in T} \sum_{n \in N} co2_{jj'pn} X_{jj'ptn}.
\end{aligned} \tag{1}$$

S. t.

$$A_{jhita} VA_{jhita} \leq Q_{jit} \quad \text{for all } j \in S, h, i, t. \tag{3}$$

$$\sum_{h \in H} A_{jhita} = Y_{jt} \quad \text{for all } j \in S, i, t. \tag{4}$$

$$Q_{jit} = \sum_{j' \in M} \sum_{n \in N} X_{jj'itn} \quad \text{for all } j \in S, i, t. \tag{5}$$

$$\begin{aligned}
& \sum_{j \in S} \sum_{n \in N} X_{jj'itn} + \sum_{j \in U} \sum_{n \in N} X_{jj'itn} - VQ_{j'it} + VQ_{j'i,t-1} \\
& = \sum_{j \in W} \sum_{n \in N} \sum_{p \in P} X_{j'jptn} \delta_{ip} \quad \text{for all } j' \in M, i, t.
\end{aligned} \tag{6}$$

$$\begin{aligned}
& \sum_{j \in M} \sum_{n \in N} X_{jj'ptn} + \sum_{j \in R} \sum_{n \in N} X_{jj'ptn} + IQ_{j'p,t-1} - \sum_{j \in E} \sum_{n \in N} X_{j'jptn} = IQ_{j'pt} \quad \text{for all } j' \\
& \in W, p, t
\end{aligned} \tag{7}$$

$$\sum_{j \in W} \sum_{n \in N} X_{jj'ptn} + \sum_{j \in R} \sum_{n \in N} X_{jj'ptn} = \sum_{j \in C} \sum_{n \in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{8}$$

$$De_{j'p,t} + sh_{j'p,t-1} - sh_{j'pt} = \sum_{t < T} \sum_{j \in E} \sum_{n \in N} X_{jj'ptn} \quad \text{for all } j' \in C, p, t. \tag{9}$$

$$\alpha_{j'pt} \sum_{j \in E} \sum_{n \in N} X_{jj'p,t-1,n} = \sum_{j \in E} \sum_{n \in N} X_{j'jptn} \quad \text{for all } j' \in C, p, t. \tag{10}$$

$$\beta_{pt} \sum_{j \in C} \sum_{n \in N} X_{jj'ptn} = \sum_{j \in R} \sum_{n \in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{11}$$

$$(1 - \beta_{pt}) \sum_{j \in C} \sum_{n \in N} X_{jj'ptn} = \sum_{j \in U} \sum_{n \in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{12}$$

$$\gamma_{pt} \sum_{j \in E} \sum_{n \in N} X_{jj'ptn} = \sum_{j \in E} \sum_{n \in N} X_{j'jptn} \quad \text{for all } j' \in R, p, t. \tag{13}$$

$$(1 - \gamma_{pt}) \sum_{j \in E} \sum_{n \in N} X_{jj'ptn} = \sum_{j \in W} \sum_{n \in N} X_{jj'ptn} \quad \text{for all } j' \in R, p, t. \quad (14)$$

$$\theta_{it} \sum_{j \in E} \sum_{n \in N} \sum_{p \in P} X_{jj'ptn} \delta_{ip} = \sum_{j \in M} \sum_{n \in N} \sum_{p \in P} X_{jj'itn} \quad \text{for all } j' \in U, i, t. \quad (15)$$

$$(1 - \theta_{it}) \sum_{j \in E} \sum_{n \in N} \sum_{p \in P} X_{jj'ptn} \delta_{ip} = \sum_{j \in L} \sum_{n \in N} \sum_{p \in P} X_{jj'itn} \quad \text{for all } j' \in U, i, t. \quad (16)$$

$$\sum_{j \in M} \sum_{n \in N} X_{jj'itn} \leq \text{cap}_{ji} Y_{jt} \quad \text{for all } j \in S, i, t. \quad (17)$$

$$VQ_{jit} \leq \text{cap}_{ji} Y_{jt} \quad \text{for all } j \in M, i, t. \quad (18)$$

$$\sum_{j' \in W} \sum_{n \in N} X_{jj'ptn} \leq \text{cap}_{jp} Y_{jt} \quad \text{for all } j \in M, p, t. \quad (19)$$

$$IQ_{jpt} \leq \text{cap}_{jp} Y_{jt} \quad \text{for all } j \in W, p, t. \quad (20)$$

$$\sum_{j \in W} \sum_{n \in N} X_{jj'ptn} + \sum_{j \in R} \sum_{n \in N} X_{jj'ptn} \leq \text{cap}_{j'p} Y_{j't} \quad \text{for all } j' \in E, p, t. \quad (21)$$

$$\sum_{j \in C} \sum_{n \in N} X_{jj'ptn} \leq \text{cap}'_{j'p} Y_{j't} \quad \text{for all } j' \in E, p, t. \quad (22)$$

$$\sum_{j \in E} \sum_{n \in N} X_{jj'ptn} \leq \text{cap}_{j'p} Y_{j't} \quad \text{for all } j' \in U, p, t. \quad (23)$$

$$\sum_{j \in E} \sum_{n \in N} X_{jj'ptn} \leq \text{cap}_{j'p} Y_{j't} \quad \text{for all } j' \in R, p, t. \quad (24)$$

$$\sum_{j \in U} \sum_{n \in N} X_{jj'itn} \leq \text{cap}_{j'i} Y_{j'i} \quad \text{for all } j' \in L, i, t. \quad (25)$$

$$Y_{j,t-1} = 0 \quad \text{for all } j \in G, t = 1. \quad (26)$$

$$Y_{j,t+1} = 0 \quad \text{for all } j \in G, t = T. \quad (27)$$

$$X_{jj'itn}, VQ_{mit}, Q_{sit} \geq 0 \quad \text{for all } j, j') \in A_1, i, n, t, s, m. \quad (28)$$

$$X_{jj'ptn}, IQ_{wpt}, sh_{cpt} \geq 0 \quad \text{for all } j, j') \in A_2, p, n, t, w, c. \quad (29)$$

$$Y_{jt} \in \{0, 1\} \quad \text{for all } j \in G, t. \quad (30)$$

The objective *Function (1)* seeks to minimize the costs of the entire supply chain network. These costs include: annual fixed costs, establishing and closing a facility, transportation costs of raw materials and products between facilities, storage costs of raw materials and finished products in the related warehouse, operational costs related to each facility (cost of production, distribution, collection, repair, recycling, destruction) and finally penalty costs are faced with product shortage. *Eq. (2)* shows the second objective function of the problem related to minimizing the amount of CO_2 gas released by moving cargo vehicles between facility centers. The constraint in *Inequality (3)* expresses the total amount of raw materials purchased from suppliers' discount levels. The constraint in *Eq. (4)* guarantees that if a potential supplier is selected, raw materials can be purchased from only one discount level in each period. The constraint in *Eq. (5)* sends suppliers' total raw material purchases to manufacturing plants. The limitation in *Eq. (6)* shows the volume of the raw material flow from the supplier and the recycling center to the factory; part of the raw material is stored in the factory warehouse after the production of the product. The restriction in *Eq. (7)* controls the volume of incoming and outgoing flow to the warehouse. *Eq. (8)* shows the equilibrium constraint on the distribution center and ensures that the volume of the incoming flow from the repair and warehouse center to the distribution center is equal to the volume of the outgoing flow from the distribution center to the customer. The constraint in *Eq. (9)* guarantees that the customer's demand must be satisfied until the last period of the time horizon. The constraint in *Eq. (10)* shows the percentage of the customer's discarded products in each period. Constraints in *Eqs. (11) and (12)* state the collection center, after inspecting the products, send a percentage of it that can be repaired to the repair center and the rest of the products to the recycling center. The constraints in *Eqs. (13) and (14)* show that, after repairing the returned products, the repair

center sends a percentage of it to the distribution center and a percentage of the products to the warehouse. The constraints in *Eqs. (15) and (16)* also show that the recycling center, after inspecting the products and disassembling them products, sends a percentage of the raw materials that can be used to the manufacturing plant and the rest of the products to the destruction center for destruction. The constraints in *Inequality (17) to (25)* represent the constraints related to the capacity of the network facilities so that the constraint in the *Inequality (17)* shows the maximum capacity of the supplier in the provision of raw materials. Constraint in *Inequality (18)* limits the storage amount of each raw material in the factory warehouse. The constraint in *Inequality (19)* expresses the maximum production capacity of each product for the created factories. The constraint in *Inequality (20)* guarantees that the maximum amount of product storage cannot exceed the warehouse capacity if a warehouse is created. *Limitations (21) and (22)* states that if a dual collection and recycling center is established, the amount of distribution and collection will not exceed the capacity of this facility. The constraint in *Inequality (23)* shows the maximum amount of ability to recycle products in the recycling center. The constraint in *Inequality (24)* guarantees that if a repair center is established, the maximum number of repairable products does not exceed the repair capacity of the said center. The constraint in *Inequality (25)* also limits the capacity to destroy unusable raw materials. *Constraints (26) and (27)* make the value of the variable in the objective function zero for certain periods. *Constraints (28) to (30)* state the types of decision variables and their allowed values in the problem.

4 | Solution Method

In this article, due to the high complexity of the proposed model, a new decoding based on modified priority is used. In this solution, the chromosome is a permutation of the number of facilities available at each level. Suppose a level of the supply chain includes 4 customers and 3 distributors according to *Fig. 2*. In this case, the initial solution will be a permutation of the number 7.

There are 2 main steps to decrypt this solution:

Step 1. First, the optimal number of centers (distributors) should be obtained. Therefore, for this purpose, the highest priority is selected among the distributors, and the capacity of that center is compared with the total demand of customers. If the center's capacity (centers) is less than the total demand, another distributor with the next highest priority is selected. This process continues until the selected centers' total capacity exceeds the total customer demand. Finally, the priority of not selected centers will be changed to zero.

Step 2. After determining the number of optimal centers, the number of goods should be allocated between the customers and the selected centers. For this, the highest priority among the customers (centers) is selected and connected to the centers (customers) with the lowest transportation cost. Then it is allocated according to the minimum capacity of the selected center and the customer's demand. If the amount of capacity or demand becomes zero, the corresponding priority will also change to zero. This continues until all requests are met.

This solution is described for one supply chain level and for one product and one period. To solve the proposed problem, chromosome should be considered in the total number of products, all periods, and all levels of the supply chain. Until the decoding of one level is done, the decoding of another level should not be done.

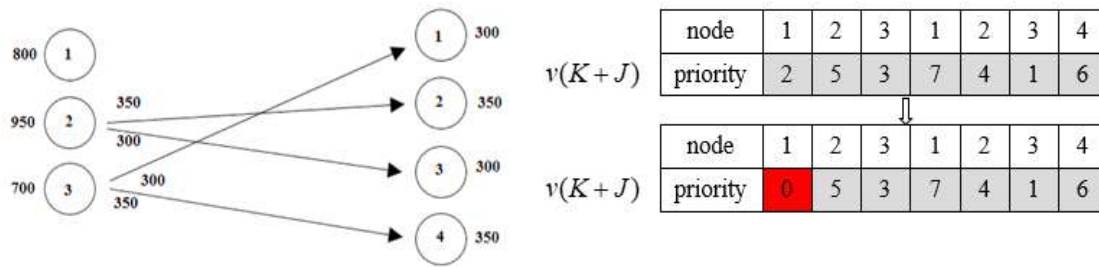


Fig. 2. Encoding and decoding of a supply chain level.

To compare meta-heuristic algorithms with each other, a series of numerical experiments are designed for the proposed multi-objective model. The nominal data were generated using the uniform distribution shown in Table 1. Also, the size of the designed sample problems is also shown in Table 2.

Table 1. Range of produced nominal data.

Fi _{Gt}	(40000,45000)~	VA _{shit}	(4000,10000)~	C _{5upt}	(0.5,1.5)~
cl _{Gt}	(4000000,6000000)~	C _{2ept}	(0.5,1.5)~	π _{cpt}	(150,200)~
op _{Gt}	(2500000,5000000)~	C _{4rpt}	(0.5,1.5)~	δ _{ip}	(1,3)~
cap _{si}	(12000,15000)~	C _{6lit}	(0.5,1)~	β _{pt}	(0.4,0.5)~
cap _{mp}	(1600,2200)~	De _{cpt}	(200,300)~	θ _{it}	(0.2,0.3)~
cap _{ep}	(1300,1500)~	α _{cpt}	(0.1,0.2)~	cap' _{ep}	(200,300)~
cap _{rp}	(200,250)~	γ _{pt}	(0.4,0.5)~	h _{mit}	(0.2,0.5)~
cap _{lp}	(1000,1600)~	TC _{jj'in}	(2.5,4)~	h' _{wpt}	(0.8,1.2)~
cap _{mi}	(4000,6000)~	TC _{jj'pn}	(5,15)~	Pr _{shit}	(1,1.5)~
cap _p	(2000,2500)~	Co _{2jj'in}	(2.5,4)~	C _{1mpt}	(0.5,1.5)~
cap _{up}	(200,250)~	Co _{2jj'pn}	(5,15)~	C _{3ept}	(0.5,1.5)~

Table 2. Dimension levels of designed sample problems.

Size	Problem	S*M*W*E*C*R*U*L*T*P*I*N*H
Small	1	6*6*6*6*10*4*4*4*6*2*2*3*3
	2	6*6*6*6*10*4*4*4*6*3*2*3*3
	3	6*6*6*6*10*4*4*4*8*2*3*3*3
	4	6*6*6*6*12*4*4*4*6*2*2*4*3
	5	6*6*6*6*12*4*4*4*8*3*3*4*3
Medium	6	10*10*10*10*15*6*6*6*10*3*3*3*3
	7	10*10*10*10*15*6*6*6*12*4*4*4*3
	8	10*10*10*10*15*6*6*6*14*4*3*5*3
	9	10*10*10*10*16*6*6*6*12*3*4*4*3
	10	10*10*10*10*15*6*6*6*10*3*4*5*3
Large	11	15*15*15*15*20*10*10*10*18*4*4*5*3
	12	15*15*15*15*20*10*10*10*18*4*5*5*3
	13	15*15*15*15*22*10*10*10*20*4*4*6*3
	14	15*15*15*15*22*10*10*10*20*3*4*5*3
	15	15*15*15*15*20*10*10*10*18*3*4*6*3

In this paper, Taguchi's methodology is used through the design of experiments to obtain all the optimal combinations of the factors (algorithm parameters) proposed. In this method, at first, the appropriate factors should be identified, then the levels of each factor should be selected, and then the appropriate test plan should be determined for these control factors. After the test plan is determined, the tests are performed, and the tests are analyzed to find the best combination of parameters. In this article, 3 levels are considered for each algorithm and each factor, and according to the number of factors and the number of their levels, the experiment's design and implementation are determined. It should be noted that each experiment was repeated 5 times on average and the average values obtained were evaluated

in the final analysis. *Table 3* shows the parameter setting levels of the proposed algorithms. Bold data in *Table 3* shows the parameter set for each algorithm.

Table 3. Levels and adjusted parameters of the proposed algorithm.

Algorithm	Parameter	Low	Medium	High
NSGA II	Maximum number of iterations	200	300	500
	Number of population	100	150	200
	Composition rate	0.3	0.5	0.7
	Mutation rate	0.3	0.5	0.7
MOPSO	Maximum number of iterations	200	300	500
	Number of particles	100	150	200
	Number of archives	20	50	70
	Initial speed coefficient	0.1	0.5	0.8
SPEA2	Secondary speed coefficient	0.3	0.5	0.7
	Maximum number of iterations	200	300	500
	Number of population	100	150	200
	Arshid number	20	50	70
	Composition rate	0.3	0.5	0.7
	Mutation rate	0.3	0.5	0.7

5 | Test Results and Analysis of Results

For comparing and analyzing the results of meta-heuristic algorithms, 15 numerical examples in three sizes, small, medium, and large, were selected, and from each problem, a data sample was generated and solved according to *Table 1*. *Fig. 3* shows an example of the problem solved for problem 4 for the proposed algorithms.

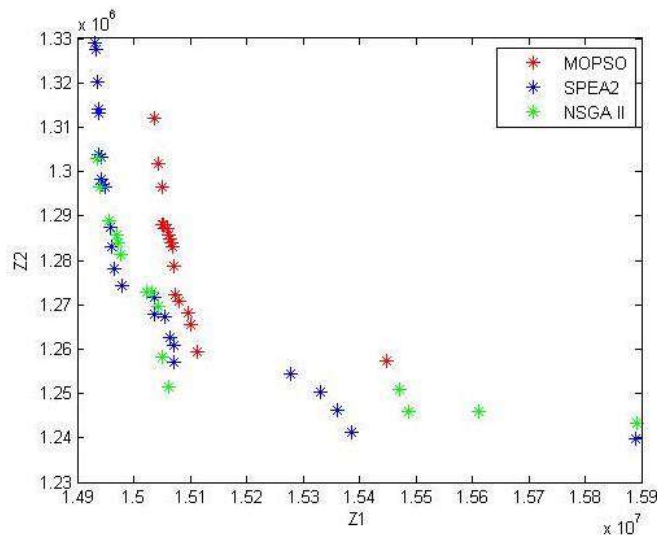


Fig. 3. An example of a problem solved by algorithms.

As seen in *Fig. 3*, the number of Pareto solutions obtained by the MOPSO algorithm is more than other algorithms. If the dispersion of efficient solutions of the NSGA II algorithm is better than other algorithms. *Table 4* shows the calculation results for all the designed problems; in this table, the number of efficient solutions (NPF), More Expansion Index (MSI), Spacing Index (SI), distance metric index (SM), and computing time (CPU-time) indicates each algorithm. According to *Table 4* and the obtained results, it can be seen that the average number of Pareto solutions obtained from the SPEA2 algorithm is more than other algorithms. On average, the calculation time of the MOPSO algorithm is lower than other algorithms.

Table 4. Computational results of sample problems.

Problem	NPF	MSI	SI	SM	CPU Time
1	14	433620.8	24356.12	0.44	130.1
2	20	835769.9	76533.37	0.6	149.45
3	14	853519.7	149878.5	0.7	138.54
4	15	956206.1	7562.21	0.83	150.23
5	13	783100	43304.24	0.73	171.55
6	13	1341179	78569.39	0.78	178.23
7	14	228346	8452.15	0.37	185.06
8	17	842071.7	75882.34	0.62	184.42
9	22	1650103	215436.1	0.69	193.65
10	8	472835.4	33311.04	0.58	218.94
11	15	1059873	71764.21	0.83	304.98
12	15	1786672	304626.1	0.79	291.61
13	15	1059873	59484.57	0.62	312.97
14	8	875864	129859.8	0.62	307.95
15	20	1292680	57939.01	0.73	320.56
1	9	512623.9	32258.58	0.46	34.12
2	31	849502.6	30198.74	0.81	40.23
3	12	327400.9	25311.65	0.84	38.56
4	17	414037	81921.48	0.74	41.21
5	5	234949.1	10020.79	0.23	51.17
6	16	954906.8	14201.89	0.65	86.45
7	7	892546	294427.1	0.79	87.65
8	21	1416885	59595.35	0.76	110.53
9	17	1286576	48061.21	0.70	84.25
10	20	1134990	31184.24	0.77	108.26
11	20	1254616	74754.02	0.97	239.86
12	23	1548515	38258.32	0.74	249.34
13	21	1882374	81827.01	0.85	259.59
14	23	1716464	28222.24	0.54	250.99
15	17	1538293	85243.26	0.52	262.53
1	18	587377.3	42644.47	0.98	98.1
2	17	745374.3	63967.08	0.66	97.81
3	14	568505.4	65360.28	0.68	110.24
4	25	963311.3	99913.29	0.71	113.37
5	18	506117.6	25790.64	0.7	119.01
6	15	1333088	64858.64	0.71	123.23
7	8	482408	70125.88	0.46	149.92
8	27	909092.2	28159.93	0.65	170.56
9	27	1153317	22505.3	0.56	161.16
10	19	810930.3	18806.11	0.73	177.2
11	15	493434.9	19606.03	0.42	311.74
12	19	955545.2	41922.03	0.7	313.29
13	9	1139443	116988.5	0.71	314.94
14	17	1472409	163432	0.63	311.81
15	12	1316889	82819.48	0.85	326.99

Table 5. Average calculation indices in different sizes.

Algorithm	Size	NPF	MSI	SM	CPU Time
NSGA II	Small	15.2	772443.3	0.66	147.9
MOPSO		14.8	467702.7	0.61	41.05
SEPA2		18.4	674137.2	0.74	107.7
NSGA II	Medium	14.8	906906.9	0.6	192
MOPSO		16.2	1137181	0.73	95.4
SEPA2		19.2	937767.1	0.62	156.4
NSGA II	Large	14.6	1220063	0.73	307.6
MOPSO		20.8	1588052	0.72	252.4
SEPA2		14.4	1075544	0.66	315.7

According to Table 5, the MOPSO algorithm has obtained the largest number of Pareto solutions in the large size, while the SPEA algorithm has included more Pareto solutions in the small and medium sizes.

This is despite the fact that in different sizes, the MOPSO algorithm has the lowest calculation time among all algorithms. Therefore, the TOPSIS method has been used to compare algorithms to determine the best algorithm in each size. This method selects 4 indicators of the number of Pareto solutions, MSI, metric distance index, and computing time. It is more suitable if the first and second indexes have a larger value and the third and fourth indexes have a smaller value. *Table 6* shows the results obtained from the comparison of algorithms using the TOPSIS method. In this table, the weight of each index is obtained through the entropy method.

Table 6. The results were obtained from the TOPSIS method.

Size	Weight (Entropy Method)				Algorithm
	w1	w2	w3	w4	
Small	0.03	0.14	0.02	0.49	MOPSO>SPEA2>NSGA II
Medium	0.11	0.09	0.06	0.71	MOPSO >SPEA2>NSGA II
Large	0.03	0.95	0.002	0.01	SPEA2>MOPSO>NSGA II

According to the results obtained from the TOPSIS method according to *Table 6*, it can be seen that the MOPSO algorithm in small and medium sizes and the SPEA2 algorithm in larger sizes have better performance than other proposed algorithms.

5 | Conclusion

In this article, a dual-objective, multi-period, and multi-product green supply chain model was modeled and solved by considering tactical decisions, including the application of a quantity discount by the supplier and compensable shortage. The objectives of the proposed model included minimizing the cost of logistics and the number of CO2 emissions by cargo vehicles. Multi-objective meta-heuristic algorithms, including NSGA II, MOPSO, and SEPA2 with new encryption based on modified priority, were used to solve the proposed model. After adjusting the parameters by the Taguchi method and calculating the results by the TOPSIS method, the aforementioned algorithms were compared with each other in different sizes, and the best algorithm was selected. Due to the high complexity of the proposed model, the SEPA2 algorithm was chosen as the most efficient algorithm in very large dimensions. Studies in the field of the supply chain are very extensive. However, it is possible to develop more supply chain models. In this article, the supply chain model is designed by considering the deterministic parameters. Therefore, it is suggested that in future studies, the developed model should be put on the agenda by considering non-deterministic parameters and using fuzzy or stable methods. Also, considering the development of meta-heuristic algorithms, it is suggested to design and solve the developed model with newer algorithms.

References

- [1] Hugos, M. H. (2018). *Essentials of supply chain management*. John Wiley & Sons.
- [2] Ghahremani-Nahr, J., Nozari, H., & Bathaee, M. (2021). Robust box Approach for blood supply chain network design under uncertainty: hybrid moth-flame optimization and genetic algorithm. *International journal of innovation in engineering*, 1(2), 40–62.
- [3] Szmelter Jarosz, A., Ghahremani-Nahr, J., & Nozari, H. (2021). A neutrosophic fuzzy optimisation model for optimal sustainable closed-loop supply chain network during Covid-19. *Journal of risk and financial management*, 14(11), 519. <https://www.mdpi.com/1911-8074/14/11/519>
- [4] Ghahremani Nahr, J., Pasandideh, S. H. R., & Niaki, S. T. A. (2020). A robust optimization approach for multi-objective, multi-product, multi-period, closed-loop green supply chain network designs under uncertainty and discount. *Journal of industrial and production engineering*, 37(1), 1–22.
- [5] Zhu, Q., & Sarkis, J. (2006). An inter-sectoral comparison of green supply chain management in China: drivers and practices. *Journal of cleaner production*, 14(5), 472–486.
- [6] Taleizadeh, A. A., Haghighi, F., & Niaki, S. T. A. (2019). Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products. *Journal of cleaner production*, 207, 163–181.

- [7] Pishvaei, M. S., Rabbani, M., & Torabi, S. A. (2011). A robust optimization approach to closed-loop supply chain network design under uncertainty. *Applied mathematical modelling*, 35(2), 637–649.
- [8] Khatami, M., Mahootchi, M., & Farahani, R. Z. (2015). Benders' decomposition for concurrent redesign of forward and closed-loop supply chain network with demand and return uncertainties. *Transportation research part e: logistics and transportation review*, 79, 1–21.
- [9] Saeedi, S., Mohammadi, M., & Torabi, S. (2015). A De Novo programming approach for a robust closed-loop supply chain network design under uncertainty: An M/M/1 queueing model. *International journal of industrial engineering computations*, 6(2), 211–228.
- [10] Mohammed, F., Hassan, A., & Selim, S. Z. (2018). Robust optimization for closed-loop supply chain network design considering carbon policies under uncertainty. *International journal of industrial engineering*, 25(4), 526–558.
- [11] Polo, A., Peña, N., Muñoz, D., Cañón, A., & Escobar, J. W. (2019). Robust design of a closed-loop supply chain under uncertainty conditions integrating financial criteria. *Omega*, 88, 110–132.
- [12] Kim, J., Do Chung, B., Kang, Y., & Jeong, B. (2018). Robust optimization model for closed-loop supply chain planning under reverse logistics flow and demand uncertainty. *Journal of cleaner production*, 196, 1314–1328.
- [13] Darestani, S. A., & Hemmati, M. (2019). Robust optimization of a bi-objective closed-loop supply chain network for perishable goods considering queue system. *Computers & industrial engineering*, 136, 277–292.
- [14] Ghahremani-Nahr, J., Nozari, H., & Najafi, S. E. (2020). Design a green closed loop supply chain network by considering discount under uncertainty. *Journal of applied research on industrial engineering*, 7(3), 238–266.
- [15] Gholizadeh, H., Fazlollahtabar, H., & Khalilzadeh, M. (2020). A robust fuzzy stochastic programming for sustainable procurement and logistics under hybrid uncertainty using big data. *Journal of cleaner production*, 258, 120640. <https://doi.org/10.1016/j.jclepro.2020.120640>
- [16] Vahdani, B., & Mohammadi, M. (2015). A bi-objective interval-stochastic robust optimization model for designing closed loop supply chain network with multi-priority queueing system. *International journal of production economics*, 170, 67–87.
- [17] Fathollahi-Fard, A. M., Ahmadi, A., & Al-e-Hashem, S. M. J. M. (2020). Sustainable closed-loop supply chain network for an integrated water supply and wastewater collection system under uncertainty. *Journal of environmental management*, 275, 111277. <https://doi.org/10.1016/j.jenvman.2020.111277>
- [18] Kalantari Khalil Abad, A. R., & Pasandideh, S. H. R. (2022). Green closed-loop supply chain network design with stochastic demand: A novel accelerated benders decomposition method. *Scientia Iranica*, 29(5), 2578–2592.
- [19] Pishvaei, M. S., & Razmi, J. (2012). Environmental supply chain network design using multi-objective fuzzy mathematical programming. *Applied mathematical modelling*, 36(8), 3433–3446.
- [20] Hamidieh, A., Naderi, B., Mohammadi, M., & Fazli-Khalaf, M. (2017). A robust possibilistic programming model for a responsive closed loop supply chain network design. *Cogent mathematics*, 4(1), 1329886. <https://doi.org/10.1080/23311835.2017.1329886>
- [21] Ghahremani-Nahr, J., Kian, R., & Sabet, E. (2019). A robust fuzzy mathematical programming model for the closed-loop supply chain network design and a whale optimization solution algorithm. *Expert systems with applications*, 116, 454–471.
- [22] Liu, Y., Ma, L., & Liu, Y. (2021). A novel robust fuzzy mean-UPM model for green closed-loop supply chain network design under distribution ambiguity. *Applied mathematical modelling*, 92, 99–135.
- [23] Boronoo, M., Mousazadeh, M., & Torabi, S. A. (2021). A robust mixed flexible-possibilistic programming approach for multi-objective closed-loop green supply chain network design. *Environment, development and sustainability*, 23, 3368–3395.
- [24] Sadrnia, A., Ismail, N., Zulkifli, N., Ariffin, M. K. A., Nezamabadi-pour, H., & Mirabi, H. (2013). A multiobjective optimization model in automotive supply chain networks. *Mathematical problems in engineering*, 2013. <https://doi.org/10.1155/2013/823876>



Measuring Effective Indicators for Waste Disposal in Order to Assess the Sustainable Environment: Application of Fuzzy Approach

Mohammad Hossein Kabgani* 

Faculty of Business and Economics, Persian Gulf University, Bushehr, Iran; mh.kabgani@pgu.ac.ir.

Citation:



Kabgani, M. H. (2023). Measuring effective indicators for waste disposal in order to assess the sustainable environment: application of fuzzy approach. *International journal of research in industrial engineering*, 12(3), 287-305.

Received: 06/11/2022

Reviewed: 09/12/2022

Revised: 19/01/2023

Accepted: 21/02/2023

Abstract

Selecting appropriate locations for Municipal Solid Waste (MSW) management facilities, such as landfills, is an important issue in rapidly developing regions. Multiple alternatives and evaluation attributes need to be analyzed to finalize the locations of these facilities. The selection of a landfill site in an urban area is a critical issue due to the involvement of many parameters. The decisive parameters are environmental, economic, and social, some of them conflicting, making landfill site selection a tedious and complex process. Multi Attribute Decision Making (MADM) approaches are found to be very effective for ranking several potential locations and, hence, selecting the best among them based on the identified attributes. Therefore, this study presents a two-stage MADM model that also accounts for all possible combinations of locations. This study evaluates economic, environmental, social, and technical attributes based on realistic conditions. Based on the results, 15 attributes are first identified through a comprehensive literature review and with the help of municipal officials during field surveys. These attributes are categorized into four types, i.e., economic, technical, environmental, and social, based on their respective propensity.

In the second step, a statistical analysis questionnaire was distributed among the study population, and Cronbach's alpha was explained for all four main factors of the study. Therefore, in the last step, the rank of all research variables was calculated using the Nonlinear analysis method. Based on the results of this study, the technical variable was ranked first, the economic variable was ranked second, and the environmental and social variable was ranked third. This article has three theoretical, practical, and technical contributions. Also, this article provides a clear explanation of the theoretical contribution related to the accumulated knowledge, both in the introduction and theoretical background sections of the article. Therefore, studying the past research describes a relatively complete background of the planned theoretical contributions of this article compared to the previous research. Therefore, the theoretical contribution of this article solves the scientific gap about effective indicators for determining the location of waste disposal. From the point of view of practical contribution, this article presents practical concepts related to managers and experts and has practical suggestions presented in the conclusion section. Also, the technical contribution of this article is presented by combining fuzzy logic and Nonlinear mathematical programming.

Keywords: Municipal solid waste, Landfill, Sustainable environment, Multi attribute decision making.

1 | Introduction

The growth of the urban population in developing countries is occurring more rapidly. Instinctively, urbanization itself is not the root of the problems associated with sustainability; however, unplanned and haphazard urbanization growth leads to many economic, social, and environmental challenges. Municipal Solid Waste (MSW) management is an example of one such challenge, directly associated with rapid urbanization. Rapid urbanization has enormously increased the amount of MSW generated in urban centers.

This MSW must be disposed of properly and promptly to avoid possible health and environmental hazards. Also, waste production is one of the most important sources of environmental threats. To deal with this problem, sanitary landfill has been accepted as a practical method in all countries. Choosing the right landfill is a major problem in waste management. Despite many efforts in the field of waste management to reduce waste from the source, recycling, and converting of waste into usable material have been done; however, in all these methods, some material must be buried.



Licensee
International Journal of
Research in Industrial
Engineering. This article
is an open access article
distributed under the
terms and conditions of
the Creative Commons
Attribution (CC BY)
license
(<http://creativecommons.org/licenses/by/4.0>).



Corresponding Author: mh.kabgani@pgu.ac.ir



<https://doi.org/10.22105/riej.2023.368774.1345>

The production of solid waste is of major environmental concern since it can release organic and inorganic contaminants to water resources, pollute the food sources, and have esthetic impacts. In addition, solid waste biodegradation can release Greenhouse Gasses (GHGs) from landfill sites into the atmosphere, contributing to global warming. A proper solid waste management plan is of major importance to protect public health and contribute to sustaining the environment. It should cover the waste generation phase to the disposal process stages. Waste disposal methods include incineration, other thermal processes, recycling, landfilling, and composting. Many factors affect the selection of disposal methods, such as population, location, technology, etc. Among the mentioned methods, landfilling is still the most widely applied method used in developed countries.

The increasing development of urban areas and the uncontrolled increase of population have led to the production of various types of municipal waste, so selecting landfills for municipal waste is one of the important steps in urban waste management. Due to these places' destructive environmental, economic, social, and ecological effects, the landfill site must be selected carefully and through a scientific process. The waste management system comprises six main stages of waste generation, storage, collection, transportation, recycling, and disposal. Most of the financial and human resources are spent on collection and transportation. Collection, transportation, and waste landfills are done in different ways according to necessity and facilities.

Waste management problems are due to increased per capita waste production, the need for high levels of capital in physical infrastructure (incinerators, recycling facilities, and landfills), organizational barriers, and a wide range of stakeholders. The activities undertaken to optimize waste management services require the participation of all relevant departments for the success of all credible, transparent, socially sustainable activities, and as practical and appropriate as possible for the participants.

In the past decades, many studies have been conducted to identify the best viable location for landfilling. Some of the used procedures and methods include diagramming, grey systems theory (clustering), expert systems [1], Analytic Hierarchy Processes (AHP) [2], Geographic Information System (GIS) with AHP [3], Analytic Network Process (ANP), GIS with Weighted Linear Combination (GIS/WLC), the Simple Additive Method (SAM), fuzzy logic [1], Ordered Weighted Averaging (OWA) [4].

Each method shows specific advantages, disadvantages, and applicability that may change the final result, which in the case of landfill site selection is the ranking of the most suitable sites. In Multi-criteria Decision-Making (MCDM), five distinct steps can be taken: 1) determination of purpose: identification of the problem, which, for example, could be finding a new location for a landfill, 2) criteria identification: clarification of the requirements and converting them into criteria, 3) weights identification: allocation of weight to each criterion based on its importance via a MCDM method, 4) determination of alternatives: determination of viable options for comparison, and 5) evaluation of alternatives: finding the best option through evaluating and subsequently ranking each option (for example landfill sites) [5].

The primary purpose of the present study is to investigate an appropriate criteria location for a landfill site by considering environmental, economic, and socio-technical criteria at the macro level in Bushehr province by applying MCDM techniques. Bushehr province was selected as the case study in this research. Nevertheless, to the best of the authors' knowledge, no previous investigation has specifically reported the results of a systematic analysis of analysis for landfill site selection. Considering the scarcity of literature in this area, the fuzzy method-Factor Analysis (FA) was implemented as the first assessment for a sustainable landfill site selection. This research consists of three parts. In the first part, after reviewing the research literature, the indicators of the research model are expressed. In the second part, the main indicators of the research were analyzed using the basics of statistical science. Finally, in the third part, the weight and rank of all variables were determined using the fuzzy nonlinear technique.

2 | Literature Review

A literature review was carried out comprehensively to understand current knowledge published in the social performance field of waste management systems in general and in developing countries. This was achieved by reviewing the research studies published in leading international journals indexed in recognized databases over the last decade (e.g., JCR) by the Scopus searching tool. All the reviewed research studies were related to assessing any social aspect (exclusively or not) of waste management systems. Waste management practices can be divided into categories, ranging from waste collection and separation to waste recovery and recycling. While extensive literature exists regarding optimizing general waste collection and recovery operations, the literature on waste management in smart cities is limited. In this section, first, we will provide an overview of research on waste collection and recovery operations scheduling. Then we will discuss the most recent studies on waste management practices in smart cities.

To identify research gaps in waste collection problems in smart cities, first, we will review the literature on vehicle routing problems. To name a few studies, various heuristic and non-heuristic models have been offered in transportation literature for solving routing problems. Reed et al. [6] have proposed a dynamic model for capacitated vehicle routing problems using the ant colony system algorithm. Hemmelmayr et al. [7] have proposed a heuristic solution for solid waste collection as a periodic truck routing problem, where the collected waste can be delivered to some intermediate facilities, and not every collection point needs to be covered daily. Banditvilai and Niraso [8] have proposed a simulation framework for modeling the night shift solid waste collection in Phuket municipality, Thailand, and developed a heuristic approach for assigning waste collection zones and routings.

Waste management systems are normally optimized by taking the economic perspective into account, along with the environmental one, but generally leave aside the recommendation of the United Nations in 2014 of also considering the social point of view. However, to analyze and improve waste management systems, especially in developing countries, it is necessary to integrate socio-economical and environmental aspects into the decision-making process, such as the sustainable development concept proposes [9].

Population growth, public health concerns, and unwanted local settlements to build landfills around them are some of the problems that need to be overcome. In locating landfills, paying attention to environmental factors is very important because these pits may pose certain environmental hazards to the general public or the living environment around the area. Assessing hazardous waste landfills is complex because it requires data from various social and environmental areas. This data often involves the processing of significant amounts of spatial information that the GIS can use as an important tool for land use sustainability analysis [10].

Waste management has become one of the most complex issues facing countries today. In other words, in developed countries, if the rate of waste generated is between 0.8 and 1.4 kg/person/day is appropriate [11]. Compared to developed countries, the average generation rate of MSW in developing countries is 0.3–0.5 kg/person/day, but the management is inadequate and improper. So, SWM in various cities in developing countries is becoming a complicated challenge [12]. Instinctively, urbanization itself is not the root of the problems associated with sustainability; however, unplanned and haphazard urbanization growth leads to many economic, social, and environmental challenges. MSW management is an example of one such challenge, which is directly associated with rapid urbanization [13], [14].

Levels of service in solid waste collection strongly depend on the number of collection periods, collection points, and types of solid waste collected. Increasing the transport time increases the waiting time for the collection of useful waste at each shipment, thus reducing its efficiency. Environmental, political, economic, socio-cultural, and cultural conditions in any society widely affect municipalities' efforts and their decision-making process [15].

The increase in waste production is due to the increase in population and the exponential growth of urbanization. Most countries face many problems in waste management because their subsets do not have sufficient funding for waste management activities. Therefore, they need to develop a regular policy plan for waste management to minimize costs and overcome the challenges that arise. Therefore, waste disposal methods are used in most countries to overcome its accumulation in the community. Currently, CO₂ in the atmosphere is reaching approximately 390 ppm, which leads to global warming. The rapid growth of urbanization, population, and environmental concerns have created a critical situation for waste management [16].

Recycling waste can be a less costly method than recycling options, which is why it attracts the attention of most city managers. Also, with the advancement of technology, landfilling does not seem to be a sustainable solution to the problem of waste accumulation. Landfills come with many concerns, such as pollution affecting landfill space shortage, which is scarce [17].

Different cities face different problems with waste managers. In most cities, the executive does not have a coherent waste collection policy. Most researchers have found that these problems occur in communities facing increasing populations, and local governments often do not have enough data. On the other hand, waste collection creates high costs for these communities, so waste collection and transportation are the most costly [18].

One of the important aspects of decision making is MCDM, which is divided into two categories: 1) continuous, which can be solved by Multi-Objective Decision-Making (MODM) methods to deal with the continuous problems, which include a very large number of alternative solutions that are not explicitly known at the beginning, and 2) discrete, that uses the Multi Attribute Decision Making (MADM) methods to solve the discrete problems, which has a finite number of alternative solutions that are known at the beginning [19]. MCDM ranks all the alternatives to find the optimum choice by applying a specific approach concerning different criteria [20]. Several MCDM methods have been applied for site selection in recent years, such as AHP, ANP, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Complex Proportional Assessment (COPRAS) method, Best Worst Multi-criteria (BWM) method and so forth [21].

Table 1 reports the results of reviewing internationally published studies in which different waste management systems were analyzed from at least a social perspective. The following issues were identified for each study: the waste fraction considered the analyzed aspects (environmental, economic, technical, or social), data sources, and the methodology applied to characterize the social impact.

Table 1. Comparison of the most related works.

Authors	Aspects				Data Source				Methodology
	Economic	Technical	Environmental	Social	Simulation Data	Primary Data (Specific Data)	Secondary Data (Generic Data)	Forecasting Data	
Babaei Tirkolaei et al. [22]	*	*	*		*	*			Mathematical modeling and optimization approach
Yadav et al. [23]	*	*	*	*				*	MADM approach
Rabbani et al. [10]			*		*	*			Optimization approach

Table 1. Continued.

Authors	Aspects				Data Source				Methodology
	Economic	Technical	Environmental	Social	Simulation Data	Primary Data (Specific Data)	Secondary Data (Generic Data)	Forecasting Data	
Bovea et al. [24]	*	*	*		*		*		Simulation and optimization approach
Archetti et al. [25]		*			*	*			Exact algorithm
Jatinkumar Shah et al. [26]	*		*				*	*	Stochastic optimization
Boonmee et al. [27]	*		*		*			*	Mathematical modeling and optimization approach
Toro et al. [28]			*	*		*		*	Mathematical modeling and optimization approach
Yıldız et al. [29]	*		*			*			Application of questionnaires
Mirdar Harijani et al. [30]			*				*	*	Fuzzy AHP

3 | Model Development

After examining the theoretical foundations, mainly obtained from literature and new texts, the relevant conceptual model was designed. Based on the following model, the criteria for selecting a suitable place for landfilling municipal waste are classified into four categories. The main factors mentioned in the following model are geological criteria, environmental criteria, social criteria, and economic criteria. Also, to confirm the model's structure, the exploratory FA method has been used, the results of which will be mentioned in the research method section. The model of this research is finalized in *Table 2*.

Table 2. Identified evaluation attributes with their respective descriptions.

	Attributes	Descriptions
Economic	MSW generation	Proximity to the wards with the higher generation of MSW
	Land ownership	Land ownership by municipality/government to establish TSs
	Proximity to other facilities	Proximity of TS locations to the processing or landfill sites
	Overall cost	Optimal overall cost for the entire MSW management system
	Distance traveled	Total distance traveled by PCVs and SCVs
Technical	Interference with routine traffic	To avoid interference with the routine traffic of urban centers
	Size of land	Size of land available to build TSs
	Accessibility	Access to the TS locations through major roads
	Availability of basic amenities	Availability of electricity and water supplies to the locations
	Flexibility for size expansion	Flexibility to expand the capacity of TSs in the future
Environmental-social	Remoteness to water bodies	Euclidean distances of the TS location from water bodies
	Total emissions	Total vehicular emissions from PCVs and SCVs
	Protection from flood hazards	Euclidean distances of flood-prone areas from TSs
	Public acceptability	Acceptability of residents to have TSs
	Kids population density	Remoteness to areas with higher population densities of kids

The proposed method for selecting appropriate locations for landfills consists of two basic assessment stages (as shown in *Fig. 1*): 1) identification of attributes and economic evaluation of all possible combinations and 2) evaluation of shortlisted alternatives using Nonlinear analysis method.

In stage one of the assessment, multiple pertinent attributes are identified based on a thorough literature review and field surveys. Further, a focused workshop with municipal officials is conducted to score alternatives concerning the selected attributes individually. The economic evaluation of all possible permutations and combinations is then performed for all potential locations of landfills. The second stage of the assessment consolidates the average scores given to all alternatives for the attributes. The following subsections provide a detailed description of these two assessment stages.

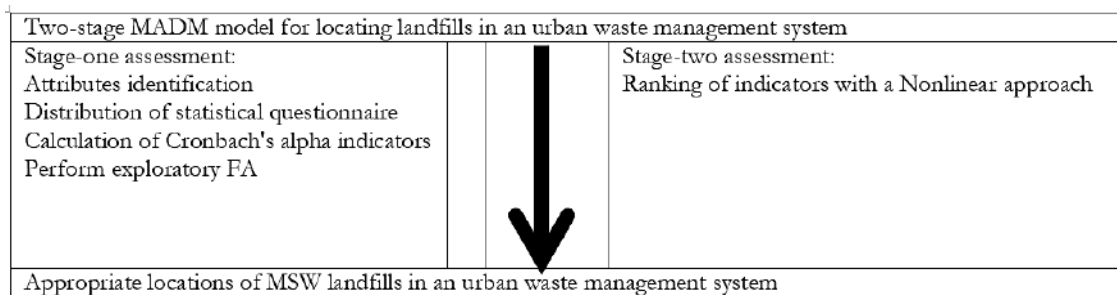


Fig. 1. Scheme describing the overall methodology.

4.1 | Stage-One Assessment

The stage-one assessment can be explained using the following steps:

Step 1. The 15 attributes are first identified through a comprehensive literature review and with the help of municipal officials during field surveys. These attributes are categorized into four types, i.e., economic, technical, environmental, and social (see *Table 2*), based on their respective propensity. Including all types of attributes in selecting the best locations for landfills provides a useful reference for the stakeholders with specialized knowledge about specific locations. After identifying the attributes, the next step is distributing a statistical questionnaire.

Step 2. With a quantitative modeling approach, this research pursues the goal of assessing and prioritizing each effective criteria for selecting a municipal waste disposal site. The data collection tool is a researcher-made questionnaire. The statistical population of the research is 150 university professors, students, and experts in urban planning management. Therefore, Cochran's method was used at a 5% error level and 95% confidence level to calculate the number of samples; 109 questionnaires were distributed to the statistical population, and 100 questionnaires were returned. In this research, Cochran's sampling formula was used to estimate the sample size, and the sample size was determined using the following formula:

$$n = \frac{\frac{z^2 \times pq}{d^2}}{1 + \frac{1}{N} \left[\frac{z^2 \times pq}{d^2} - 1 \right]} \quad (1)$$

n: statistical sample size.

P: The proportion of the trait in the statistical population. Here, P=0.5 is considered.

q: It is the proportion of absence of a trait in the statistical population. Here, since $q=0.5$ is considered, $q=1-p$ is equal to 0.5.

Z: In this research, considering the significance level of 0.95, the value of Z is equal to 1.96.

d: Is the desired possible accuracy (error level) and is considered here as 0.05.

N: population size.

In this research, due to the limited statistical population, an available sampling method was used; in this way, the online questionnaire was shared with experts. Also, the size of the available population is considered to be 150 people, and based on placement in the Cochran formula, the sample size is 109 people. Also, the number of samples to be used in fuzzy nonlinear mathematical programming to rank the research indicators is ten people, consisting of university professors and experts in urban planning. The selection criteria of these people include the level of education in the field of urban planning and executive experience in the field of waste management.

Step 3. In this study, Cronbach's alpha method was used to assess the reliability of the questionnaire. The reliability of a measure is its ability to achieve consistent results. In this method (alpha calculation), reliability is operated as internal consistency, which forms the degree of internal correlation between items on a scale. *Table 3* shows the Cronbach's alpha value obtained for the main criteria of the research model. As it turns out, all the numbers obtained represent good values. Also, the Cronbach's alpha value of the whole questionnaire is 0.933, which is desirable.

Table 3. Cronbach's alpha value for each of the main criteria of the model.

Main Criteria of the Model	Cronbach's Alpha Coefficients
Economic	0.832
Technical	0.756
Environmental-social	0.789

Step 4. Exploratory FA is a statistical method used to identify the underlying categories of a set of items. In some studies, researchers first prepare a large number of items to measure the main phenomenon under study. Then, it is necessary to categorize these items in an orderly manner. The Exploratory Factor Analysis (EFA) EFA method helps to emerge different clusters according to the internal correlation between items. In each cluster, several elements have semantic correlation. Each cluster is called a factor. In this way, reaching specific and limited clusters from a large and scattered set of objects is possible. The researcher can choose a suitable title for that cluster based on the items placed in each cluster. FA is used to find out the underlying variables of a phenomenon or summarize a set of data. The primary data for FA is the correlation matrix between the variables. FA does not have predetermined dependent variables.

In other words, exploratory FA is one of the data clustering methods in the data mining field. This technique is used in management studies to identify the underlying factors of a set of questions. If you have identified many questions based on research literature or interviews and have no idea how to categorize them, you can use exploratory FA. FA, by creating a correlation matrix, shows that the variables are gathered in clusters so that the variables of each cluster are correlated with each other and are not correlated with other clusters. These clusters are the dimensions of the subject under investigation. The variables of each cluster are the measurement items of that dimension. Variables that do not correlate with other variables should be removed because the analyzed variables should have a reasonable correlation with some other variables of the analysis.

Two methods of measuring the proportionality of sample size for exploratory FA are the calculation of Kaiser-Mayer-Olkin (KMO) statistic and Bartlett's test of sphericity. The KMO sample adequacy index is specific to exploratory FA and shows whether the data are sufficient to perform exploratory FA calculations or not. KMO value must be greater than 0.5; some believe that the value of KMO should be greater than 0.9. Some texts state that if the KMO value is greater than 0.9, it is excellent, and if smaller

than 0.5, it is unacceptable. Others believe that the value of this statistic is more than 0.7; the existing correlations are very suitable for FA. If it is between 0.5 and 0.69, you should be very careful, and if it is less than 0.5, it is not suitable for FA.

Also, to maximize the relationship between items and agents, the axes should be rotated. Rotating factors create the best combination of items and factor structure. The main goal of factor rotation is to transform the factor structure into a simple factor load structure that can be easily interpreted. The interpretation of the factors of the rotated matrix is much simpler than the interpretation of the factors of the unrotated matrix.

Usually, there are four orthogonal rotation methods, including Varimax, Quartimax, and Equamax, and two inclined methods, including Oblimin Direct and Promax. Among the group of rotation methods, the most popular and widely used method is varimax rotation. In varimax rotation, the independence between mathematical factors is preserved. From an engineering point of view, this issue means that at the time of rotation, the axes remain perpendicular. In other words, by keeping the angles of the list of factors, they remain perpendicular to each other. Through varimax rotation, the factors are transferred to new axes so that they can be interpreted through a set of test items with a simple structure that shows the main and relatively clear lines to arrive at the solutions. Although other rotation methods have different interpretations, they are all used to maximize the relationship between variables and some factors.

In this study, three factors have been identified as effective factors in selecting a suitable place for landfilling of municipal waste. For each of these factors, a separate FA should be performed. To factorize these variables based on the data extracted from 100 returned questionnaires, FA was performed several times, the outputs of which are shown in *Table 4*, respectively. In the first line of this table, the number of variables is mentioned, which are the indicators considered for the effective factors in choosing a suitable place for landfilling municipal waste. For example, the number of economic variables is 5. Considering that FA aims to explain the desired phenomena with a smaller number of primary variables, it is necessary to maintain factors that have formal or theoretical validity. Therefore, FA is repeated to achieve such a goal.

Table 4. Results of exploratory FA to select a suitable place for landfilling municipal waste.

	Economic	Technical	Environmental-Social
Number of variables	5	5	5
Number of repetitions of FA	1	1	3
KMO test	0.734	0.798	0.660
Bartlett test	0.0032	0.009	0.000

4.2 | Stage-Two Assessment

As mentioned in this study, the fuzzy nonlinear prioritization method has been used to measure the weight and rank of effective criteria for selecting the landfill of municipal waste. Since the fuzzy weight determination methods use the pairwise comparison matrix and are inspired by the definitive hierarchical analysis method, the reciprocal matrix (elements below the diameter) is explained (by inverting the numbers above the diameter), which leads to problems. In addition, sometimes decision makers may or may not want to make all the comparisons, so Mikhailov's nonlinear method is used in this study. The steps for using this method are as follows:

Step 1. Drawing the hierarchical tree: in this step, the structure of the decision hierarchy is drawn using the target and option target levels.

Step 2. Formation of a fuzzy decision matrix: agreed fuzzy decision matrices are formed based on the opinions of decision makers. Therefore, it is necessary to use fuzzy numbers in explaining people's preferences and polls, which is important in this study.

Certainty in a phenomenon indicates that the effective structures and variables in modeling that phenomenon are definitely obvious and clear, and there is no doubt about their occurrence and amount. Most common tools for conventional modeling have a strict, definitive, and precise nature that is the phenomena are mostly placed in two special situations, and instead of being compared with expressions such as more or less, they are separated only in the form of yes or no.

In other words, in this case, in the science of logic, a statement can be stated as true or false; in the theory of sets, a member can only belong to a set or not, and in optimization, it can only be about whether it is practical or not. The result of the analysis gave an opinion. But as it was said, partial uncertainty is inseparable in complex systems, which are mainly part of natural phenomena, and the use of mathematical language in these conditions does not seem safe. Consequently, the complexity and consequences of modeling in this situation are divided into two categories. First, real and real situations are not so strict and cannot be described accurately; this is beyond human control.

Therefore, the use of fuzzy triangular numbers in this research is due to the uncertainty in the phenomena, which is divided into two categories. The first category is caused by the lack of knowledge and information about a phenomenon and is referred to as probabilistic or random uncertainty. The theory of statistics and probabilities can model the phenomena that fall into this category. However, the second category is more dependent on understanding the concepts and providing accurate meanings of the studied phenomenon and is referred to as uncertainty caused by ambiguity. Uncertainties of this category can be analyzed by fuzzy logic and will be discussed further.

Defuzzification is a method to convert fuzzy numbers into definite numbers. This operation causes the results of fuzzy inference to be presented understandably for the audience. According to the scope of the application, various defuzzification methods are also provided, such as the surface center method, center of gravity method, Minkowski method, and CFCS algorithm. The purpose of all these methods is to transform fuzzy results into non-fuzzy or regular results. In a fuzzy system, fuzzification of the input elements is used first. After that, calculations are done by fuzzy method, and finally, the results must be de-phased. By defuzzifying the results of a fuzzy computing system, reports can be presented understandably for their users. The method of diffusing triangular numbers in this research is the center of gravity method. The reason for using the center of gravity method to defuzzify fuzzy numbers in this research:

- I. Simplicity in use.
- II. It can be used for an MCDM model with a combination of deterministic and fuzzy criteria.

Table 5. Linguistic scales for pairwise comparisons and their fuzzy equivalents.

Linguistic Values for Pairwise Comparisons	Triangular Fuzzy Scales
Preferred equally	(1, 2, 3)
Preferred moderately	(2, 3, 4)
Preferred strongly	(3, 4, 5)
Very strongly preferred	(4, 5, 6)
Extremely preferred	(5, 6, 7)

Step 3. To obtain the weight of the criteria and sub-criteria in the research model, it is necessary to calculate the alpha cut for the matrix of pairwise comparisons, solve the model, and finally integrate the weights in different levels of alpha to obtain the final weight. Therefore, the reason for using fuzzy Nonlinear programming in this research is to eliminate the stages of achieving the final weights. In this way, weights are obtained whose ratio is approximately applicable in the initial judgments $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, in other words: $l_{ij} \leq \frac{w_j}{w_i} \leq u_{ij}$. Also, other reasons for using fuzzy Nonlinear programming in this research are:

- I. The possibility of simulating human logic and thinking.
- II. The possibility of creating two solutions or answers for a problem.
- III. Suitable for solving problems with approximate answers.
- IV. Ability to create nonlinear functions with arbitrary complexity.
- V. Strong dependence on the researcher's opinion in creating fuzzy logic models.

Formulation and solution of the model: the model is formulated and solved using the upper and lower limits of the resulting matrix elements. The Nonlinear model used in this research is as follows:

$$\begin{aligned} &\text{Maximise } \lambda, \\ &\text{s. t.} \end{aligned} \quad (2)$$

$$\begin{aligned} &(m_{ij} - l_{ij})\lambda w_j - w_i + l_{ij}w_j \leq 0, \\ &(u_{ij} - m_{ij})\lambda w_j + w_i - u_{ij}w_j \leq 0, \end{aligned} \quad (3)$$

$$\sum_{k=1}^n w_k = 1, \quad (4)$$

$$w_k > 0, \quad k = 1, 2, \dots, n, \quad i = 1, 2, \dots, n-1, \quad j = 2, 3, \dots, n, \quad j > i. \quad (5)$$

Due to the non-linearity of the model, it can not be solved by the simplex method and must be solved using appropriate quantitative methods and software (such as Lingo). Positive optimal values for the λ index indicate that all weight ratios are completely true in the initial judgment. Still, if this index is negative, it can be seen that the fuzzy judgments are strongly inconsistent, and the ratio weight gain is almost always true of these judgments.

5 | Result and Discussion

The steps related to the evaluation and ranking of effective factors for a suitable place for landfilling of municipal waste in this research are divided into two main parts: 1) determining the matrix of pairwise comparisons based on the integration of experts, and 2) application of mathematical modeling in ranking and obtaining bringing the weights of the factors in the research model.

5.1 | Ranking of the Main Criteria of the Model

During the survey, based on the summary of expert opinions, the matrix of pairwise comparisons of the main criteria relative to each other is shown in *Table 6*.

Table 6. Ranking of the main criteria of the model.

	W_1			W_2			W_3		
W_1	-	-	-	-	-	-	-	-	-
W_2	2.40	3.30	5.60	-	-	-	-	-	-
W_3	2.2	2.98	4.5	1.09	2.05	4.02	-	-	-

$$\begin{aligned} &\text{Maximise } \lambda, \\ &\text{S. t.} \\ &3/30 - 2/40)\lambda w_1 - w_2 + 2/40w_1 \leq 0, \\ &5/60 - 3/30)\lambda w_1 + w_2 - 5/60w_1 \leq 0, \\ &2/98 - 2/2)\lambda w_1 - w_3 + 2/2w_1 \leq 0, \\ &4/5 - 2/98)\lambda w_1 + w_3 - 4/5w_1 \leq 0, \\ &2/05 - 1/09)\lambda w_2 - w_3 + 1/09w_2 \leq 0, \\ &4/02 - 2/05)\lambda w_2 + w_3 - 4/02w_2 \leq 0, \\ &w_1 + w_2 + w_3 = 1, \\ &w_k \geq 0, \quad k = 1, 2, 3. \end{aligned}$$

As can be seen, the above model has been solved using Lingo software, and the importance of each of the main factors of the research model and the degree of compatibility λ have been calculated as shown in the table below. As shown in *Table 7*, a positive value for the λ compatibility index indicates acceptable matrix compatibility.

Table 7. Weight and ranking of factors related to the main dimensions of the research model derived from the fuzzy nonlinear model.

Main Criteria of the Model	Criteria Code	Weight	Rank	Value Object Function
Economic	W ₁	0.3559699	2	0.3677686
Technical	W ₂	0.5136857	1	
Environmental-social	W ₃	0.1303444	3	

5.2 | Ranking of Economic Factors

During the survey, based on a summary of the opinions of matrix experts, the pairwise comparisons of economic factors with each other are shown in *Table 8*.

Table 8. Ranking of the economic criteria of the model.

	W1	W2	W3	W4	W5
W1	-	-	-	-	-
W2	1.15	1.65	2.06	-	-
W3	1.65	2.71	3.74	1	1.32
W4	1.15	1.89	2.57	1	1.56
W5	1.13	1.39	2.47	1.1	1.29

Maximise λ ,

S. t.

$$\begin{aligned}
 &1/65 - 1/15)\lambda w_1 - w_2 + 1/15w_1 \leq 0, \\
 &2/06 - 1/65)\lambda w_1 + w_2 - 2/06w_1 \leq 0, \\
 &2/71 - 1/65)\lambda w_1 - w_3 + 1/65w_1 \leq 0, \\
 &3/74 - 2/71)\lambda w_1 + w_3 - 3/74w_1 \leq 0, \\
 &2/71 - 1/65)\lambda w_2 - w_3 + 1/65w_2 \leq 0, \\
 &3/74 - 2/71)\lambda w_2 + w_3 - 3/74w_2 \leq 0, \\
 &1/89 - 1/15)\lambda w_1 - w_4 + 1/15w_1 \leq 0, \\
 &2/57 - 1/89)\lambda w_1 + w_4 - 1/89w_1 \leq 0, \\
 &1/32 - 1)\lambda w_2 - w_4 + w_2 \leq 0, \\
 &1/56 - 1/32)\lambda w_2 + w_4 - 1/56w_2 \leq 0, \\
 &0/49 - 0/37)\lambda w_3 - w_4 + 0/37w_2 \leq 0, \\
 &0/76 - 0/49)\lambda w_3 + w_4 - 0/76w_3 \leq 0 \\
 &1/39 - 1/13)\lambda w_1 - w_5 + 1/13w_1 \leq 0, \\
 &2/47 - 1/39)\lambda w_1 + w_5 - 2/47w_1 \leq 0, \\
 &1/29 - 1/1)\lambda w_2 - w_5 + 1/1w_2 \leq 0, \\
 &2/39 - 1/29)\lambda w_2 + w_5 - 2/39w_2 \leq 0, \\
 &0/9 - 0/8)\lambda w_3 - w_5 + 0/8w_3 \leq 0, \\
 &1 - 0/9)\lambda w_3 + w_5 - w_3 \leq 0, \\
 &1 - 0/9)\lambda w_4 - w_5 + 0/9w_4 \leq 0, \\
 &1/5 - 1)\lambda w_4 + w_5 - 1/5w_4 \leq 0, \\
 &w_1 + w_2 + w_3 + w_4 + w_5 = 1, \\
 &w_k \geq 0 \quad k = 1,2,3,4,5.
 \end{aligned}$$

As can be seen, the above model has been solved using Lingo software, and the importance of each of the economic factors of the research model and the degree of compatibility λ have been calculated as shown in the table below. As shown in *Table 9*, a positive value for the λ compatibility index indicates acceptable matrix compatibility.

Table 9. Weight and ranking of factors related to the economic dimensions of the research model derived from the fuzzy nonlinear model.

Economic Criteria of the Model	Criteria Code	Rank	Weight	Value Object Function
MSW generation	W ₁	1	0.2991997	0.3068245
Land ownership	W ₂	5	0.1162146	
Proximity to other facilities	W ₃	4	0.1514756	
Overall cost	W ₄	2	0.2485399	
Distance traveled	W ₅	3	0.1845702	

5.3 | Ranking of Technical Factors

During the survey, based on a summary of the opinions of matrix experts, the pairwise comparisons of technical factors with each other are shown in *Table 10*.

Table 12. Ranking of the environmental-social criteria of the model.

	W ₁	W ₂	W ₃	W ₄	W ₅
W ₁	-	-	-	-	-
W ₂	2.16	3.27	5.65	-	-
W ₃	1.42	3.32	4.3	1.32	2.67
W ₄	1.09	2.18	2.87	0.95	1
W ₅	1.15	1.89	2.57	0.8	0.9

Maximise λ ,

S. t.

$$3/27 - 2/16)\lambda w_1 - w_2 + 2/16w_1 \leq 0,$$

$$5/65 - 3/27)\lambda w_1 + w_2 - 5/65w_1 \leq 0,$$

$$3/32 - 1/42)\lambda w_1 - w_3 + 1/42w_1 \leq 0,$$

$$4/3 - 3/32)\lambda w_1 + w_3 - 4/3w_1 \leq 0,$$

$$2/67 - 1/32)\lambda w_2 - w_3 + 1/32w_2 \leq 0,$$

$$3/4 - 2/67)\lambda w_2 + w_3 - 3/4w_2 \leq 0,$$

$$2/18 - 1/09)\lambda w_1 - w_4 + 1/09w_1 \leq 0,$$

$$2/87 - 2/18)\lambda w_1 + w_4 - 2/87w_1 \leq 0,$$

$$1 - 0/95)\lambda w_2 - w_4 + 0/95w_2 \leq 0,$$

$$1/1 - 1)\lambda w_2 + w_4 - 1/1w_2 \leq 0,$$

$$1/6 - 0/7)\lambda w_3 - w_4 + 0/7w_2 \leq 0,$$

$$2/3 - 1/6)\lambda w_3 + w_4 - 2/3w_3 \leq 0,$$

$$1/89 - 1/15)\lambda w_1 - w_5 + 1/15w_1 \leq 0,$$

$$2/57 - 1/89)\lambda w_1 + w_5 - 2/57w_1 \leq 0,$$

$$0/9 - 0/8)\lambda w_2 - w_5 + 0/8w_2 \leq 0,$$

$$1/56 - 0/9)\lambda w_2 + w_5 - 1/56w_2 \leq 0,$$

$$0/49 - 0/37)\lambda w_3 - w_5 + 0/37w_3 \leq 0,$$

$$0/76 - 0/49)\lambda w_3 + w_5 - 0/76w_3 \leq 0,$$

$$0/99 - 0/8)\lambda w_4 - w_5 + 0/8w_4 \leq 0,$$

$$1/31 - 0/99)\lambda w_4 + w_5 - 1/31w_4 \leq 0,$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1,$$

$$w_k \geq 0, \quad k = 1, 2, 3, 4, 5.$$

As can be seen, the above model has been solved using Lingo software and the importance of each of the research model's environmental-social factors and the degree of compatibility λ have been calculated as shown in the table below. As shown in *Table 13*, a positive value for the λ compatibility index indicates acceptable matrix compatibility.

Table 13. Weight and ranking of factors related to the environmental-social dimensions of the research model derived from the fuzzy nonlinear model.

Environmental-Social Criteria of the Model	Criteria Code	Weight	Rank	Value	Object Function
Remoteness to water bodies	W ₁	0.1657970	5		
Total emissions	W ₂	0.1690169	4		
Protection from flood hazards	W ₃	0.1743852	3	0.07569974	
Public acceptability	W ₄	0.2357956	1		
Kids population density	W ₅	0.1811216	2		

After obtaining the weight of the main criteria and sub-criteria of the model, the normalized weight of each sub-criteria and their final rank can be calculated, the calculations of which are shown in *Table 14*.

Table 14. Normalized weight of the research model.

No	Main Criteria	Weight	Attributes	Weight	Normalized Weight	Rank
1	Economic	0.355	MSW generation	0.299	0.106	2
			Land ownership	0.116	0.041	10
			Proximity to other facilities	0.151	0.053	9
			Overall cost	0.248	0.088	5
			Distance traveled	0.184	0.065	8
2	Technical	0.512	Interference with routine traffic	0.178	0.091	4
			Size of land	0.183	0.093	3
			Accessibility	0.258	0.132	1
			Availability of basic amenities	0.165	0.084	6
			Flexibility for size expansion	0.148	0.075	7
3	Environmental-social	0.133	Remoteness to water bodies	0.165	0.021	15
			Total emissions	0.169	0.022	14
			Protection from flood hazards	0.174	0.023	13
			Public acceptability	0.235	0.031	11
			Kids population density	0.181	0.024	12

6 | Conclusions and Recommendations

This research article aims to explain a novel two-stage MADM model ranking of appropriate criteria for selecting an MSW facility for landfills in urban centers. This model expands the conventional approach of only utilizing economic considerations for site selection models and includes other important attributes into the decision-making process; this makes the approach holistic. The model has produced an MSW collection system characterized by an optimum cost, minimal environmental emissions, and good suitability given societal and technical attributes.

These scores are aggregated to form a standard decision matrix for evaluation as per general MADM protocols. Decision makers should seek the most rational solution to an optimization problem according to their decision criteria. To that end, Multi criteria analysis can be crucial since the formulation potentialities are wide.

The results of this study show that three economic, technical, and environmental-social factors are effective in choosing a suitable place for municipal waste disposal. The weights related to the three variables were extracted by analyzing the decision decision matrices, which are shown in the figure below:

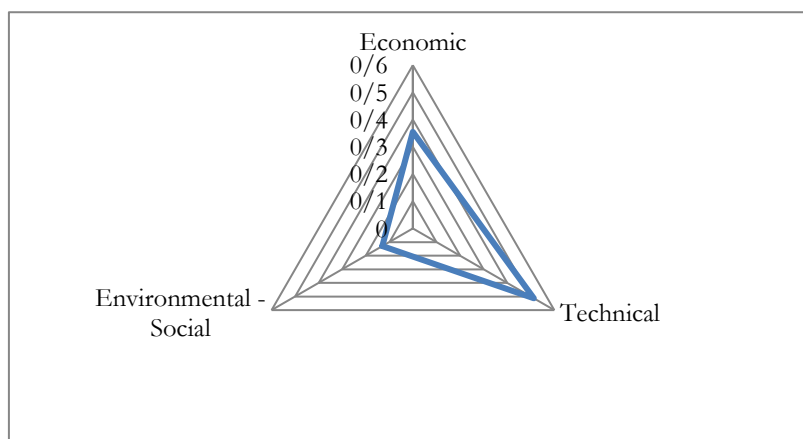


Fig. 2. Radar chart related to the main factors of the research model.

Based on the results of identifying, ranking, and prioritizing the components and factors related to each of them using the FMADM model, it has been determined that three economic components (including MSW generation, land ownership, proximity to other facilities, overall cost, and distance traveled); technical (interference with routine traffic, size of land, accessibility, availability of basic amenities, flexibility for size expansion); and environmental-social (including remoteness to water bodies, total emissions, protection from flood hazards, public acceptability and kids population density), in reducing production and separation of the origin of waste is effective with the participation of the people. In other words, these indicators can be used to select a suitable place for landfilling production waste in the city.

This article has three theoretical, practical, and technical contributions. Also, this article provides a clear explanation of the theoretical contribution related to the accumulated knowledge, both in the introduction and theoretical background sections of the article. Therefore, studying the past research describes a relatively complete background of the planned theoretical contributions of this article compared to the previous research. Therefore, the theoretical contribution of this article solves the scientific gap about effective indicators for determining the location of waste disposal. From the point of view of practical contribution, this article presents practical concepts related to managers and experts and has practical suggestions presented in the conclusion section. It has been tried to reduce the practical vacuum for evaluating the sustainable environment with practical suggestions to managers. Also, the technical contribution of this article is presented by combining fuzzy logic and nonlinear mathematical programming.

The methodology presented provides decision makers with a tractable tool that could be employed either by private investors or public authorities. The procedure could be easily adopted e with slight modifications and adjustments to the special requirements of the problem under consideration to solve similar problems in areas other than the one examined in the present analysis. The methodological framework is also not limited to supporting the specific decision; it can also be used to locate optimal sites for developing other types of required infrastructure, such as collection points, sorting centers, etc. Different criteria may be decided to be utilized in all those cases, but the overall methodology may remain practically unaltered.

Researchers are always faced with limitations in their research, some of which show themselves even at the beginning of their work. This research is not excluded from other research and has some shortcomings, which are mentioned in this part: Cross-sectional research is one of the limitations of any research. It is somewhat difficult to generalize the results of research that are cross-sectional and not longitudinal because the validity and reliability of data and opinions may have changed over time, or people may have made an incomplete estimate of the items when commenting on the research at the time of implementation. Have. Also, the non-cooperation of some of the statistical community in distributing questionnaires is another limitation of this research. Finally, there is a lack of accurate and

complete acquaintance of experts with the concepts and definitions of some variables and items in the questionnaire, which may create a knowledge gap between academic experts and experts in the field of waste management and distort the result in different stages of carrying out this research.

References

- [1] Cao, L. W., Cheng, Y. H., Zhang, J., Zhou, X. Z., & Lian, C. X. (2006). Application of grey situation decision-making theory in site selection of a waste sanitary landfill. *Journal of china university of mining and technology*, 16(4), 393–398. DOI:10.1016/S1006-1266(07)60033-9
- [2] Bahrani, S., Ebadi, T., Ehsani, H., Yousefi, H., & Maknoon, R. (2016). Modeling landfill site selection by multi-criteria decision making and fuzzy functions in GIS, case study: Shabestar, Iran. *Environmental earth sciences*, 75(4), 1–14. DOI:10.1007/s12665-015-5146-4
- [3] Eskandari, M., Homaei, M., & Falamaki, A. (2016). Landfill site selection for municipal solid wastes in mountainous areas with landslide susceptibility. *Environmental science and pollution research*, 23(12), 12423–12434. DOI:10.1007/s11356-016-6459-x
- [4] Beskese, A., Demir, H. H., Ozcan, H. K., & Okten, H. E. (2015). Landfill site selection using fuzzy AHP and fuzzy TOPSIS: a case study for Istanbul. *Environmental Earth sciences*, 73, 3513–3521. <https://doi.org/10.1007/s12665-014-3635-5>
- [5] Hanine, M., Boutkhoul, O., Tikniouine, A., & Agouti, T. (2016). Comparison of fuzzy AHP and fuzzy TODIM methods for landfill location selection. *Springer plus*, 5(1), 1–30. DOI:10.1186/s40064-016-2131-7
- [6] Reed, M., Yiannakou, A., & Evering, R. (2014). An ant colony algorithm for the multi-compartment vehicle routing problem. *Applied soft computing journal*, 15, 169–176. DOI:10.1016/j.asoc.2013.10.017
- [7] Hemmelmayr, V., Doerner, K. F., Hartl, R. F., & Rath, S. (2013). A heuristic solution method for node routing based solid waste collection problems. *Journal of heuristics*, 19(2), 129–156. DOI:10.1007/s10732-011-9188-9
- [8] Banditvilai, S., & Niraso, M. (2017). Simulation of the Night Shift Solid Waste Collection System of Phuket Municipality. In *Soft Methods for data science* (pp. 17–24). Springer International Publishing.
- [9] Sarra, A., Mazzocchitti, M., & Rapposelli, A. (2017). Evaluating joint environmental and cost performance in municipal waste management systems through data envelopment analysis: Scale effects and policy implications. *Ecological indicators*, 73, 756–771.
- [10] Rabbani, M., Amirhossein Sadati, S., & Farrokhi-Asl, H. (2020). Incorporating location routing model and decision making techniques in industrial waste management: Application in the automotive industry. *Computers and industrial engineering*, 148, 106692. DOI:10.1016/j.cie.2020.106692
- [11] Das, A. K., Islam, M. N., Billah, M. M., & Sarker, A. (2021). COVID-19 pandemic and healthcare solid waste management strategy – a mini-review. *Science of the total environment*, 778, 146220. DOI:10.1016/j.scitotenv.2021.146220
- [12] Hantoko, D., Li, X., Pariatamby, A., Yoshikawa, K., Horttanainen, M., & Yan, M. (2021). Challenges and practices on waste management and disposal during COVID-19 pandemic. *Journal of environmental management*, 286, 112140. DOI:10.1016/j.jenvman.2021.112140
- [13] Goel, S., Ranjan, V. P., Bardhan, B., & Hazra, T. (2017). Forecasting solid waste generation rates. *Modelling trends in solid and hazardous waste management*, 35–64. DOI:10.1007/978-981-10-2410-8_3
- [14] Mostafayi Darmian, S., Moazzeni, S., & Hvattum, L. M. (2020). Multi-objective sustainable location-districting for the collection of municipal solid waste: Two case studies. *Computers and industrial engineering*, 150, 106965. DOI:10.1016/j.cie.2020.106965
- [15] Lin, Z., Xie, Q., Feng, Y., Zhang, P., & Yao, P. (2020). Towards a robust facility location model for construction and demolition waste transfer stations under uncertain environment: The case of Chongqing. *Waste management*, 105, 73–83. DOI:10.1016/j.wasman.2020.01.037
- [16] Pérez-López, G., Prior, D., Zafra-Gómez, J. L., & Plata-Díaz, A. M. (2016). Cost efficiency in municipal solid waste service delivery. Alternative management forms in relation to local population size. *European journal of operational research*, 255(2), 583–592.
- [17] Schoeman, Y., Oberholster, P., & Somerset, V. (2021). A decision-support framework for industrial waste management in the iron and steel industry: A case study in Southern Africa. *Case studies in chemical and environmental engineering*, 3, 100097. DOI:10.1016/j.cscee.2021.100097

- [18] Monzambe, G. M., Mpofu, K., & Daniyan, I. A. (2021). Optimal location of landfills and transfer stations for municipal solid waste in developing countries using non-linear programming. *Sustainable futures*, 3, 100046. DOI:10.1016/j.sftr.2021.100046
- [19] Yannis, G., Kopsacheili, A., Dragomanovits, A., & Petraki, V. (2020). State-of-the-art review on multi-criteria decision-making in the transport sector. *Journal of traffic and transportation engineering*, 7(4), 413–431. DOI:10.1016/j.jtte.2020.05.005
- [20] Guo, S., & Zhao, H. (2017). Fuzzy best-worst multi-criteria decision-making method and its applications. *Knowledge-based systems*, 121, 23–31.
- [21] Ali, S. A., Parvin, F., Al-Ansari, N., Pham, Q. B., Ahmad, A., Raj, M. S., ... Thai, V. N. (2021). Sanitary landfill site selection by integrating AHP and FTOPSIS with GIS: a case study of Memari Municipality, India. *Environmental science and pollution research*, 28(6), 7528–7550.
- [22] Tirkolaee, E. B., Mahdavi, I., Esfahani, M. M. S., & Weber, G. W. (2020). A robust green location-allocation-inventory problem to design an urban waste management system under uncertainty. *Waste management*, 102, 340–350. DOI:10.1016/j.wasman.2019.10.038
- [23] Yadav, V., Kalbar, P. P., Karmakar, S., & Dikshit, A. K. (2020). A two-stage multi-attribute decision-making model for selecting appropriate locations of waste transfer stations in urban centers. *Waste management*, 114, 80–88. DOI:10.1016/j.wasman.2020.05.024
- [24] Ibáñez-Forés, V., Bovea, M. D., Coutinho-Nóbrega, C., & de Medeiros, H. R. (2019). Assessing the social performance of municipal solid waste management systems in developing countries: Proposal of indicators and a case study. *Ecological indicators*, 98, 164–178. DOI:10.1016/j.ecolind.2018.10.031
- [25] Archetti, C., Coelho, L. C., & Grazia Speranza, M. (2019). An exact algorithm for the inventory routing problem with logistic ratio. *Transportation research part e: logistics and transportation review*, 131, 96–107. DOI:10.1016/j.tre.2019.09.016
- [26] Jatinkumar Shah, P., Anagnostopoulos, T., Zaslavsky, A., & Behdad, S. (2018). A stochastic optimization framework for planning of waste collection and value recovery operations in smart and sustainable cities. *Waste management*, 78, 104–114. DOI:10.1016/j.wasman.2018.05.019
- [27] Boonmee, C., Arimura, M., & Asada, T. (2018). Location and allocation optimization for integrated decisions on post-disaster waste supply chain management: On-site and off-site separation for recyclable materials. *International journal of disaster risk reduction*, 31, 902–917.
- [28] Toro, E. M., Franco, J. F., Echeverri, M. G., & Guimarães, F. G. (2017). A multi-objective model for the green capacitated location-routing problem considering environmental impact. *Computers & industrial engineering*, 110, 114–125.
- [29] Yıldız-Geyhan, E., Altun-Çiftcioglu, G. A., & Kadirgan, M. A. N. (2017). Social life cycle assessment of different packaging waste collection system. *Resources, conservation and recycling*, 124, 1–12.
- [30] Mirdar Harijani, A., Mansour, S., Karimi, B., & Lee, C. G. (2017). Multi-period sustainable and integrated recycling network for municipal solid waste – A case study in Tehran. *Journal of cleaner production*, 151, 96–108. DOI:10.1016/j.jclepro.2017.03.030

Research questionnaire (1)

Dear respondent

The present questionnaire has been prepared and set up to conduct a scientific research. Your answers are considered completely confidential and they will only be used scientifically. Your sincere cooperation and accuracy in completing this questionnaire can be useful in achieving important results.

Thank you in advance for your time.

Very Agree	Agree	No Comment	Opposite	Very Opposite	Attributes	Main Criteria	No
					MSW generation	Economic	1
					Land ownership		
					Proximity to other facilities		
					Overall cost		
					Distance traveled		
					Interference with routine traffic	Technical	2
					Size of land		
					Accessibility		
					Availability of basic amenities		
					Flexibility for size expansion		
					Remoteness to water bodies	Environmental - Social	3
					Total emissions		
					Protection from flood hazards		
					Public acceptability		
					Kids population density		

Research questionnaire (2)

Dear respondent

The present questionnaire has been prepared and set up to conduct a scientific research. Your answers are considered completely confidential and they will only be used scientifically. Your sincere cooperation and accuracy in completing this questionnaire can be useful in achieving important results.

Thank you in advance for your time.

Answering method for *Tables 2 to 5*: to answer these tables that measure the importance of these skills relative to each other, you should use *Table 1*.

Table 1. Linguistic scales for pairwise comparisons and their fuzzy equivalents.

Linguistic Values for Pairwise Comparisons	Triangular Fuzzy Scales
Preferred equally	(1, 2, 3)
Preferred moderately	(2, 3, 4)
Preferred strongly	(3, 4, 5)
Very strongly preferred	(4, 5, 6)
Extremely preferred	(5, 6, 7)

Table 2. Matrix of pairwise comparisons of the main criteria of the research model.

	Economic			Technical			Environmental-Social		
	L	M	U	L	M	U	L	M	U
Economic									
Technical									
Environmental-social									

Table 3. Matrix of pairwise comparisons of economic factors.

	MSW Generation			Land Ownership			Proximity to Other Facilities			Overall Cost			Distance Traveled		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
MSW generation															
Land ownership															
Proximity to other facilities															
Overall cost															
Distance traveled															

Table 4. Matrix of pairwise comparisons of technical factors.

	Interference with Routine Traffic			Size of Land			Accessibility			Availability of Basic Amenities			Flexibility for Size Expansion		
	L	M	U	L	M	U	L	M	U	L	M	U	L	M	U
Interference with routine traffic															
Size of land															
Accessibility															
Availability of basic amenities															
Flexibility for size expansion															

Table 5. Matrix of pairwise comparisons of environmental-social factors.

[illegible]



Paper Type: Research Paper



The Impact of Digital Transformation on Sustainability: A Case of the Iranian Telecom Industry

Jamal Aghayari¹, Changiz Valmohammadi^{2,*} , Mahmood Alborzi³¹ Department of IT Management, Faculty of Management, South Tehran Branch, Islamic Azad University, Tehran, Iran; jamalaghayari@gmail.com.² Department of Industrial Management, Faculty of Management, South Tehran Branch, Islamic Azad University, Tehran, Iran, Iran; ch_valmohammadi@azad.ac.ir.³ Department of Information Technology Management, Science and Research Branch, Islamic Azad University, Tehran, Iran; mahmood_alborzi@yahoo.com.

Citation:

Aghayari, J., Valmohammadi, Ch., & Alborzi, M. (2023). The impact of digital transformation on sustainability: a case of the Iranian telecom industry. *International journal of research in industrial engineering*, 12(3), 306-320.

Received: 18/12/2022

Reviewed: 21/01/2023

Revised: 11/02/2023

Accepted: 20/03/2023

Abstract

The corporate landscape is highly affected by two market factors, namely digitalization and sustainability. These two driving forces have been the topic of several studies on how they change management methods, businesses, and society in general. However, the point that these two trends meet each other has been mostly neglected by research studies. Modern organizations and corporations are dealing with the adopting digital transformation issue as a new strategic paradigm. The present study attempts to elaborate on the relationship between digital transformation and sustainability. Therefore, through an in-depth review of the relevant literature, critical factors and their indicators were determined, and based on the proposed conceptual model, six hypotheses were developed. Then, a questionnaire was designed and distributed among 120 Iranian experts, managers, and consultants, and 97 complete questionnaires were returned. Reliability, Content Validity Ratio (CVR), and Content Validity Index (CVI) of the questionnaire were calculated, and the hypotheses were tested through Structural Equation Modeling (SEM) using SmartPLS Software. The results showed that digital transformation significantly affected an organization's sustainability aspects through operation, customer, business model, technology, workforce, and collaboration. Digital transformation and sustainability should constitute integral parts of organizational strategy. Considering that business practices affect the environment, society, and economy, digital transformation can influence the business sustainability. Digital technologies transform markets and create novel paradigms in the industry. In addition, they present new solutions to organizations to cope with sustainability issues. Due to this importance for organizations as consumers and other stakeholders, they are sensitive to the effects of business on brand value, revenues, and company valuation.

Keywords: Digital transformation, Sustainability, Corporate sustainability, Aligning.

1 | Introduction

Recently, sustainability has become an important criterion in research, development, and business. The increasing attraction to this critical point causes most pioneer societies and organizations to require the establishment of financial and environmental macro-strategies [1]. Meanwhile, organizations need to consider other challenging and contradictory factors which affect their operations. Constant capturing and employing the major changes can lead any pioneer organization to be prosperous [1].

On the other hand, the digitalization concept has become broadly pervasive in many layers of business and economy. This relevance motivates the organization to follow digital transformation as a critical process. The process has many levels of granularity and should be applicable in a broad range of organizations from a small one to nationwide. Moreover, the United Nations considers



digitalization as its goal for sustainable development [2], [3]. Consequently, the organization and market leaders have attempted to explore the potential possibilities of digital transformation to overcome sustainability challenges and other related problems [1], [4].

New industry evolution is based on novel business models, and smart environments and services appeared through multi-dimensional digitalization in manufacturing [5]. In addition, rethinking best practices to achieve sustainability by leveraging digitalization has become a significant aim for many organizations and companies [6].

To survive in the complex and dynamic environment, organizations need new approaches to organizational strategy development. These can lead them to sustainability and balanced performance [7]. Nowadays, two major factors in the industrial world are digitalization and sustainability, and the way that these factors influence the practices of organizations or businesses and societies in general across the world has been extensively studied [7]–[9].

As a result, the present study attempts to provide a conceptual model for a better understanding of the digital evolution elements and its impact on sustainability in the Iranian context as a developing country. Therefore, in this research, the required analysis of digital transformation for retaining sustainability has been studied.

This paper is organized as follows: in the next section, the literature review on sustainability and digital transformation and related concepts is presented, and the research method and the results are provided in the upcoming sections. Finally, we present the conclusions in the last section.

2 | Literature Review

2.1 | Digital Transformation

Digital transformation is a dramatic change in the performance of an organization or a country centered on transformational technologies IT. Internet of Things (IoT), cloud computing, mobile applications, social media, virtual and augmented reality, data analytics, Artificial Intelligence (AI), and Blockchain are some of the most important types of transformational technologies [1], [11]–[13]. Consequently, productivity and revenue grow, and costs decrease [14].

Digitalization facilitates innovation in business models and supports sustainable industry. The process of implementing digitalization is a challenging task and needs an ongoing commitment for realization of the complete capability and maturity of an organization. Doubtlessly, business model innovation brings critical benefits to the triple bottom line; therefore, establishing a sustainable industry is the objective and its success entails targeting the sustainable economic and social benefits in the long run. In general, industrial activists believe that creating value is realized optimally through incremental and radical digitalization advances that directly influence the economic performance of the company. Higher efficiency in the processes is realized by continuous analysis of operational data and facilitation of spotting and removing process-performance bottlenecks [16]. Systems with the capability of automatic self-correct can improve process efficiency and result in shorter downtime, optimized capacity, and decreased repair-time averages [16]. In addition, process optimization and observability of cost-efficient resources and operational costs reduction are some other aspects of digitalization. Through predictive approaches, it is easy to find quality and operational defects. Additionally, analytics facilitates finding the causes of defects (e.g., human, machine, or environment), which leads to achieving a decrease in scrap rate and lead time [17].

Regarding new digital technologies growth, it is easy to see that these technologies have the potential to change the game in each sector, significantly. Many industries and businesses have been empowered by applying advanced digital technologies.

2.2 | Sustainability

Sustainability means meeting the social, economic, and environmental needs of the present generation without compromising the social and environmental needs of future generations [18]. A modern definition of sustainability has broadened the scope recognizing the interconnectedness between environmental health, social prosperity, and economic well-being. Abdoli Bidhandi and Valmohammadi [19] and El Hilali et al. [20] raised the notion of triple bottom based on concept sustainability framework, encompassing an organization's impact on planet (environmental aspect), people (social aspect), and profit (economic aspect).

For decades, only current customer needs and shareholder profitability were important to organizations. But today, due to fierce competition, most of the stakeholders must be satisfied to ensure the growth and survival of the organization.

Balogun et al. [21] studied the role of digitalization in improving environmental sustainability by considering nine cases in different countries using big data and IoT to address issues related to environmental sustainability. In addition, Westerman et al. [22] examined the impact of digital workplaces on environmental sustainability.

Positive impacts of digital technologies, such as big data analytics, AI, IoT, mobile technologies, and social platforms on society and industry have been known. More specifically, companies now contribute to environmental sustainability and carbon emission reduction activities employing big data analytics, AI, and IoT [23], [24].

The main challenge is that sustainability is needed to make sure of a constant quality of life. The social aspect of sustainability is a main success factor for long-term future prosperity [25]. Businesses should not merely focus on the direct economic aspect of sustainability, such as minimizing energy consumption to cut costs and enjoy higher ROI and profit.

Therefore, the main hypothesis of the present study is proposed as follows:

H1: digital transformation affects organizational sustainability.

2.3 | Emerging Technologies of Digital Transformation

The role of digital technologies in the development of industrial platforms with efficient use of resources has been proven. These technologies reduce costs and promote the manufacturing systems flexibility and help to adapt sustainability goals [23].

Big data [12], [26]-[32], IoT [33]-[35], blockchain [36], [37], virtual reality [38], augmented reality [39], and AI [40] are the main categories of digital technologies analyzed broadly in this study. Thus, the first sub-hypothesis is put forth as follows:

H1a: digital technologies affect organizational sustainability.

Business model: undeniable characteristics of the modern age i.e., rapid industrial modernization [9] have internal and external environmental complexity that organizations and social institutes are faced with. As the business environment has experienced many changes, businesses attempt to increase their adaptability power accordingly. These changes are not avoidable; therefore, the excellence and sustainability of organizations is a function of the coordination level with environmental changes [10].

In addition, companies have accompanied the digital revolution emerged by cutting-edge startups and have tried to adapt their businesses to digital systems. Adopting the features of digital transformation

needs to accept radical changes concerning the creation and representation of relevant values. Therefore, the accordance of digital transformation with sustainability is an important issue needing further analysis [41]. The presence of digital technologies, such as cloud computing, blockchain, and big data analytics is growing so that it is becoming a main factor in the realization of business results and the success of management models [42].

The counterpoint of these two trends chooses digital transformation as a strategy to ensure the sustainability of organizations which has been neglected by researchers. Following the development of more efficient supply chains and efficiency of processes, we now witness a decrease in product lifecycles. Information and Communication Technology (ICT) has created new ways for global logistics and communication by managing the immense volume of data transferred with unprecedented speed. As a consequence, even large organizations can enjoy agility [19], which means the ability of an organization to thrive in a continuously changing, unpredictable business environment.

Businesses use analytics to optimize resources deployment and control risks [43]. The increasing need, for instance, interaction and coordination and the emphasis on the necessity of lean manufacturing and minimized inventory [36], [44] fuel the need for business mobility solutions, first-class logistics, and broadband connectivity [45].

In addition, digital transformation brings business benefits by adopting an integrated approach to IT, supply chain, operation, and the rest of the functions that an organization performs. All these lead to sustainable values, lower costs, higher operational efficiencies, and expansion of a sense of urgency. Therefore, the second sub-hypothesis is suggested as follows:

H1b: business model affects organizational sustainability.

Customer: the aim of improving customers' experience needs a deeper perception of the customers, management, or digital presence of the organization, improving customer engagement, and more effective brand promotion, and realizing these factors requires a clear understanding of the customers and what can be expected from the organization [46].

The digital transformation of a business provides flexibility in the viability of its products and incorporates customers' feedback [28], leading to increased market share, revenues, and customer satisfaction. In addition, digitization enables customers to collaborate and compels industries to coordinate themselves with varying market conditions and to adapt themselves to consumer behavior. Growing technological advancements, enhanced consumer power, and fierce competition are symptoms showing commoditization threats [47]. The expansion of e-commerce and Internet shopping during the past couple of years dramatically reduces the costs for customers as well as enterprises from economic, social, and environmental aspects. Thus, the third sub-hypothesis is suggested as follows:

H1c: customer affects organizational sustainability.

Workforce: it is clear to organizational leaders that digital transformation and workforce transformation are interconnected; however, there are few insights to lead these interlinked efforts [48]. Businesses need to recruit and keep digital talents and promote a culture where employees, temporary workers, and robots cooperate, effectively. Lack of skillful talents is a challenge in the way of businesses to find and keep the right talents. Creating a digital workforce is not limited to recruiting and developing talents. On the hand, there is also a need to improve their workforce in other ways. Businesses can find skilled workers for temporary projects, which is also a shorter way of finding talent. Thus, the fourth sub-hypothesis is put forth as follows:

H1d: workforce affects organizational sustainability.

Operations: a key approach is to formulate a digital transformation strategy that functions as a key concept to integrate the whole process of coordinating, prioritizing, and implementing digital transformations in a company. Using and integrating digital technologies normally influences major parts of companies and sometimes extends beyond the organizational borders through products, business processes, sales channels, and supply chains. The potential advantages of digitalization include higher sales or productivity and innovations in value creation [49]. Thus, we suggest the fifth sub-hypothesis as follows:

H1e: digital transformation operations affect organizational sustainability.

Collaboration: the major part of this task is to improve industry collaboration with suppliers and partners in the value chain and develop a circular economy where the resources remain in use as long as feasible, the highest possible value is extracted from them and finally products and materials are recovered and regenerate at the end of their service life. Along with industry collaboration and new circular economy approaches, it is essential to examine each of the emerging and enabling technologies in terms of digital transformation initiatives and determine the way to leverage them and achieve notable improvements in sustainability. As a result, the seventh hypothesis is suggested as follows:

Corporations try to act in line with digital transformation to survive in the digital age. On the other hand, they are affected by complex activities related to digital transformation; therefore, different strategic alternatives should be analyzed via models and tools. Thus, the sixth sub-hypothesis is suggested as follows:

H1f: collaboration affects organizational sustainability.

3 | Research Methodology

In terms of objective, this study is an applied one. As far as the topics of the study are related to the telecom industry and based on the familiarity and the level of expertise of the Iranian ministry of communication, the sample of the study consisted of all top managers and experts of this ministry, such as the vice ministers in ICT industries, senior executive managers and chairman of the boards in telecom industries in public and private sectors, middle class manages, and consultants in the industry with minimum 10-years working experience in ICT management and operations. In addition, the opinion of academicians includes faculty members, post-doc, and senior researchers in the field of information technology management, computer engineering, and industrial engineering were explored. In this research and at the first phase of the methodology, based on an in-depth review of the relevant literature, the main constructs of digital transformation and their sub-construct were determined. Then, the indicators of the constructs and sub-constructs were identified by holding semi-structural interviews with ten experts of the Iranian Telecom ministry. It should be noted that due to the novelty of the topic in the country, the sample size was selected based on the purposive sampling method, and as a result, 112 respondents were selected. The demographics of the respondents are shown in *Table 5*. The study was carried out from July 2018 to May 2019. In terms of the method, the study was descriptive and the data was collected from the determined sample using a questionnaire. Therefore, the study is also a survey one. Based on the data analysis method, the study was correlational and used structural equations modeling in particular. Before distributing the designed questionnaire among respondents to assess its content validity, three academicians and two experts were asked to study the questionnaire. After applying a few modifications, the questionnaire was finalized. In addition, CVR and CVI coefficients were calculated. As the order of the questions can impact the response and to avoid such an impact, half of the questionnaires were distributed in one order and the other half in another one. In addition, to minimize self-report bias in the data, the respondents were informed to fill in the form even with their name or fill in anonymously [26], and the non-response bias test (wave analysis) was done. The responses of early and late waves of returned surveys were compared, and the results of the t-test indicated there were no statistically significant differences between early-wave and late-wave groups [11]. The obtained

results indicated that the opinions of late respondents were representative of the opinions of non-respondents. Therefore, non-response bias was not a concern [55].

The questionnaires were analyzed using the Partial Least Square-Structural Equation Modeling (PLS-SEM) method. The method is a multivariate analysis technique that has been widely used by researchers in recent years [50]. The PLS-SEM is known as a powerful tool that imposes minimum restrictions on measure scales. It is also used to model latent constructs that are not normally distributed [51]. Before using the method, the reliability and validity of the measurement model should be confirmed. Afterward, a non-iterative application of ordinary least squares regression was needed to achieve outer weights, loadings, and the relationships of the structure model for the latent and visible variables. Eventually, the bootstrap re-sampling procedure was used to determine if a structural path is significant. One hundred twelve questionnaires were returned.

The study was carried out based on the validation of documents and library studies; as a result, books, journals, and articles published in other countries on the theoretical foundation of theories on the subject matter were used. In terms of objective, the study was an applied one.

Fig. 1 illustrates the proposed conceptual model. As shown in *Fig. 1*, the considered basis for digital transformations includes Business model, customer, technology, workforce, operation, and collaboration. As described before, sustainability is also categorized into economic, environmental, and social elements.

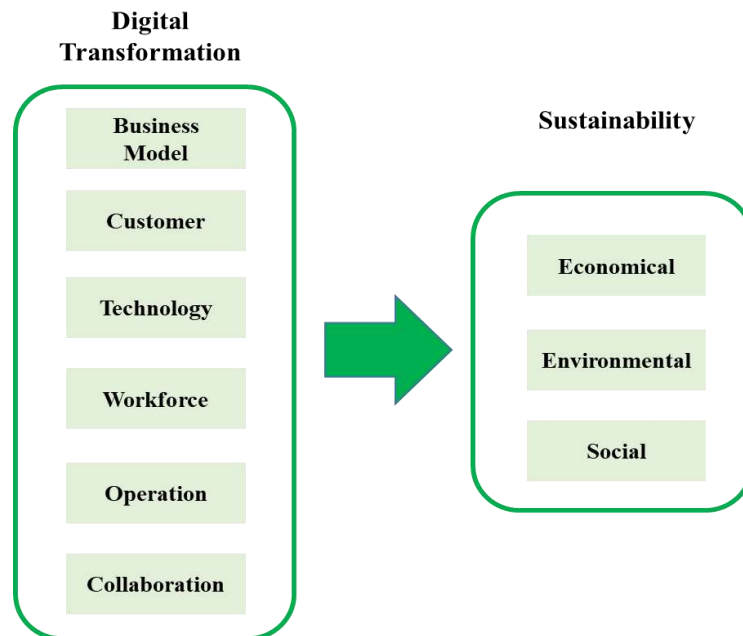


Fig. 1. Proposed conceptual model.

Hypothesis

H1: sustainability is affected by digital transformation technologies.

H2: organizational sustainability is affected by business models developed based on digital evolution.

H3: sustainability is affected by the customer.

H4: organizational sustainability is affected by the workforce in the field of digital evolution.

H5: organizational sustainability is affected by digital transformation operations.

H6: organizational sustainability is affected by collaborations in the field of digital evolution.

Table 1 shows the demographic information of the respondents.

Table 1. Demographic information of experts.

Education Level	Reference
MA	65
Ph.D. student	20
Ph.D.	27
Frequency	Field of study
38	Information technology
32	Management
42	Industrial engineering

As the independent variable (digital transformation) and dependent variable (organizational sustainability) are informative and reflective constructs [32] according to PLS-SEM analysis, the one-dimensionality of each component in the model needs to be checked. Based on the smart-PLS 3 algorithms, the result of the analysis is shown in Fig. 2.

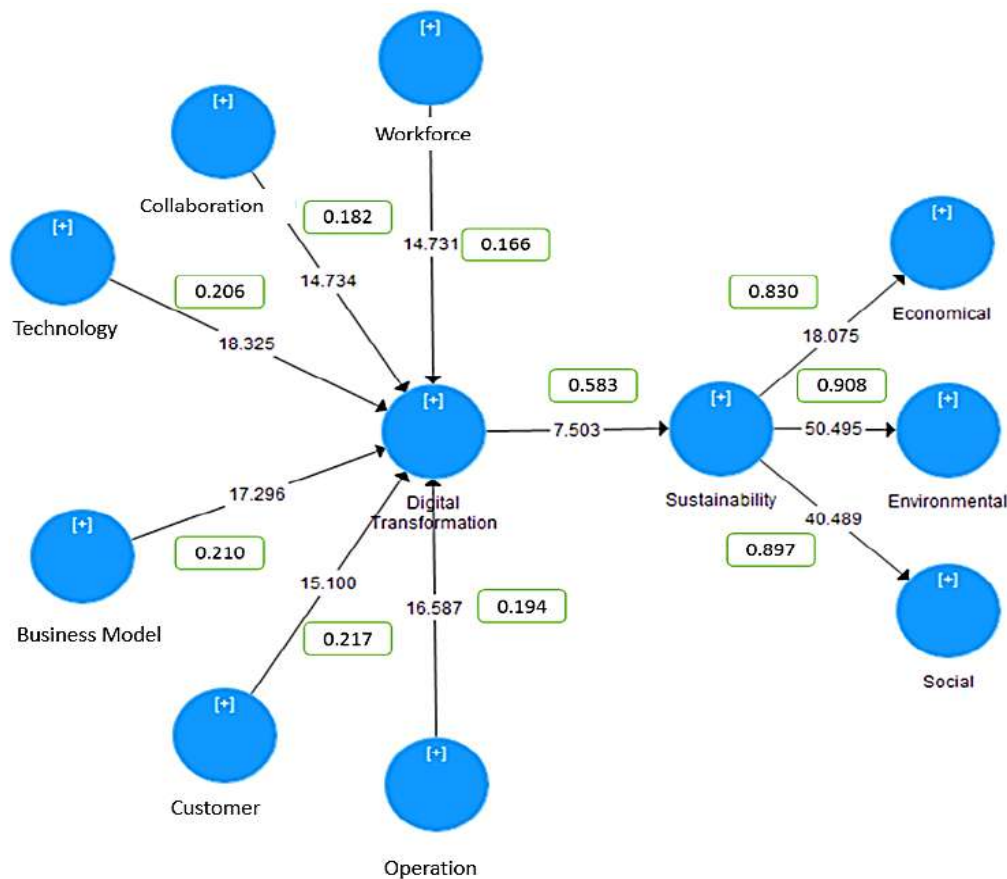


Fig. 2. Smart PLS 3 – PLS algorithm, bootstrapping.

By definition, a component is unidimensional when Cronbach's alpha and Composite Reliability (CR) are higher than 0.7. As listed in Table 2 Cronbach's alpha ranges from 0.70 to 0.94, while CR values range from 0.92 to 0.96 -i.e., exceeding the threshold value (0.7). In addition, the table shows the estimation by the model, including the outer weights, outer loadings, and Average Variance Extracted (AVE) measures.

Table 2. Cronbach's Alpha, Rho_A, CR, AVE.

	Cronbach's Alpha	Rho_A	CR	AVE
Technology	0.855	0.856	0.933	0.874
Customer	0.838	0.838	0.925	0.860
Operation	0.725	0.725	0.879	0.784
Workforce	0.811	0.821	0.913	0.841
Sustainability	0.939	0.941	0.947	0.599
Collaboration	0.823	0.824	0.919	0.850
Business model	0.801	0.814	0.909	0.833
Economical	0.724	0.726	0.879	0.784
Environmental	0.841	0.841	0.926	0.862
Social	0.826	0.828	0.920	0.851
Digital transformation	0.894	0.898	0.919	0.655

The loading of the reflective-visible variables and the respective latent values are depicted by outer loadings. The loadings can be used to examine the reliability of each item. When the loading is bigger than 0.7, the item is considered reliable [61], and all outer loadings (0.80-0.95) were greater than 0.7. In addition, the AVE measures were used to examine the convergent validity of the constructs. Here, the AVE measures ranged from 0.55 to 0.80, which was greater than the threshold of 0.5. In addition, the square root of AVE on each construct was higher than the correlations of the intended construct with other constructs. By validating the measurement model, the structural model can be estimated that determined the relationships of latent variables.

According to [52], divergent validity is acceptable only when AVE values are greater than the common variance between the intended construct and other constructs. Therefore, the acceptable divergent validity of a measurement model shows that a construct in the model has more interactions with its sub-constructs rather than with other constructs [26]. In the PLS method, this is obtained by a matrix whose values are the correlation coefficients between the constructs and the main diameter of the root matrix of AVE for each construct.

The latent variable correlation section of the output file was applied by Smart PLS. In addition, the original diameter used the AVE squared (*Table 3*).

Table 3. Fornall locker.

	Technology	Customer	Operations	Workforce	Sustainability	Collaboration	Business Model	Economic	Environmental	Social	Digital Transformation
Technology	0.93										
Customer	0.71	0.92									
Operation	0.70	0.73	0.88								
Workforce	0.61	0.58	0.51	0.91							
Sustainability	0.88	0.88	0.83	0.79	0.77						
Collaboration	0.26	0.35	0.38	0.32	0.38	0.92					
Business model	0.46	0.57	0.56	0.41	0.56	0.62	0.91				
Economical	0.61	0.59	0.54	0.81	0.59	0.24	0.36	0.88			
Environmental	0.45	0.59	0.57	0.40	0.57	0.59	0.75	0.35	0.92		
Social	0.80	0.79	0.70	0.59	0.49	0.36	0.48	0.58	0.49	0.92	
Digital transformation	0.45	0.58	0.58	0.43	0.58	0.83	0.80	0.37	0.797	0.51	0.8

Structural model: at this point, the structural model of the study was evaluated. In this study, in contrast to the measurement model, the structural model was not related to the questions (observed variables), and the latent variables, and their relationships were tested. To examine the fitness of the structural model, one of the most famous criteria, i.e., t-value was utilized (*Table 4*). Based on the bootstrap command, smart

PLS measures these coefficients. Measuring the fitness of the structural model by obtaining coefficients is according to the presumption that the obtained values must be greater than 1.96 at the confidence level of 95%. Based on the analysis done by the software, these values for all the items were greater than 1.96.

Table 4. Outer loading-T statistic.

	Outer Loading	P value	T
Technology	18.325	0	0.206
Customer	15.1	0	0.217
Operation	16.58	0	0.194
Workforce	14.73	0	0.182
Sustainability	7.5	0	0.583
Collaboration	14.73	0	0.166
Business model	17.29	0	0.210
Economical	18.07	0	0.830
Environmental	50.49	0	0.908
Social	40.48	0	0.897

As it can be seen, the t-value of the environmental and social components was the maximum t-value, which are equal to 50.49 and 40.48, respectively. Moreover, the t-values for the Technology and economic components were 18.325 and 18.07, respectively; however, the other components had the lowest t-values in comparison with the other indices (Sustainability = 7.5, Collaboration = 14.73, Workforce = 14.73).

The obtained data through the surveys and literature review was examined and analyzed to find the common themes between digital parameters and sustainability. Digital transformation is the main area of focus, not on the inter-relationship between traditional ITs, like enterprise applications and business processes. Therefore, data analyses were mainly concentrated on the effects of digital transformation elements, including technology, customer, operation, workforce, business model, collaboration, on business processes. Therefore, the impact types were examined, if needed, in terms of sustainability.

The result is shown in *Table 8*. T-value of Environmental and Social domains had the maximum t-value along with other domains and the values were equal to 50.49 and 40.48, respectively. Furthermore, technology and economical had the t-value of 18.325 and 18.07, respectively. The other domains have the lowest t-values in comparison to the other indices (TSustainability = 7.5, TCollaboration = 14.73, TWorkforce = 14.73).

5 | Discussion

Ensuring the alignment of adopted strategies with sustainability is one of the requirements of modern and leading organizations. Having a suitable business strategy in place for transportation and shipping routes, production and maintenance plans means avoiding wasting time, products, and resources which affect the sustainability performance of the organization. Digital transformation is a dramatic change in the performance of an organization or a country centered on transformational technologies [53]. Pointed out that the use of technological advances is one of the prerequisites for sustainability. Additionally, some researchers considered digital transformation technologies to be a powerful tool for promoting sustainability [24], [54] and believed that the effects of digital transformation and sustainability are intertwined. In addition, Blockchain and other uses of IoT help organizations to utilize more sustainable solutions than traditional information-sharing strategies [36] for controlling their supply chain and improving the efficiency of their operations. This leads us to the second important point in which the most dominant feature of digital transformation is mobility.

Dehbasteh et al. [23] findings indicated the sustainable consequences of the digitalization of production processes. Moreover, they found out that if the expected benefits are achieved through digital technologies, they can affect sustainability. One of the important benefits of digital transformation is

the reduction of using paper books, records, magazines, and contracts by digital communications and digital file management. Through cloud storage, we could eliminate paper waste and overhead costs of traditional storage and secure crushing, and it also provides constant access to documents from any place. In addition, Blockchain and other uses of IoT help organizations to utilize more sustainable solutions than traditional information-sharing strategies [36] for controlling their supply chain and improving the efficiency of their operations.

Some companies have been able to attract customers who are concerned about the environment by offering green products to them [10].

The functionalities that support sustainability cover a wide range from better product design to predictive maintenance and product tracking [55]. Moreover, sustainability is achievable by improving the efficiency of operations where the environmental footprint decreases compared to conventional manufacturing processes. For instance, monitoring operations data is a way to decrease scrap rates and equipment wear and tear [55]. There are many social benefits in digitalization, such as higher safety that is achieved by increased autonomy of processes and decreasing the rate of human errors and accidents. For instance, a sensor shuts down an operation when it detects a worker entering a restricted area [55]. In addition, using automatic machines that can be controlled remotely eliminates risky jobs in the mining industry.

In addition, the rapid advancement in the domain of digitalization has accelerated the creation of new business models leading to value creation in the digital age and creating new revenue streams compatible with new technologies [56]. According to [57] customer orientation, taking advantage of opportunities through digital and innovation capabilities, could impact various aspects of organizational sustainability. This sort of value that is usually created indirectly is rooted in digitalization, and societies can enjoy its benefits. Therefore, it can easily attract the attention of policymakers.

6 | Conclusion

Management is required to ensure that the strategy adopted by the company is perfectly aligned with the sustainability efforts. However, divergence is a usual issue, and it adds to the fragility of sustainability effects due to the lack of genuine commitment and prioritization.

Digital technologies could transform markets and create novel paradigms in business. In addition, they could bring new solutions to organizations to deal with sustainability issues. Digital transformation and sustainability complement each other.

By placing documents on the cloud and increasing the availability of such services, employees can use different work-related software and files from almost anywhere. As a result, the move towards telecommuting is increasing and the waste created by modern workplaces (overhead costs, energy consumption, commute-time emission, and the like) decreases. Indeed, unified communication providers have created that much mobile collaboration that commuting is not the only thing in which employees can skip. Nowadays, there is even no need to fly to company field offices or vendor quality inspections.

Blockchain and other IoT technologies could help us control the supply chain or automatically monitor the quality of the vendors, suppliers, and end products all without stepping outside the office. Therefore, it will be possible to have more efficient plans for shipping and transport routes, production programs, and maintenance schedules that means avoiding wasted time, product, and resources.

Through developing wider profit margins and improving energy efficiency, smart buildings and the IoT enable businesses to cut their costs mostly in terms of energy consumption. By using smart sensors and monitoring devices, it is possible to adjust electricity, heating, and cooling use for each room. In addition, in order to save resources, digital transformation can save a great volume of money.

The development of the Internet of Everything (connected objects and people) creates an immense volume of data that could be used by analytics and visualization techniques to learn the way to interact with others, businesses, and the planet. Achieving such insight gives us the ability to uncover patterns for more sustainable behavior like:

- *More reliable forecasts of natural events or disasters.*
- *Optimized agricultural production and food supply at the global scale.*
- *Predicting traffic congestion and creating zones with low emission.*
- *Adding limitations on energy production based on the exact need of consumers.*
- *Finding defects in or imminent failure of specific product components to enable preventive maintenance and avoiding expensive repair or replacement.*

Social

In this field, the digital revolution causes actual change in the game and makes it possible to introduce a new model of society through sharing that is one of the main principles of sustainability thinking.

Doubtlessly, creating such a connected world and harnessing the obtained data can create an environmental load. Using the "Green IT" techniques, such as virtualization entails efficient hardware components, free air-cooled data centers, and so on to ensure minimum impact.

Economy

In many cases, the tangible positive economic benefits created by sustainable approaches to business are quite evident, such as a decrease in waste production, lower energy consumption, and faster operations that save time.

In the case of large companies, active involvement brings more effects as follows:

- *They can attract more consumers who are concerned about environmental issues.*
- *They can reduce the "bottom-line" effect of the growing energy prices and environmental taxes.*

Thanks to the cloud approach to IT services, there is no need for prohibitive investment in new technologies and sustainable business processes. In addition, the solutions could be brought to the market using commercial approaches based on consumer mentality about time/place-free access and "only pay for what you use".

Digitization forces companies that want to remain sustainably successful in the market to adapt their existing business models to the new market environments and conditions. Indeed, when existing business models become obsolete through technological changes, companies have developed new business models [58].

This paper represents qualitative and exploratory research on the relationship between digital transformation and sustainability. Such papers stated that the use of technological advances is one of the major prerequisites for sustainability [53]. Some scholars argued that digital transformation through the use of digital technologies can be a powerful tool for promoting sustainability [24], [59] and supporting SDGs [60].

Digital transformation is reinventing business by creating new revenue streams in new ways [56]. New and adapted business models were crafted by companies to be able to capture value in the digital age. Becoming a customer-centric company, outdoing the competition, exploiting the tremendous

opportunities that digital capabilities offer, and possessing innovation capabilities are what firms look during a digital transformation [61].

The findings showed some impressive results concerning the sustainable implications of the digitalization of manufacturing processes. If the predicted benefits are achieved through digital technologies, they could massively impact sustainability [23]. The effects of digital transformation on sustainability are mixed [61].

6.1 | Recommendations and Limitations

A key requirement of organizational sustainability efforts is digital transformation. Internal and external dynamics among organizations could lead us to deeper insights into integration points between digital transformation, sustainability elements, and business processes. It also highlights the effects of the selection of technology platforms. The major results for businesses are business efficiencies, agility and innovation, cost reductions, and customer experience enhancements. The framework was examined deeper, and a few recommendations were made; therefore, there is a need to recognize digital transformation and sustainability as strategic imperatives by organizational leadership. Moreover, there is a need for organizations to find long-term partnerships with ICT companies active in digital technology fields. Through this, the long-term results of sustainability could be linked to digital transformation. There is also a need to find an individual or committee with adequate influence on the strategy of the organization to stay in charge of the digital transformation of the organization. Such a person might be the Chief Financial Officer (CFO), Chief Information Officer (CIO), Chief Technology Officer (CTO), or chief digital officer, and the internal structure of the organization decides which one is the best choice. Furthermore, there is a need for a specific person in charge of digital transformation in an organization. In addition, there is a need to create an alignment between the digital strategy and the sustainability strategy of the organization. Thus, the directors of sustainability, strategy, and digital works need to cooperate and define the strategic initiatives and projects.

It has been more than a decade since we have faced with the challenges of sustainability. The end of economic stagnation is not near, and we are moving towards a period of low growth when financial resources for sustainability are going to be scarce. On the other hand, ecological problems in the world emphasize the need for such investment. Technological development and fast digitalization are opportunities for businesses and organizations to achieve higher productivity, innovations, and chances to adapt to the rapidly changing world. These changes also bring the risk of changes in employment patterns, more income inequality, privacy concerns, higher dependence on the cyber world, and disruptive-business models. The ability of organizations to control sustainability challenges depends on creating and controlling technology and finding new solutions.

Conflicts of interest

All co-authors have seen and agreed 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.

References

- [1] Ferfuaia, C., Zuliani, F., Danuso, F., Piani, B., Cattivello, C., Dorigo, G., & Baldini, M. (2021). Performance and stability of different monoecious hemp cultivars in a multi-environments trial in North-Eastern Italy. *Agronomy*, 11(7), 1424. <https://doi.org/10.3390/agronomy11071424>
- [2] Bican, P. M., & Brem, A. (2020). Digital business model, digital transformation, digital entrepreneurship: Is there a sustainable “digital”? *Sustainability*, 12(13), 5239. <https://doi.org/10.3390/su12135239>
- [3] Katsamakas, E. (2022). Digital transformation and sustainable business models. *Sustainability*, 14(11), 6414. <https://doi.org/10.3390/su14116414>

- [4] Hiner, J. (2017). *Big data and digital transformation: how one enables the other*. <https://www.zdnet.com/article/big-data-and-digital-transformation-how-one-enables-the-other/>
- [5] Fakheri, S. (2022). A comprehensive review of big data applications. *Big data and computing visions*, 2(1), 9–17.
- [6] Bonini, S., Görner, S., & Jones, A. (2010). *How companies manage sustainability: McKinsey Global Survey results*. <https://www.mckinsey.com/capabilities/sustainability/our-insights/how-companies-manage-sustainability-mckinsey-global-survey-results>
- [7] Valmohammadi, C. (2014). Impact of corporate social responsibility practices on organizational performance: an ISO 26000 perspective. *Social responsibility journal*, 10(3), 455–479.
- [8] Bai, C., Dallasega, P., Orzes, G., & Sarkis, J. (2020). Industry 4.0 technologies assessment: A sustainability perspective. *International journal of production economics*, 229, 107776. <https://doi.org/10.1016/j.ijpe.2020.107776>
- [9] Garzella, S., Fiorentino, R., Caputo, A., & Lardo, A. (2021). Business model innovation in SMEs: The role of boundaries in the digital era. *Technology analysis & strategic management*, 33(1), 31–43.
- [10] Matt, C., Hess, T., & Benlian, A. (2015). Digital transformation strategies. *Business & information systems engineering*, 57, 339–343.
- [11] Ohmae, K. (1988). *Getting back to strategy*. <https://store.hbr.org/product/getting-back-to-strategy/88609>
- [12] Kane, G. C., Palmer, D., Phillips, A. N., Kiron, D., & Buckley, N. (2015). Strategy, not technology, drives digital transformation. *MIT sloan management review*. https://www.cubility.com.au/wp-content/uploads/2018/11/dup_strategy-not-technology-drives-digital-transformation.pdf
- [13] Valmohammadi, C., Sofiyabadi, J., & Kolahi, B. (2019). How do knowledge management practices affect sustainable balanced performance? Mediating role of innovation practices. *Sustainability*, 11(18), 5129. <https://doi.org/10.3390/su11185129>
- [14] Michelman, P. (2019). Key words for digital transformation. *Mit sloan management review*, 60(2), 1–7.
- [15] Paavola, R., Hallikainen, P., & Elbanna, A. (2017). Role of middle managers in modular digital transformation: the case of Servu. *European conference on information systems* (pp. 887-903). Association for Information Systems. <https://core.ac.uk/download/pdf/301372324.pdf>
- [16] Hanna, N. K. (2016). Mastering digital transformation: Towards a smarter society, economy, city and nation. *Mastering digital transformation: towards a smarter society, economy, city and nation* (pp. i–xxvi). Emerald Group Publishing Limited. <https://doi.org/10.1108/978-1-78560-465-220151009>
- [17] Gholami, R., Watson, R. T., Hasan, H., Molla, A., & Bjorn-Andersen, N. (2016). Information systems solutions for environmental sustainability: How can we do more? *Journal of the association for information systems*, 17(8), 2. <https://aisel.aisnet.org/jais/vol17/iss8/2>
- [18] Haddadi Harandi, A. A., Bokharai Nia, M., & Valmohammadi, C. (2019). The impact of social technologies on knowledge management processes: The moderator effect of e-literacy. *Kybernetes*, 48(8), 1731–1756.
- [19] Abdoli Bidhandi, R., & Valmohammadi, C. (2017). Effects of supply chain agility on profitability. *Business process management journal*, 23(5), 1064–1082.
- [20] El Hilali, W., El Manouar, A., & Idrissi, M. A. J. (2020). Reaching sustainability during a digital transformation: a PLS approach. *International journal of innovation science*, 12(1), 52–79.
- [21] Balogun, A. L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., ... & Salehi, P. (2020). Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. *Sustainable cities and society*, 53, 101888. <https://doi.org/10.1016/j.scs.2019.101888>
- [22] Westerman, G., Calm ejane, C., Bonnet, D., Ferraris, P., McAfee, A., & others. (2011). Digital Transformation: A roadmap for billion-dollar organizations. *MIT center for digital business and capgemini consulting*, 1, 1–68. <https://dokumen.tips/documents/digital-transformation-a-road-map-for-billion-dollar-organizations.html?page=1>
- [23] Dehbasteh, K., Pourebrahimi, A., Valmohammadi, C., & Afshar Kazemi, M. A. (2019). Identification of the determinants of Blockchain-based business model using hybrid method: content analysis & system dynamics. *Romanian journal of information technology and automatic control*, 29(4), 17–34.
- [24] Savastano, M., Zentner, H., Spremi , M., & Cucari, N. (2022). Assessing the relationship between digital transformation and sustainable business excellence in a turbulent scenario. *Total quality management & business excellence*, 1–22. <https://doi.org/10.1080/14783363.2022.2063717>

- [25] Pourghader Chobar, A., Adibi, M. A., & Kazemi, A. (2021). A novel multi-objective model for hub location problem considering dynamic demand and environmental issues. *Journal of industrial engineering and management studies*, 8(1), 1–31.
- [26] Esmailian, B., Sarkis, J., Lewis, K., & Behdad, S. (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resources, conservation and recycling*, 163, 105064. <https://doi.org/10.1016/j.resconrec.2020.105064>
- [27] Morakanyane, R., Grace, A. A., & O'reilly, P. (2017). Conceptualizing digital transformation in business organizations: A systematic review of literature. *BLED 2017 Proceedings* (pp. 427–444). University of Maribor Press. <https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1028&context=bled2017>
- [28] Gharanfoli, B., & Valmohammadi, C. (2019). Identification and prioritization of construction projects investment risks using a hybrid fuzzy approach. *Journal of multi-criteria decision analysis*, 26(3–4), 113–127.
- [29] Heeks, R. (2014). Future priorities for development informatics research from the post-2015 development agenda. *Development informatics working paper*, (57). <https://ssrn.com/abstract=3438434>
- [30] Vial, G. (2021). Understanding digital transformation: A review and a research agenda. *Managing digital transformation*, 13–66. <https://www.sciencedirect.com/science/article/pii/S0963868717302196>
- [31] Kumar, A., & Thomaz, A. C. F. (2022). Smart bus ticketing system through IoT enabled technology. *Big data and computing visions*, 2(1), 1–8.
- [32] Salah, B., Abidi, M. H., Mian, S. H., Krid, M., Alkhalefah, H., & Abdo, A. (2019). Virtual reality-based engineering education to enhance manufacturing sustainability in industry 4.0. *Sustainability*, 11(5), 1477. <https://doi.org/10.3390/su11051477>
- [33] Benkhelifa, E., Abdel-Maguid, M., Ewenike, S., & Heatley, D. (2014). The internet of things: the eco-system for sustainable growth. *2014 IEEE/ACS 11th international conference on computer systems and applications (AICCSA)* (pp. 836–842). IEEE. <https://doi.org/10.1109/AICCSA.2014.7073288>
- [34] Knothe, T., Oertwig, N., Obenaus, M., & Butschek, P. (2018). Evaluation model for the derivation of a sustainable digitisation strategy. *2018 international conference on intelligent systems (IS)* (pp. 826–834). IEEE. <https://doi.org/10.1109/IS.2018.8710541>
- [35] Zandbiglari, K., Ameri, F., & Javadi, M. (2023). A text analytics framework for supplier capability scoring supported by normalized google distance and semantic similarity measurement methods. *Journal of computing and information science in engineering*, 23(5), 51011. <https://doi.org/10.1115/1.4062173>
- [36] Dadashnejad, A.-A., & Valmohammadi, C. (2018). Investigating the effect of value stream mapping on operational losses: a case study. *Journal of engineering, design and technology*, 16(3), 478–500. DOI: 10.1108/JEDT-11-2017-0123
- [37] I-SCOOP. (2019). *Reporting on digital transformation, Industry 4.0, Internet of Things, cybersecurity, and emerging technologies*. <https://www.i-scoop.eu/>
- [38] Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature sustainability*, 2(9), 805–814.
- [39] Ayer, S. K., Messner, J. I., & Anumba, C. J. (2016). Augmented reality gaming in sustainable design education. *Journal of architectural engineering*, 22(1), 4015012. [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000195](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000195)
- [40] Chong, A. Y. L., Chan, F. T. S., Ooi, K.-B., & Sim, J. J. (2011). Can Malaysian firms improve organizational innovation performance via SCM? *Industrial management & data systems*, 111(3), 410–431.
- [41] El Hilali, W., & El Manouar, A. (2018). SMART companies: how to reach sustainability during a digital transformation. *Proceedings of the 3rd international conference on smart city applications* (pp. 1–6). Association for Computing Machinery. <https://doi.org/10.1145/3286606.3286812>
- [42] Šimberová, I., Korauš, A., Schüller, D., Smolíková, L., Straková, J., & Váchal, J. (2022). Threats and Opportunities in Digital Transformation in SMEs from the Perspective of Sustainability: A Case Study in the Czech Republic. *Sustainability (switzerland)*, 14(6), 3628. DOI: 10.3390/su14063628
- [43] Geng, R., Mansouri, S. A., & Aktas, E. (2017). The relationship between green supply chain management and performance: A meta-analysis of empirical evidences in Asian emerging economies. *International journal of production economics*, 183, 245–258.
- [44] Clayton, T., & Radcliffe, N. (2018). *Sustainability: a systems approach*. Routledge. <https://books.google.com>
- [45] Hair, J. F., Ringle, C. M., & Sarstedt, M. (2011). PLS-SEM: Indeed a silver bullet. *Journal of marketing theory and practice*, 19(2), 139–152.
- [46] Mehdikhani, R., & Valmohammadi, C. (2019). Strategic collaboration and sustainable supply chain management. *Journal of enterprise information management*, 32(5), 778–806. DOI: 10.1108/JEIM-07-2018-0166

- [47] Pourghader Chobar, A., Sabk Ara, M., Moradi Pirbalouti, S., Khadem, M., & Bahrami, S. (2022). A multi-objective location-routing problem model for multi-device relief logistics under uncertainty using meta-heuristic algorithm. *Journal of applied research on industrial engineering*, 9(3), 354–373.
- [48] Demartini, M., Evans, S., & Tonelli, F. (2019). Digitalization technologies for industrial sustainability. *Procedia manufacturing*, 33, 264–271.
- [49] Maffei, A., Grahm, S., & Nuur, C. (2019). Characterization of the impact of digitalization on the adoption of sustainable business models in manufacturing. *Procedia CIRP*, 81, 765–770.
- [50] Gutierrez, A., Mylonadis, C., Orozco, J., & Serrano, A. (2008). Business-IS alignment: assessment process to align IT projects with business strategy. *AMCIS 2008 proceedings*, 290. <https://www.researchgate.net/publication/220890900>
- [51] Tandon, A., Kaur, P., Mäntymäki, M., & Dhir, A. (2021). Blockchain applications in management: A bibliometric analysis and literature review. *Technological forecasting and social change*, 166, 120649. <https://doi.org/10.1016/j.techfore.2021.120649>
- [52] Fitzgerald, M., Kruschwitz, N., Bonnet, D., & Welch, M. (2014). Embracing digital technology: A new strategic imperative. *MIT sloan management review*, 55(2), 1-16. <https://emergenceweb.com/blog/wp-content/uploads/2013/10/embracing-digital-technology.pdf>
- [53] Tenenhaus, M., Vinzi, V. E., Chatelin, Y. M., & Lauro, C. (2005). PLS path modeling. *Computational statistics & data analysis*, 48(1), 159–205.
- [54] Boffa, E., & Maffei, A. (2023). Development and application of an Integrated Business Model framework to describe the digital transformation of manufacturing-a bibliometric analysis. *Production & manufacturing research*, 11(1), 2164952. <https://www.tandfonline.com/doi/pdf/10.1080/21693277.2023.2164952>
- [55] Bressanelli, G., Adrodegari, F., Perona, M., & Saccani, N. (2018). Exploring how usage-focused business models enable circular economy through digital technologies. *Sustainability*, 10(3), 639. <https://doi.org/10.3390/su10030639>
- [56] Karimi, J., & Walter, Z. (2015). The role of dynamic capabilities in responding to digital disruption: A factor-based study of the newspaper industry. *Journal of management information systems*, 32(1), 39–81.
- [57] Hanna, N. K. (2009). *Enabling enterprise transformation: business and grassroots innovation for the knowledge economy*. Springer Science & Business Media. <http://dx.doi.org/10.1007%2F978-1-4419-1508-5>
- [58] Ahmad, M. U., & Murray, J. (2019). Understanding the connect between digitalisation, sustainability and performance of an organisation. *International journal of business excellence*, 17(1), 83–96.
- [59] Leng, J., Ruan, G., Jiang, P., Xu, K., Liu, Q., Zhou, X., & Liu, C. (2020). Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey. *Renewable and sustainable energy reviews*, 132, 110112. <https://doi.org/10.1016/j.rser.2020.110112>
- [60] Techtarget. (2019). *Enterprise desktop definitions from techtarget*. <https://www.techtarget.com/searchenterprisedesktop/definitions>
- [61] Rogers, D. L. (2016). *The digital transformation playbook: rethink your business for the digital age*. Columbia University Press. <https://doi.org/10.7312/roge17544>



Paper Type: Research Paper



Improving Classic Hungarian Algorithm Considering Uncertainty by Applying for Grey Numbers

Shahram Ariafar^{1,*} , Seyed Hamed Moosavirad¹, Ali Soltanpour²

¹ Department of Industrial Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran; ariafar@gmail.com; s.h.moosavirad@uk.ac.ir.

² Organization and Jobs Classification, National Iranian Copper Industries Company, Iran; soltanpourali1@gmail.com.

Citation:



Ariafar, Sh., Moosavirad, S. H., & Soltanpour, A. (2023). Improving classic hungarian algorithm considering uncertainty by applying for grey numbers. *International journal of research in industrial engineering*, 12(3), 321-336.

Received: 05/11/2022

Reviewed: 07/12/2022

Revised: 19/01/2023

Accepted: 24/02/2023

Abstract

The Hungarian Algorithm is the most famous method for solving Linear Assignment Problems (LAP). Linear Assignment Method (LAM), as an application of LAP, is among the most popular approaches for solving Multi Criteria Decision Making (MCDM) problems. LAM assigns a priority to each alternative based on a Decision Matrix (DM). The elements of the DM are often deterministic in MCDM. However, in the real world, the value of the elements of the DM might not be specified precisely. Hence, using interval grey numbers as the value of the DM to consider the uncertainty is reasonable. In this research, for providing a real circumstance, the classic Hungarian algorithm has been extended by using the concept of grey preference degree as the Grey Hungarian Algorithm (GHA) to solve LAM under uncertainty. To verify the proposed GHA, a real case for ranking several items of mining machinery warehouse from Sarcheshmeh Copper Complex has been solved by the GHA. Also, the same case study has been prioritized by two other methods: Grey TOPSIS and Grey VIKOR. The results of all mentioned approaches are identical, showing the validity of the proposed GHA developed in this research.

Keywords: Grey interval number, Hungarian algorithm, Grey VIKOR, Grey TOPSIS, Preference degree.

1 | Introduction

In a real environment, when the aim is to select alternatives by Multi Criteria Decision Making (MCDM) methods based on their maximum impacts, using the Linear Assignment Method (LAM) is reasonable. The main specification of this approach is that each alternative shall be assigned just to one rank, and each ranking shall be occupied just by one alternative. This kind of problem has been well studied and solved by the Hungarian algorithm developed by Kuhn [1].

Researchers have done various studies to extend the context of the Linear Assignment Problem (LAP) and Hungarian Algorithm. In early research done by Das and Deo [2], they developed a parallel Hungarian Algorithm by using an Exclusive Read and Exclusive Write (EREW) and a Parallel Random Access Machine (PRAM) [2]. In another study by Ishibuchi and Tanaka [3], they developed a binary linear assignment mathematical model that used interval numbers as the coefficients of the



objective function. Aldous [4] used a usual probabilistic model to address a random assignment problem. Li et al. [5] developed a serial-parallel system to improve the Hungarian Algorithm. Rajabi-Alni and Bagheri [6] used the Hungarian Algorithm to solve the many-to-many matching problems considering demands and capacity. In the Many-to-many matching problems, each element of one set matches at least one item of another set.

Bai [7] introduced the grey LAM by providing two solution approaches; one of the solution methods was using the average of the grey numbers to transform the model into a deterministic problem, and another approach was applying the grey forecasting method. Majumdar [8] has extended the Hungarian method for solving assignment models with interval parameters. However, the proposed method is not completely accurate because in dividing two interval parameters in the proposed method, the lower endpoint of the first interval number has been divided by the lower endpoint of the second interval number as the lower endpoint of the generated interval number.

Similarly, the upper endpoint of the interval number has been calculated by dividing the upper endpoint of the first number by the upper endpoint of the second number that is not correct. For instance, if the interval number is $[2, 4]$ that is divided by $[1, 5]$ according to the dividing method that has been considered by Majumdar [8], the answer will be equal to $[\frac{2}{1}, \frac{4}{5}]$, which is not correct; because the lower endpoint of the generated interval is greater than the upper endpoint of this number.

Several studies applied the Hungarian Algorithm as a part of their solution approach; for instance, the application of the Hungarian Algorithm for solving error-tolerant matching [9], [10]. Lan et al. [11] studied the scheduling of physicians and medical staff in the outpatient ward of a large hospital. They proposed a meta-heuristic algorithm based on the Iterated Hungarian Algorithm named IHA. Yadav et al. [12] applied the Hungarian Algorithm to LAPs for solving resource allocation in wireless communication systems. Khan et al. [13] presented an algorithm based on the Hungarian Algorithm and fractional programming for beamforming and scheduling strategy in a cloud radio access network.

Yang et al. [14] proposed a multi-objective MIP model for internal truck allocation when the internal trucks are shared among several nearby container terminals and solved the model by applying the Hungarian Algorithm. Kumarnnath and Batri [15] developed a modified PSO-based iterative Hungarian Algorithm to provide maximum throughput traffic with the least blocking probability in the transmission of data between nodes of an optical network. MacLean et al. [16] developed a method for maximizing the satisfaction of medical students regarding their clinical preference rotation at the University of Texas Southwestern Medical Center (UTSW). They used the Hungarian Algorithm to solve the problem. Stevens and Sciacchitano [17] used the Hungarian Algorithm and hierarchical clustering method for vortex detection and tracking in the complex and turbulent flow study.

Katariya et al. [15] improved the Hungarian Algorithm to solve the unbalanced assignment problem. In this problem, some fictitious machines in the system cannot be assigned to any tasks. In this situation, all the tasks must be allocated to a given number of machines [15]. Zhu et al. [18] developed a model for infrared target trajectories based on Gaussian distribution. They used a Munkres version of the Hungarian Algorithm to solve the model. Zhang et al. [19] applied the Hungarian Algorithm for task assignment optimization in a remote sensing big data workflow.

However, investigating the requirements of the real world shows that in actual circumstances, precise, sufficient, or fully covered information cannot be provided often. For instance, when the inventory items should be ranked or prioritized based on two criteria ("Scarcity" and "Availability of the Technical Specifications" in this research) by the experts of the warehouse department, the experts might not be confident about the priorities of each inventory item based on the mentioned criteria. Hence, the uncertainty of the environment should be considered in the problem to make more reasonable and realistic decisions in such a situation.

On the other hand, reviewing the literature showed that several methods have been developed to consider the imprecise experts' opinions to make realistic decisions: fuzzy, stochastic, and grey methods [20]. The stochastic method needs a probability distribution function of the events and facts.

If there were enough data regarding the facts, then the experts' opinions regarding those facts would not be required. On the other hand, another method for considering the ambiguity of judgment is applying fuzzy numbers. The membership function of a fuzzy number should be available if the fuzzy number would like to be used. Hence, the interval grey numbers application to consider the uncertainty of the environment is more reasonable.

To the best of the researchers' knowledge of this study, no study has extended the context of grey numbers in the Hungarian Algorithm. Hence, this study develops a method for solving the Hungarian Algorithm with interval grey numbers, which is the main contribution of this study. The remainder of the paper is as follows. In Section 2, grey theory and interval grey numbers will be discussed. Section 3 will be dedicated to the Grey Hungarian Algorithm (GHA) development and an explanation of Grey VIKOR and Grey TOPSIS, followed by an illustration of the proposed methods by solving a sample problem, sensitivity analysis, and discussion in Section 4. Finally, Section 5 concludes the paper.

2 | Grey Theory and Interval Grey Numbers

At first, Deng [21] proposed the basic thinking of Grey Systems Theory. It is one of the new effective mathematical theories to solve uncertain problems with incomplete information. The theory is categorized into five major parts: 1) grey forecasting, 2) grey relational analysis, 3) grey decision-making, 4) grey programming, and 5) grey control.

In grey systems theory, the darkness of the color is usually used to show the degree of accuracy of information. In the grey theory, the entire system is divided into three categories: white, black, and grey sections. White represents the completion, certainty, and transparency of information in a system, and black shows unknown and incomplete information in a system [22], [23]. While the grey section is placed between two white and black sections, showing insufficient information between two clear boundaries. The concept of grey systems is shown in *Fig. 1*. So, a grey number $\otimes G$ in a grey system may be shown with a closed interval with upper and lower endpoint, i.e. $[\underline{\mu}_G(x), \overline{\mu}_G(x)]$ [24].

Each grey system is described with grey numbers, grey equations, grey matrices, etc., while grey numbers are considered minor parts of a grey system, like atoms or cells. In other words, a grey number's exact value is unclear, but its interval endpoints are clear. In a practical situation, a grey number will be stated by an interval or a whole set of numbers [23]. For example, ranking the alternatives based on a criterion in decision-making will be expressed by linguistic variables, that could be stated by numerical intervals that include uncertain information [21].

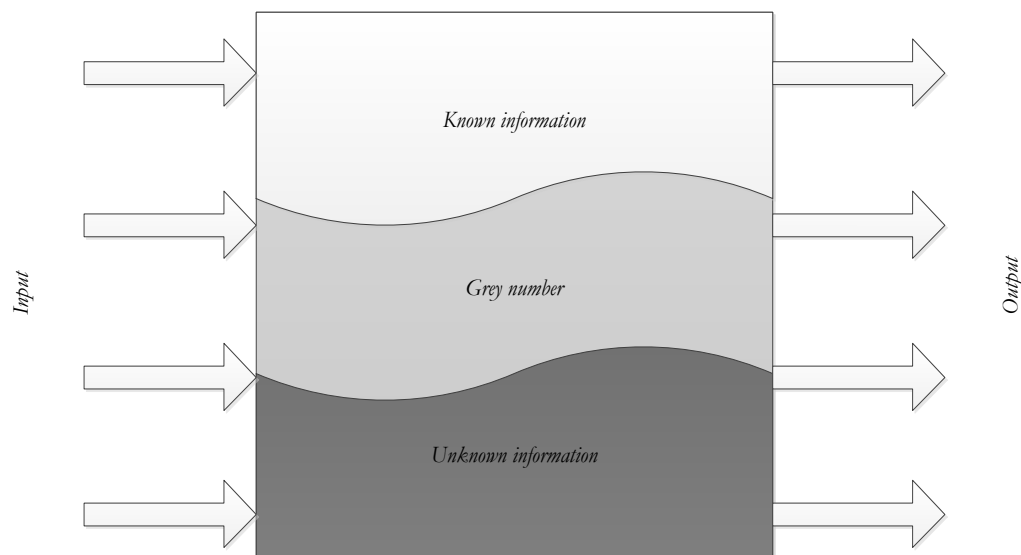


Fig. 1. The concept of the grey system.

Generally, the arithmetic operators defined for real numbers can also be extended for the set of grey intervals [23]. These interval operators were developed by Moore [25]. The basic operation laws of two grey numbers $\otimes G_1 = [\underline{G}_1, \overline{G}_1]$, and $\otimes G_2 = [\underline{G}_2, \overline{G}_2]$ are defined as follows [21]:

$$\otimes G_1 + \otimes G_2 = \left[\underline{G}_1 + \underline{G}_2, \overline{G}_1 + \overline{G}_2 \right]. \quad (1)$$

$$\otimes G_1 - \otimes G_2 = \left[\underline{G}_1 - \overline{G}_2, \overline{G}_1 - \underline{G}_2 \right]. \quad (2)$$

$$\otimes G_1 \times \otimes G_2 = \left[\min(\underline{G}_1 \times \underline{G}_2, \underline{G}_1 \times \overline{G}_2, \overline{G}_1 \times \underline{G}_2, \overline{G}_1 \times \overline{G}_2), \max(\underline{G}_1 \times \underline{G}_2, \underline{G}_1 \times \overline{G}_2, \overline{G}_1 \times \underline{G}_2, \overline{G}_1 \times \overline{G}_2) \right]. \quad (3)$$

$$\otimes G_1 \div \otimes G_2 = \left[\underline{G}_1, \overline{G}_1 \right] \times \left[\frac{1}{\overline{G}_2}, \frac{1}{\underline{G}_2} \right]. \quad (4)$$

$\overline{G}_2 \neq 0, \underline{G}_2 \neq 0.$

3 | Research Methodology

The developed solution approach of the study will be expressed in this section. Hence, at first, the GHA will be explained, followed by the explanation for the Grey VIKOR and Grey TOPSIS that have been applied to verify the developed method of this study.

3.1 | Developed Grey Hungarian Algorithm

The proposed GHA of this study is based on the classic Hungarian algorithm [1], [26] that has been extended to consider Grey interval numbers. The flowchart of the GHA method is shown in Fig. 2.

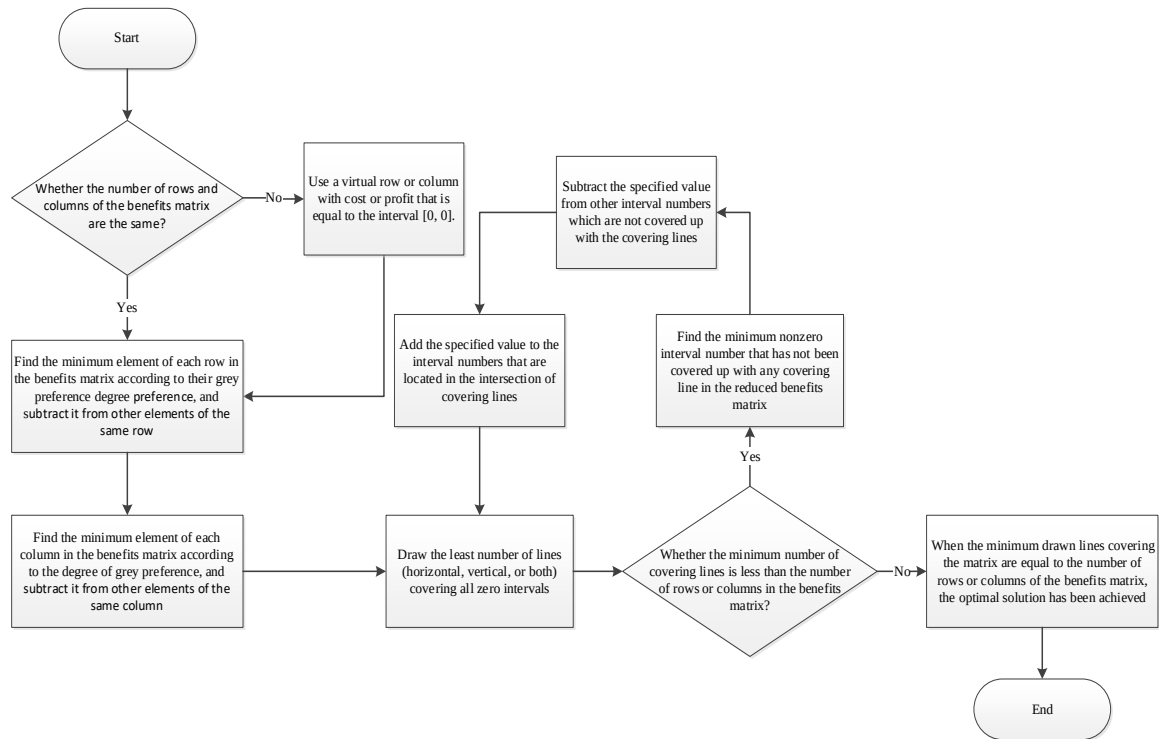


Fig. 2. The flowchart of the proposed GHA.

The steps of the proposed GHA are as follows:

Step 1. Find the minimum element of each row in the benefits matrix (objective function coefficients for the assignment problem) according to their grey preference degree relation and subtract it from other elements of the same row. Then, go to the *Step 2*.

Step 2. Find the minimum element of each column in the benefits matrix obtained from *Step 1* according to the degree of grey preference and subtract it from other elements of the same column. Then go to the *Step 3*.

Step 3. Draw the least number of lines (horizontal, vertical, or both) covering all zero intervals (zero intervals are those where their average interval points are equal to zero). Then go to the *Step 4*.

Step 4. The optimal solution will be achieved if the number of minimum drawn lines covering the matrix equals the number of rows or columns of the benefits matrix. It is available among the covered zero intervals. If the minimum number of covered lines is less than the number of rows or columns in the benefits matrix, go to *Step 5*.

Step 5. Find the minimum nonzero interval number that has not been covered up with any covering line in the reduced benefits matrix. Subtract the specified value from other interval numbers that are not covered up with the coverage lines; then, add it to the numbers that have been covered by two covering lines simultaneously. Then go to the *Step 3*.

3.2 | Grey VIKOR Algorithm

VIKOR method is an MCDM approach. This method is used when there are conflicting criteria, and this method finds a solution close to the ideal solution by using a compromised ranking list. The use of the VIKOR method for decision problems in the literature is abundant. It has been extended to solving interval numbers by Sayadi et al. [27], but the lack of normalization for the Decision Matrix (DM) can be sensed. This study has improved the Grey VIKOR method by normalizing the DM. The steps of Grey VIKOR of this study are as follows:

Table 1. DM in the Grey VIKOR method.

	C_1	C_2	$\dots$	C_n
A_1	$[g_{11}^l, g_{11}^u]$	$[g_{12}^l, g_{12}^u]$	$\dots$	$[g_{1n}^l, g_{1n}^u]$
A_2	$[g_{21}^l, g_{21}^u]$	$[g_{22}^l, g_{22}^u]$	$\dots$	$[g_{2n}^l, g_{2n}^u]$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_m	$[g_{m1}^l, g_{m1}^u]$	$[g_{m2}^l, g_{m2}^u]$	$\dots$	$[g_{mn}^l, g_{mn}^u]$

$\otimes W = [\otimes w_1, \otimes w_2, \dots, \otimes w_n]$

As can be seen from Table 1, which is the DM, $A_1, A_2, \dots, A_m$ are the alternatives, while $C_1, C_2, \dots, C_n$ are the required criteria for selecting alternatives. g_{ij} is the rank of alternative A_i according to the C_j^{th} criterion whose value is not crisp, $g_{ij} \in [g_{ij}^l, g_{ij}^u]$ while $\otimes W$ is the weight of j^{th} criteria.

Step 1. In the development of the Grey VIKOR Method, at first, the DM should be normalized. In the following, the normalization process for the cost (minimizing) and profit (maximizing) criterion has been provided.

$$\otimes f_{ij} = \left[\frac{\otimes G_j^{\max} - \overline{\otimes G_{ij}}}{\otimes G_j^{\max}}, \quad \frac{\otimes G_j^{\max} - \otimes G_{ij}}{\otimes G_j^{\max}} \right], \quad \otimes G_j^{\max} = \max_{1 \leq i \leq m} \{ \overline{\otimes G_{ij}} \}, \quad \text{for Cost} \quad (5)$$

Criterion.

$$\otimes f_{ij} = \left[\frac{\otimes G_{ij}}{\otimes G_j^{\max}}, \quad \frac{\overline{\otimes G_{ij}}}{\otimes G_j^{\max}} \right], \quad \otimes G_j^{\max} = \max_{1 \leq i \leq m} \{ \overline{\otimes G_{ij}} \}, \quad \text{for Benefit Criterion.} \quad (6)$$

Step 2. Determining the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) according to the Eqs. (7) and (8).

$$A^+ = \{f_1^+, f_2^+, \dots, f_n^+\} = \left\{ \left(\max_i f_{ij}^u \mid j \in B \right) \text{ or } \left(\min_i f_{ij}^l \mid j \in C \right) \right\}. \quad (7)$$

$$A^- = \{f_1^-, f_2^-, \dots, f_n^-\} = \left\{ \left(\min_i f_{ij}^l \mid j \in B \right) \text{ or } \left(\max_i f_{ij}^u \mid j \in C \right) \right\}, \quad (8)$$

where B is the set of benefit criteria, while C is the set of cost criteria.

Step 3. Computing the intervals $[S_i^l, S_i^u]$ (Satisfaction Index), and $[R_i^l, R_i^u]$ (Regret Index) by using Eqs. (9) and (10) by considering grey uncertainty for every W_j .

$$S_i^l = \sum_{j \in B} W_j \left(\frac{f_j^+ - f_{ij}^u}{f_j^+ - f_j^-} \right) + \sum_{j \in C} W_j \left(\frac{f_{ij}^l - f_j^+}{f_j^- - f_j^+} \right) \quad i = 1, 2, \dots, m, \quad (9)$$

$$S_i^u = \sum_{j \in B} W_j \left(\frac{f_j^+ - f_{ij}^l}{f_j^+ - f_j^-} \right) + \sum_{j \in C} W_j \left(\frac{f_{ij}^u - f_j^+}{f_j^- - f_j^+} \right) \quad i = 1, 2, \dots, m.$$

$$R_i^l = \max \left\{ W_j \left(\frac{f_j^+ - f_{ij}^u}{f_j^+ - f_j^-} \right) \mid j \in B, \quad W_j \left(\frac{f_{ij}^l - f_j^+}{f_j^- - f_j^+} \right) \mid j \in C \right\} \quad i = 1, 2, \dots, m, \quad (10)$$

$$R_i^u = \max \left\{ W_j \left(\frac{f_j^+ - f_{ij}^l}{f_j^+ - f_j^-} \right) \mid j \in B, \quad W_j \left(\frac{f_{ij}^u - f_j^+}{f_j^- - f_j^+} \right) \mid j \in C \right\} \quad i = 1, 2, \dots, m.$$

Step 4. Computing the VIKOR Index: $Q_i = [Q_i^L, Q_i^U]; i = 1, \dots, m$ according to the Eq. (11).

$$Q_i^L = v \frac{(S_i^L - S^+)}{(S^- - S^+)} + (1-v) \frac{(R_i^L - R^+)}{(R^- - R^+)}, \quad i = 1, 2, \dots, m. \quad (11)$$

$$Q_i^U = v \frac{(S_i^U - S^+)}{(S^- - S^+)} + (1-v) \frac{(R_i^U - R^+)}{(R^- - R^+)},$$

where, $S^+ = \min_i S_i^L$, $S^- = \max_i S_i^U$, $R^+ = \min_i R_i^L$, $R^- = \max_i R_i^U$.

While v is defined as the strategic weight of "the majority of criteria," which is considered to be 0.5, in this study.

Step 5. According to the VIKOR method, the best alternative is an alternative with the lowest value of S_i , R_i , and Q_i , while their value is an interval Grey number. The preference degree concept is used in this study to compare the alternatives and select the best one with the minimum value.

The preference degree between two numbers $\otimes Q_1$ and $\otimes Q_2$ can be defined as follows [28]:

$$P(\otimes Q_1 > \otimes Q_2) = \frac{\max(0, \overline{Q_1} - \underline{Q_2}) - \max(0, \underline{Q_1} - \overline{Q_2})}{(\overline{Q_1} - \underline{Q_1}) + (\overline{Q_2} - \underline{Q_2})}, \quad (12)$$

$$P(\otimes Q_2 > \otimes Q_1) = \frac{\max(0, \overline{Q_2} - \underline{Q_1}) - \max(0, \underline{Q_2} - \overline{Q_1})}{(\overline{Q_1} - \underline{Q_1}) + (\overline{Q_2} - \underline{Q_2})}.$$

Also, Eq. (13) also exists for the degree of preference between two grey numbers:

$$P(\otimes Q_1 > \otimes Q_2) + P(\otimes Q_2 > \otimes Q_1) = 1, \quad (13)$$

$$\text{If } \otimes Q_1 = \otimes Q_2 \text{ Then } P(\otimes Q_1 > \otimes Q_2) = P(\otimes Q_2 > \otimes Q_1) \equiv 0.5.$$

If the midpoint of Q_1 is greater than the midpoint of Q_2 , then,

$$P(\otimes Q_1 > \otimes Q_2) > P(\otimes Q_2 > \otimes Q_1).$$

As mentioned before, the best alternative would be the one with the minimum value of the VIKOR index if the two following conditions are met [29]:

Condition 1: If alternatives A_1 and A_2 hold the first and the second ranks among the m alternatives, the following equation, Eq. (14) shall be met:

$$Q(A_2) - Q(A_1) \geq \left[\frac{1}{m-1}, \frac{1}{m-1} \right]. \quad (14)$$

Condition 2: Alternative A_1 shall be recognized as the superior rank, at least in one of the R or S groups.

In the case that the first condition is not met, all the alternatives are considered to be the best alternatives. Moreover, if the second condition is not met, both Alternatives will be selected as the best alternatives.

Step 1. To start with the Grey TOPSIS Method, the DM should be normalized. The process of normalizing is as follows [30]:

$$\otimes f_{ij} = \left[\frac{-\otimes \overline{G_{ij}}}{\otimes G_j^{\min}} + 2, \quad \frac{-\otimes G_{ij}}{\otimes G_j^{\min}} + 2 \right], \quad \otimes G_j^{\min} = \min_{1 \leq i \leq m} \{ \otimes G_{ij} \}, \text{ for Cost Criterion.} \quad (15)$$

$$\otimes f_{ij} = \left[\frac{\otimes G_{ij}}{\otimes G_j^{\max}}, \quad \frac{\otimes \overline{G_{ij}}}{\otimes G_j^{\max}} \right], \quad \otimes G_j^{\max} = \max_{1 \leq i \leq m} \{ \otimes \overline{G_{ij}} \}, \text{ for Benefit Criterion.} \quad (16)$$

$$A^+ = \{f_1^+, f_2^+, \dots, f_n^+\} = \left\{ \left(\max_i f_{ij}^u \mid j \in B \right) \text{ or } \left(\min_i f_{ij}^l \mid j \in C \right) \right\}. \quad (17)$$

$$A^- = \{f_1^-, f_2^-, \dots, f_n^-\} = \left\{ \left(\min_i f_{ij}^l \mid j \in B \right) \text{ or } \left(\max_i f_{ij}^u \mid j \in C \right) \right\}. \quad (18)$$

Step 2. The next step is determining the NIS and the PIS based on the following equations.

Where B is the set of benefit criteria, while C is the set of cost criteria.

Step 3. Calculate the Euclidean distance from the PIS as D_i^+ , and the Euclidean distance from the NIS as D_i^- .

$$D_i^+ = \sqrt{\frac{1}{2} \left(\sum_{j=1}^m W_j \left[\left(f_j^+ - f_{ij}^l \right)^2 + \left(f_j^+ - f_{ij}^u \right)^2 \right] \right)}. \quad (19)$$

$$D_i^- = \sqrt{\frac{1}{2} \left(\sum_{j=1}^m W_j \left[\left(f_j^- - f_{ij}^l \right)^2 + \left(f_j^- - f_{ij}^u \right)^2 \right] \right)}. \quad (20)$$

Step 4. Calculate the closeness grade of TOPSIS based on the D_i^+ and D_i^- that have been calculated in the previous step.

$$C_i = \frac{(D_i^-)^2}{(D_i^+)^2 + (D_i^-)^2}. \quad (21)$$

4 | Numerical Example

In this section, a real case for multi-criteria inventory classification of items has been done from the General Mechanic and Standardization (GMS) Ordering Group of Sarcheshmeh Copper Complex to verify the proposed Grey Hungarian. Sarcheshmeh Copper Complex is one of the world's largest open deposit copper mines that produces copper products such as 8 mm Copper Rods, Copper Slabs, and non-copper materials such as Sulfuric Acid and Slime. In this research, four items based on the opinion of an expert from the GMS Ordering Group have been introduced to be ranked by the two criteria: "Scarcity" and "Availability of the Technical Specifications". According to the two qualitative criteria that the mentioned expert has considered, the information for these four items has been converted to quantitative grey numbers based on [31] and summarized in *Table 2*.

Table 2. Initial information and grey DM.

Name of Items		Scarcity (C1)		Availability of the Technical Specifications (C2)	
A ₁	LINK, CRAWLER 36" for DRILL MODEL: BE 45 _R	High	[6,8]	High	[6,8]
A ₂	C-CLAMPS PIN	Medium	[4,6]	Medium	[4,6]
A ₃	CORE-VALVE TIRE WHEEL GP. for SLAG POT 621B	Low	[2,4]	Low	[2,4]
A ₄	SCREW BRASS -FLAT HEAD 3/8"X15/16" UNC TPI=16	Very Low	[1,2]	Very Low	[1,2]

Since the policy of GMS Ordering Group is to order items for Sarcheshmeh Copper Complex, then based on the mentioned criteria, the supplying of an item will be highly ranked from the point of view of "Scarcity" the item has been ranked high, so "Scarcity" is a Benefit criterion. On the other hand, based on another criterion, which is "Availability of Technical Specification," whether the specification of an item is unavailable, then the supplying process of the item because of the unavailability of the specification of the product is difficult, so the "Availability of Technical Specifications" will be taken into account as a cost criterion. Moreover, the weights of these two criteria have been evaluated by linguistic variables according to the expert's opinion as "Extremely Important," which have been converted to a grey number as [0.8, 1], based on previous research that has been done by [32]. Hence, the ranking of inventory items based on these two criteria will be summarized in Table 3. In the following, based on the acquired data from the GMS Ordering Group of Sarcheshmeh Copper Complex, two solution methods, the GHA and the Grey VIKOR method, have been developed for the real case for multi-criteria inventory classification of items of the GMS group.

As can be seen from Table 2, the available data in this table are cardinal. Hence, for using the data by the LAM, the data has been converted into ordinal data based on two previously mentioned criteria, "Scarcity," a Benefit criterion, and "availability of the technical specifications," a cost criterion.

Table 3. Ranking of alternatives according to each criterion.

	Scarcity (C1) (Benefit Criteria)	Availability of the Technical Specifications (C2) (Cost Criteria)
A1	1 st Rank	4 th Rank
A2	2 nd Rank	3 rd Rank
A3	3 rd Rank	2 nd Rank
A4	4 th Rank	1 st Rank

4.1 | Results

After identifying the real case in the following, the case will be solved by GHA, Grey VIKOR, and Grey TOPSIS to show the validity of the proposed GHA.

4.1.1 | Grey Hungarian Algorithm

In this section, based on Table 3, Table 4 has been constructed by considering each criterion's weight. As seen from Table 3, A1 has been ranked as the first rank according to the C1 criterion, while it has been considered the fourth rank based on the C2 criterion. Hence, in Table 4 in the A1 row, under First rank and Fourth rank, there will be amounts in the Table that for zero values are [0, 0] and for one value are [0.8, 1]. Table 4 is the DM of the LAM, which contains the objective function coefficients of the LAM Problem.

Table 4. The benefits matrix (objective function coefficients for the assignment problem).

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[0.8,1]	[0,0]	[0,0]	[0.8,1]
A ₂	[0,0]	[0.8,1]	[0.8,1]	[0,0]
A ₃	[0,0]	[0.8,1]	[0.8,1]	[0,0]
A ₄	[0.8,1]	[0,0]	[0,0]	[0.8,1]

After obtaining the DM, to start solving the problem by GHA, the linear assignment model should be checked to determine whether it is maximization or minimization. If the model is in the form of maximization, then all the elements of *Table 4* will be multiplied by (-1). In this way, the problem will be transformed into a minimization problem, as seen in *Table 5*.

Then, by considering the existence of entirely negative grey numbers among the elements of *Table 5*, the grey number [0.8, 1], the highest existing symmetric number among all the grey numbers, will be added to all matrix elements. The results are shown in *Table 6*. Otherwise, there will be no need for any change at this step.

Table 5. Converting the problem from maximization to minimization.

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[-1,-0.8]	[0,0]	[0,0]	[-1,-0.8]
A ₂	[0,0]	[-1,-0.8]	[-1,-0.8]	[0,0]
A ₃	[0,0]	[-1,-0.8]	[-1,-0.8]	[0,0]
A ₄	[-1,-0.8]	[0,0]	[0,0]	[-1,-0.8]

For a maximization problem, by considering the existence of fully negative interval values among the elements of *Table 5*, the interval [0.8, 1], the highest existing symmetric value among the interval values, will be added to all elements of this matrix. The results are shown in *Table 6*.

Table 6. Adding the highest existing symmetric grey number.

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]
A ₂	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₃	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₄	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]

Subtracting row minima

In this step, the minimum grey number of each row will be subtracted from the entire grey numbers of that row that will change every grey number. However, because each row contains at least one zero interval, subtracting row minima does not affect the generated matrix.

Subtracting column minima

After subtracting row minima, the minimum grey number of every column will be subtracted from other grey numbers of that column. In this problem, subtracting column minima does not affect the matrix because each column has at least one zero interval.

Covering the generated matrix with minimal coverage lines

In this step, coverage lines with the minimum number of lines are drawn, according to the GHA, which has been explained previously. The results are shown in *Table 7*.

Table 7. The drawn coverage lines.

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]
A ₂	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₃	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₄	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]

The optimal solution has been obtained since all rows and columns of the matrix were drawn with at least a coverage line. However, this problem has multiple optimal solutions, as has been shown in Table 8 and Table 9.

Solution 1:

- A₁ = 1st Rank,
- A₂ = 2nd Rank,
- A₃ = 3rd Rank,
- A₄ = 4th Rank.

Solution 2:

- A₄ = 1st Rank,
- A₃ = 2nd Rank,
- A₂ = 3rd Rank,
- A₁ = 4th Rank.

Table 8. First solution.

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]
A ₂	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₃	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₄	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]

Table 9. Second solution.

	1 st Rank	2 nd Rank	3 rd Rank	4 th Rank
A ₁	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]
A ₂	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₃	[0.8,1]	[-0.2,0.2]	[-0.2,0.2]	[0.8,1]
A ₄	[-0.2,0.2]	[0.8,1]	[0.8,1]	[-0.2,0.2]

4.1.2 | Grey VIKOR

In this section, the Grey VIKOR method is based on [27], except for the normalization of the DM that is proposed in this research.

Normalizing the elements of DM

If the criterion type is a Cost criterion, Eq. (5) will be applied for normalization to normalize the elements of the DM. For the benefit criterion, Eq. (6) will be used [21], [33]. The results can be seen in Table 10.

Table 10. Normalized DM elements.

	C ₁	C ₂
A ₁	[0.75,1]	[0,0.25]
A ₂	[0.5,0.75]	[0.25,0.5]
A ₃	[0.25,0.5]	[0.5,0.75]
A ₄	[0.125,0.25]	[0.75,0.875]

In this step, the Positive and NISs are calculated based on *Eqs. (7) and (8)*, and are shown in *Table 11*.

Table 11. Positive and NISs.

	C ₁	C ₂
f_j^+	1	0
f_j^-	0.125	0.875

Calculating satisfaction and regret index

Satisfaction and Regret Index will be calculated based on *Eqs. (9) and (10)*, and will be shown in the following Table (*Table 12*):

Table 12. The satisfaction and regret index.

	$[S_i^L, S_i^U]$	$[R_i^L, R_i^U]$
A ₁	[[0,0], [0.457,0.571]]	[[0,0], [0.229,0.286]]
A ₂	[[0.457,0.571], [0.914,1.143]]	[[0.229,0.286], [0.457,0.571]]
A ₃	[[0.914,1.143], [1.371,1.714]]	[[0.457,0.571], [0.686,0.857]]
A ₄	[[1.371,1.714], [1.6,2]]	[[0.686,0.857], [0.8,1]]

To simplify the computation of the VIKOR index, a whitening method derived from [23] is used according to *Eq. (22)*. The results are presented in *Table 13*.

$$\otimes m = [a, b] \Rightarrow \otimes m = \alpha a + (1 - \alpha)b. \quad (22)$$

Table 13. Whitening values for the previous Table.

	$[S_i^L, S_i^U]$	$[R_i^L, R_i^U]$
A ₁	[0,0.514]	[0,0.257]
A ₂	[0.514,1.029]	[0.257,0.514]
A ₃	[1.029,1.543]	[0.514,0.771]
A ₄	[1.543,1.8]	[0.771,0.9]

Calculating the VIKOR index

In this step, the VIKOR index, based on *Eq. (11)* will be calculated as shown in *Table 14*.

Table 14. VIKOR index.

	$[Q_i^L, Q_i^U]$
A ₁	[0,0.286]
A ₂	[0.286,0.571]
A ₃	[0.571,0.857]
A ₄	[0.857,1]

Ranking the alternatives and finding the best alternative

Considering the VIKOR algorithm, the alternative with the least value $[Q_i^L, Q_i^U]$ is the best.

$$P\left([0,0.286] > [0.286,0.571]\right) = \frac{\max(0, (0.286 - 0.286)) - \max(0, (0 - 0.571))}{(0.286 - 0) + (0.571 - 0.286)} = 0 < 0.5,$$

$$P\left([0.286,0.571] > [0.571,0.857]\right) = \frac{\max(0, (0.571 - 0.571)) - \max(0, (0.286 - 0.857))}{(0.571 - 0.286) + (0.857 - 0.571)} = 0 < 0.5,$$

$$P\left([0.571,0.857] > [0.857,1]\right) = \frac{\max(0, (0.857 - 0.857)) - \max(0, (0.571 - 1))}{(0.857 - 0.571) + (1 - 0.857)} = 0 < 0.5.$$

So, according to the VIKOR index and Grey Preference Degree Relation, the ranking for the GMS inventory items is as follows:

- $A_1 = 1^{st}$ Rank,
- $A_2 = 2^{nd}$ Rank,
- $A_3 = 3^{rd}$ Rank,
- $A_4 = 4^{th}$ Rank.

Now, two previously mentioned conditions will be checked to find the best alternative in the Grey VIKOR algorithm.

Condition 1:

$$Q(A_2) - Q(A_1) \geq \left[\frac{1}{5-1}, \frac{1}{5-1} \right], \quad (23)$$

$$[0.286, 0.571] - [0, 0.286] \geq [0.25, 0.25].$$

Condition 2: Alternative A_1 in both R and S interval values ranks first among other alternatives. So, both A_1 and A_2 are the best alternatives.

4.1.3 | Grey TOPSIS

The same problem has been solved by the Grey TOPSIS method derived from [30]. The results of Grey TOPSIS are as follows:

- $A_1 = 1^{st}$ Rank,
- $A_2 = 2^{nd}$ Rank,
- $A_3 = 3^{rd}$ Rank,
- $A_4 = 4^{th}$ Rank.

4.2 | Sensitivity Analysis

In this section, it is assumed that the opinions of the GMS ordering group have been changed. For this case, the DM is as what is in Table 15.

Table 15. Change in the information of DM.

	Name of Items	Scarcity (C1)		Availability of the Technical Specifications (C2)	
A ₁	LINK, CRAWLER 36" FOR DRILL MODEL: BE 45 _R	Medium	[4,6]	Medium	[4,6]
A ₂	C-CLAMPS PIN	High	[6,8]	High	[6,8]
A ₃	CORE-VALVE TIRE WHEEL GP. FOR SLAG POT 621B	Very low	[1,2]	Very Low	[1,2]
A ₄	SCREW BRASS -FLAT HEAD 3/8"X15/16" UNC TPI=16	Low	[2,4]	Low	[2,4]

For this case, the problem has been solved by GHA, Grey VIKOR, and Grey TOPSIS. The results for this case will be changed as follows:

- A₁ = 1st Rank,
- A₂ = 2nd Rank,
- A₃ = 3rd Rank,
- A₄ = 4th Rank.

As can be seen from the results, all the priorities for the parts have been changed according to the change in the DM, but all the methods have been prioritized in the same order.

4.3 | Discussion

The GHA was developed in this study to solve the Grey LAPs. Then, a real case from the GMS Ordering Group of Sarcheshmeh Copper Complex was solved by GHA and two other methods: Grey VIKOR and Grey TOPSIS. Based on the obtained ranks that have been provided by GHA, Grey VIKOR, and Grey TOPSIS for the initial case, and also the case for sensitivity analysis, the Spearman's correlation coefficient rank has been calculated according to Eq. (24) that is derived from [33].

$$\rho = 1 - \frac{6 \sum_{a=1}^A D_a^2}{A(A^2 - 1)} \quad (24)$$

In Eq. (24), A is the total number of alternatives, and D_a indicates the difference between the ranks obtained from different MADM methods for alternative a. The results for Spearman's Correlation Coefficient Rank have been summarized in Table 16.

Table 16. Results of Spearman's correlation coefficient rank.

	Grey TOPSIS	Grey VIKOR	Grey Hungarian 1 st Solution	Grey Hungarian 2 nd Solution
Grey TOPSIS	----	1.000**	1.000**	-1.000**
Grey VIKOR	1.000**	----	1.000**	-1.000**
Grey Hungarian 1 st Solution	1.000**	1.000**	----	-1.000**
Grey Hungarian 2 nd Solution	-1.000**	-1.000**	-1.000**	----

The results show the validity of the two solution methods proposed in this study, the GHA and the Grey VIKOR method. Compared to other approaches, the advantage of using the GHA is that it finds multiple optimal solutions where more than one optimal solution is available.

5 | Conclusion

In this study, because of the necessity of considering uncertainty in making decisions, the GHA was developed based on the grey numbers operation rules and the concept of the grey preference degree. To show the validity of the proposed GHA approach, a real case from the Sarcheshmeh Copper

Complex warehouse has been solved and compared to the results of Grey VIKOR and grey TOPSIS. The identical results for all the solution approaches in the initial case and after the sensitivity analysis imply the validity of the proposed solution method. When there is poor information, and the data distribution or membership function is not available, using the GHA and other grey approaches is reasonable. If there is a lack of experience or a small size of data sampling, the grey methods application is not recommended. As a suggestion for future research, it is recommended to modify the method to overcome this limitation. The use of uncertainty concepts, which, in addition to grey numbers, leads to a combination of grey numbers and fuzzy sets, is recommended.

Acknowledgments

The Sarcheshmeh Copper Complex partially supported this study. Hence, the authors express sincere thanks for their partial support. Also, the authors intend to thank the anonymous reviewers for their valuable comments that improved this paper.

References

- [1] Kuhn, H. W. (1955). The Hungarian method for the assignment problem. *Naval research logistics quarterly*, 2((1-2)), 83–97. DOI:10.1007/978-3-540-68279-0_2
- [2] Das, S. K., & Deo, N. (1990). Parallel hungarian algorithm. *Computer systems science and engineering*, 5(3), 131-136. <https://stars.library.ucf.edu/scopus1990/1508/>
- [3] Ishibuchi, H., & Tanaka, H. (1990). Multiobjective programming in optimization of the interval objective function. *European journal of operational research*, 48(2), 219–225. DOI:10.1016/0377-2217(90)90375-L
- [4] Aldous, D. (1992). Asymptotics in the random assignment problem. *Probability theory and related fields*, 93(4), 507–534. DOI:10.1007/BF01192719
- [5] Li, T., Li, Y., & Qian, Y. (2016). Improved Hungarian algorithm for assignment problems of serial-parallel systems. *Journal of systems engineering and electronics*, 27(4), 858–870.
- [6] Rajabi-Alni, F., & Bagheri, A. (2022). Computing a many-to-many matching with demands and capacities between two sets using the Hungarian algorithm. *Journal of mathematics*, 2023. <https://doi.org/10.1155/2023/7761902>
- [7] Bai, G. Z. (2009). Grey assignment problems. In *Fuzzy information and engineering* (pp. 245-250). Springer Berlin Heidelberg. https://link.springer.com/chapter/10.1007/978-3-540-88914-4_31
- [8] Majumdar, S. (2013). Interval linear assignment problems. *Journal of applied mathematics*, 1(6), 14–16.
- [9] Serratos, F. (2015). Computation of graph edit distance: Reasoning about optimality and speed-up. *Image and vision computing*, 40, 38–48.
- [10] Serratos, F., & Cortés, X. (2015). Graph edit distance: Moving from global to local structure to solve the graph-matching problem. *Pattern recognition letters*, 65, 204–210.
- [11] Lan, S., Fan, W., Liu, T., & Yang, S. (2019). A hybrid SCA--VNS meta-heuristic based on Iterated Hungarian algorithm for physicians and medical staff scheduling problem in outpatient department of large hospitals with multiple branches. *Applied soft computing*, 85, 105813. <https://www.sciencedirect.com/science/article/abs/pii/S1568494619305940>
- [12] Yadav, S. S., Lopes, P. A. C., Ilic, A., & Patra, S. K. (2019). Hungarian algorithm for subcarrier assignment problem using GPU and CUDA. *International journal of communication systems*, 32(4), e3884. <https://doi.org/10.1002/dac.3884>
- [13] Khan, A. A., Adve, R. S., & Yu, W. (2020). Optimizing downlink resource allocation in multiuser MIMO networks via fractional programming and the hungarian algorithm. *IEEE transactions on wireless communications*, 19(8), 5162–5175.
- [14] Yang, X., Zhao, N., & Yu, S. (2020). Combined internal trucks allocation of multiple container terminals with hungarian algorithm. *Journal of coastal research*, 103(SI), 923–927.
- [15] Kumarnath, J., & Batri, K. (2021). An optimized traffic grooming through modified pso based iterative hungarian algorithm in optical networks. *Information technology and control*, 50(3), 546–557.

- [16] MacLean, M. T., Lysikowski, J. R., Rege, R. V., Sendelbach, D. M., & Mihalic, A. P. (2021). Optimizing medical student clerkship schedules using a novel application of the Hungarian algorithm. *Academic medicine*, 96(6), 864–868.
- [17] Stevens, P., & Sciacchitano, A. (2021). Application of clustering and the Hungarian algorithm to the problem of consistent vortex tracking in incompressible flowfields. *Experiments in fluids*, 62, 1–11.
- [18] Zhu, Z., Lou, K., Ge, H., Xu, Q., & Wu, X. (2022). Infrared target detection based on Gaussian model and Hungarian algorithm. *Enterprise information systems*, 16(10–11), 1573–1586.
- [19] Zhang, S., Xue, Y., Zhang, H., Zhou, X., Li, K., & Liu, R. (2023). Improved Hungarian algorithm--based task scheduling optimization strategy for remote sensing big data processing. *Geo-spatial information science*, 1–14. <https://doi.org/10.1080/10095020.2023.2178339>
- [20] Xie, N., & Liu, S. (2010). Novel methods on comparing grey numbers. *Applied mathematical modelling*, 34(2), 415–423.
- [21] Li, G. D., Yamaguchi, D., & Nagai, M. (2007). A grey-based decision-making approach to the supplier selection problem. *Mathematical and computer modelling*, 46(3–4), 573–581.
- [22] Tseng, M. L. (2009). A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. *Expert systems with applications*, 36(4), 7738–7748.
- [23] Liu, S., & Lin, Y. (2006). Grey clusters and grey statistical evaluations. In *Grey information: theory and practical applications* (pp. 139–189). Springer. https://link.springer.com/chapter/10.1007/1-84628-342-6_6
- [24] Sadeghieh, A., Dehghanbaghi, M., Dabbaghi, A., & Barak, S. (2012). A genetic algorithm based grey goal programming (G3) approach for parts supplier evaluation and selection. *International journal of production research*, 50(16), 4612–4630.
- [25] Moore, R. E. (1979). *Methods and applications of interval analysis*. SIAM. <https://epubs.siam.org/doi/pdf/10.1137/1.9781611970906.bm>
- [26] Winston, W. L. (2004). *Operations research: applications and algorithm*. Thomson Learning, Inc. https://www.academia.edu/download/58159784/Winston_4th_ed.pdf
- [27] Sayadi, M. K., Heydari, M., & Shahanaghi, K. (2009). Extension of VIKOR method for decision making problem with interval numbers. *Applied mathematical modelling*, 33(5), 2257–2262.
- [28] Sevastianov, P. (2007). Numerical methods for interval and fuzzy number comparison based on the probabilistic approach and Dempster--Shafer theory. *Information sciences*, 177(21), 4645–4661.
- [29] Parkouhi, S. V., & Ghadikolaie, A. S. (2017). A resilience approach for supplier selection: Using Fuzzy Analytic Network Process and grey VIKOR techniques. *Journal of cleaner production*, 161, 431–451.
- [30] Lin, Y. H., Lee, P. C., & Ting, H.-I. (2008). Dynamic multi-attribute decision making model with grey number evaluations. *Expert systems with applications*, 35(4), 1638–1644.
- [31] Nguyen, H. T., Dawal, S. Z. M., Nukman, Y., & Aoyama, H. (2014). A hybrid approach for fuzzy multi-attribute decision making in machine tool selection with consideration of the interactions of attributes. *Expert systems with applications*, 41(6), 3078–3090.
- [32] Esangbedo, M. O., & Che, A. (2016). Grey weighted sum model for evaluating business environment in West Africa. *Mathematical problems in engineering*, 2016. <https://www.hindawi.com/journals/mpe/2016/3824350/abs/>
- [33] Baykasouglu, A., Subulan, K., & Karaslan, F. S. (2016). A new fuzzy linear assignment method for multi-attribute decision making with an application to spare parts inventory classification. *Applied soft computing*, 42, 1–17.



Publisher: Ayandegan Institute of Higher Education, Iran.

Director-in-Charge: M. Fallah

Editor-in-Chief: F. Hosseinzadeh-Lotfi

Scientific & Executive Manager: S. A. Edalatpanah

International Journal of Research in Industrial Engineering is an international scholarly open access, peer-reviewed, interdisciplinary, and fully refereed journal published quarterly. This journal provides a domain for professionals, academicians, researchers, policymakers, and practitioners working in the fields of industrial engineering, reliability engineering, TQM, management, applied mathematics, and globalization to present their research findings, propose new methodologies, disseminate the latest findings, and to learn from each other's research directions.